



Quantitatively mapping the research status and trends of vegetation responses to climate change with bibliometric analysis

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Abstract

Purpose Vegetation is a typical sensitive indicator of climate change, and therefore provides theoretical and valuable information for addressing issues arising from climate change including improving soil ecosystem services. Exploring how vegetation responses to climate change has become one of major hotspots of research. However, few scholars have performed bibliometric analyses of this field. This study investigated the current research activities and the trend developments of vegetation responses to climate change.

Materials and methods We conducted a quantitative bibliometric analysis of 2,310 publications on vegetation responses to climate change from 1991 to 2021 retrieved in the Web of Science Core Collection. The analysis comprised significant journals, disciplines, and scholars, as well as partnerships between countries and institutions, keyword co-occurrence and burst analysis. The bibliometric analysis tools, Histcite, Vosviewer, CiteSpace software, and R (Bibliometrix package), were applied.

Results and discussion The related publications on vegetation responses to climate change had been increasing exponentially in the past 30 years and its total global cited score reached its peak in 2010. The USA and China were the leading countries, with the Chinese Academy of Sciences having the highest number of publications and citations. The scholars who had the most citations were Allen CD, Bresears DD, and Running SW. Six research clusters were generated by keywords co-occurrence analysis, including impact, response, CO₂, growth, climate change, and vegetation. These clusters represented the current research topics that highlighted the responses of vegetation to climate change, the manifestation of its impact, and coping strategies. In future research on vegetation, the emphasis is expected to be placed on “human activities” and “N₂O emission”.

Conclusion This study has performed a comprehensive and systematic and quantitative analysis of the publications on the responses of vegetation to climate change. The results reveal the characteristics, development patterns, and research trends of studies on vegetation activity in response to climate change, which sheds new insights into understanding the relationship between soil and climate.

Keywords Vegetation · Climate change · Bibliometrics · Keywords co-occurrence · Research status · Trend and prospect

1 Introduction

Vegetation can be a sensitive indicator of climate change (Sun et al. 2010; Xu et al. 2014; Fu et al. 2020; Succarie et al. 2020, 2022; Liu et al. 2021). Changes in vegetation activity are critical for understanding the mechanisms of climate

change impacts on ecosystem structure and functions (Ito and Inatomi 2012; Piao et al. 2019). Some studies have revealed that increased atmospheric carbon dioxide concentration has heightened the sensitivity of dryland vegetation to precipitation, resulting in increased water use efficiency and noted greening in tropical and high-latitude regions (Keenan et al. 2013; Zhang et al. 2022a). Nonetheless, it has been shown that extreme weather events and drought “legacy effects” can cause direct harm to vegetation and reduce its growth (Ciais et al. 2005; Anderegg 2015; Schwalm et al. 2017; Yang et al. 2023). Climate change has also taken responsibility

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for significant alterations in biodiversity and species replacement. Some research indicating that annual and perennial plants in turn dominate the primary ecological niche in the aftermath of drought and rainfall (Sun et al. 2022a, b). Moreover, the productivity and function of vegetation communities are strongly affected by climate change, resulting from the extension of vegetation growth cycles due to global warming, which is a principal reason for the noted rise in vegetation productivity (Piao et al. 2007). However, climate change may weaken vegetation productivity, potentially impacting negatively on the global land carbon sink (Zhang et al. 2022b). Conversely, vegetation can further influence the process of climate change by regulating soil moisture, improving soil quality, and increasing soil organic substance, which provides feedback on climate change (Higgins et al. 2023). Therefore, the systematic research on the relationship between vegetation and climate change, especially the responses of vegetation to climate change, is of great value to deeply understand the ecological processes and mechanisms above, while also facilitating the development of effective measures to cope with climate change (Zhang et al. 2018; Gillison 2019).

The adaptation of vegetation activities in responses to climate change performs nonlinear as influenced by a combination of multiple factors. Studies have widely reported that vegetation possesses the capacity to adapt to ever-changing environmental conditions, like variations in climate change with a currently marked acceleration (Keeling et al. 1976). This process is complex and dynamic, with responses largely reliant on the water and heat conditions in a given region. For example, the phenomenon of temperature-induced effects on photosynthesis is widely recognized (Prasad et al. 2008). Under suboptimal temperatures, photosynthesis may be stimulated, accompanied by an enhancement in soil nutrient release and nutrient use efficiency (Ow et al. 2010). However, exceeding the optimal temperature range may induce the depletion of nutrients, intensify drought effects, and trigger adverse consequences. Besides, fluctuations in precipitation also play a pivotal role in modulating vegetation activity. Climate change has the potential to induce notable alterations in the distribution, frequency, and intensity of precipitation, which may exert a profound influence on the water balance, productivity, and coverage of terrestrial ecosystems (Lavorel et al. 1998). When soil moisture content and the availability of moisture for vegetation alters due to the varying precipitation, the vegetation activity will be changed consequently (Wang et al. 2021).

The responses of vegetation activities to climate change are characterized by spatial heterogeneity (Torresan et al. 2008). The spatial heterogeneity of climate change, such as the uneven distribution of warming and cooling (Kaufmann et al. 2017), has engendered significant regional variation in the responses of vegetation activities to climate change. The findings of regional climate model simulations indicate

that the temperature increase is more pronounced in high latitude regions than in low latitude regions. For instance, vegetation zones shifted towards higher latitudes and altitudes, while specifically, the alpine grassland communities expand southward mostly to temperate grassland found in the Qinghai-Tibet Plateau region of China (Hu et al. 2017; Li et al. 2022).

Bibliometric analysis constitutes a quantitative and analytical method employed to study the publication progress, research trends, and keyword co-occurrence in specific fields. This comprehensive discipline integrates big data analysis, mathematical statistics, and computer science, and has been widely utilized across various fields (Chen 2017; Li et al. 2021). Recently, bibliometric approaches were used to investigate the impact of varied climate change phenomena, including high temperature, drought, and rising ozone concentration, on vegetation at different spatial scales (Verrall and Pickering 2020; Jimenez-Montenegro et al. 2021; Cui et al. 2022; Idris et al. 2022). Nonetheless, few bibliometric studies have hitherto focused on the overall impact of climate change on natural vegetation on a global scale. Even though a similar study has been conducted by Afuye et al. (2021) with a limited number of publications retrieved lacking the capability to fully represent the research status. Therefore, to further clarify the current vegetation research status and characteristics under climate change, a bibliometric study of this field is certainly necessary to be conducted. In this study, four visual analysis tools, namely Histcite, Vosviewer, CiteSpace, and R (Bibliometrix package), are employed to quantitatively analyze the publications on the impact of climate change on natural vegetation from 1991 to 2021. It is pertinent to note that in this study, vegetation pertains exclusively to natural vegetation, excluding artificial vegetation such as orchards, cultivated lands, and artificial grasslands. This study aimed to achieve three objectives: (1) reveal the publication evolution and trend of vegetation research under climate change globally, (2) summarize the current research statuses and hotspots, and (3) provide coping strategies for the future vegetation research under climate change.

2 Data and method

2.1 Publication search strategy

To comprehensively investigate the global landscape of research progress and trends pertaining to vegetation under climate change, the publications dataset in this study was sourced from the Web of Science (WOS) Core Collection Science Citation Index Expanded (SCI-Expand) in the 1991–2021 period. The strategy of the advanced search was selected after repeated tests (Fig. 1). By checking the records respectively in the original organized dataset based

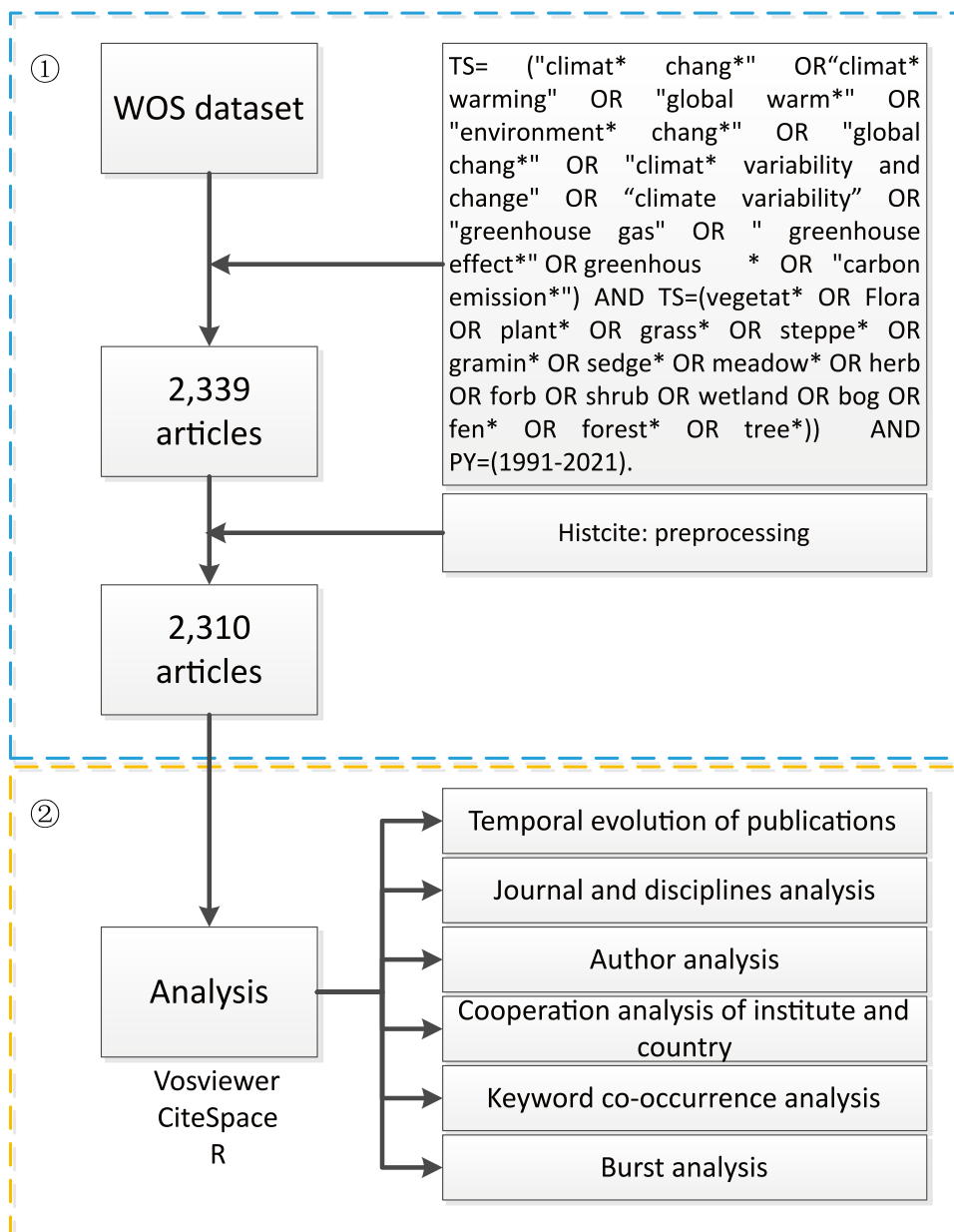
on the Hiscite software, the incorrect and duplicated publications were eliminated. The 2,310 unique publications were obtained within the final dataset for the further analysis.

2.2 Analysis software

Hiscite, a tool developed by Eugene Garfield, facilitates the analysis of a research field’s historiography through the citation relationships of publications, thereby enabling the identification of important publications and scholars as well as understanding the research landscape. For this study, Hiscite 12.03.07 was utilized for publication preprocessing and data cleaning, with selectively removing the publication featuring high information missing rates.

By analyzing the cluster and key nodes of the co-citation network, the complex relationships within retrieved publications can be uncovered (Chen 2013). Co-occurrence analysis on journals, institutes, authors and keywords, and the burst analysis were performed via Vosviewer 1.6.18 and CiteSpace 6.1R2 respectively in this study. Vosviewer, an open-source software developed by Van Eck and Waltman at Leiden University in 2009, is employed for bibliometric network visualization analysis, including the co-occurrence analysis, cooperative analysis, and co-citation analysis. Illustrated by an example of the keyword co-occurrence analysis mapping, nodes symbolize the given keywords and their size signifies the Total Link Strength (TLS), or alternatively recognize as

Fig. 1 The flow chart of the literature search and bibliometric analysis, including two steps: (1) literature search and preprocess and (2) bibliometric analysis



the co-occurrence strength. The significance of any two given keywords is demonstrated through the distance between their corresponding nodes and the number of links. Whenever two words are closely correlated, their respective nodes are in close proximity to one another, and the connection between them are more pronounced or thicker, signifying a strong relationship between the two keywords with respect to their corresponding research topics. CiteSpace, developed by Chen C at Drexel University, is a Java-based platform for analyzing and visualizing co-citation network analysis. The software analyzes the literature status at each time point of a time series to infer the evolutionary trends in the specific research field (Chen 2017). Data visualization was also carried out through Bibliometrix, a free R package developed by Aria M's team at the Federico II University of Naples, Italy in 2017. In this study, the network analysis of collaborations between countries was conducted by Bibliometrix (Aria and Cuccurullo 2017).

3 Results

3.1 Temporal evolution of publications

A significant increase had existed in publications related to vegetation research in the context of climate change over the past 30 years (Fig. 2). This period can be roughly divided into three stages based on the publication growth rate. At the first stage, before 2010, the annual volume of publication did not exceed 50, displaying a gradual growth rate of approximately 2.2 publications per year. The second stage, after 2010, saw a significant increase in the number of publications with over 100 annually and an average rate of nearly

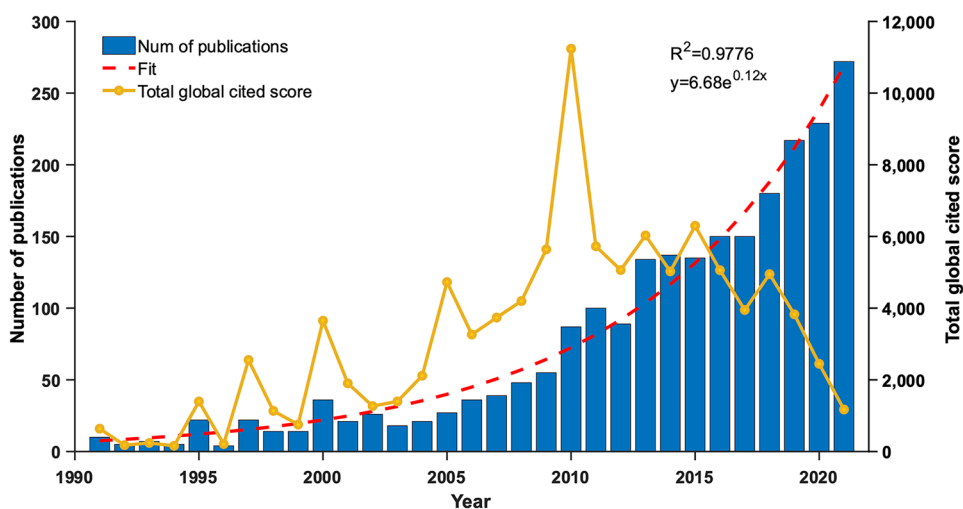
10 publications per year. The third stage, after 2017, witnessed a further surge in the number of publications, which can be attributed in part to the intensified debate over climate change, especially after the Paris Agreement was adopted at the United Nations Climate Change Conference in 2015. This agreement aimed to restrict global temperature increase in this century to below 2°C. As of 2021, 272 publications had been published, with an annual growth rate of 28.8%.

Furthermore, the total cited frequency of the publications showed a cutoff point in 2010, where the maximum number of citations reached 11,237. Prior to this, there were small peaks in 1995, 1997, 2000, and 2005, exhibiting rising volatility. However, the total number of citations in the publications remained relatively stable after 2010, which may indicate that it takes longer for recent publications to gain attention (Fig. 2).

3.2 Journals and disciplines analysis

The dataset included more than 86% of research publications, published in 495 journals. The number of publications from the top 20 journals amounted to 789, accounting for approximately 34.16% of the total, followed Pareto's principle, indicating that these journals were the mainstream sources in this field (Fig. 3a). Among the top 20 journals, *Global Change Biology* had the highest number of publications (130) and the highest journal impact factor (10.863 in 2021), ranking among the top 25% (Q1) of Journal Citation Report (JCR). The total number of citations of related publications in this journal reached 12,251. Notably, the top 10 journals did not include top comprehensive journals such as *Nature* and *Science*. Instead, the top 10 journals were more recognized by the professional and were the primary source for tracking the latest research

Fig. 2 The annual trend of the number of publications and the total citation scores from 1991 to 2021



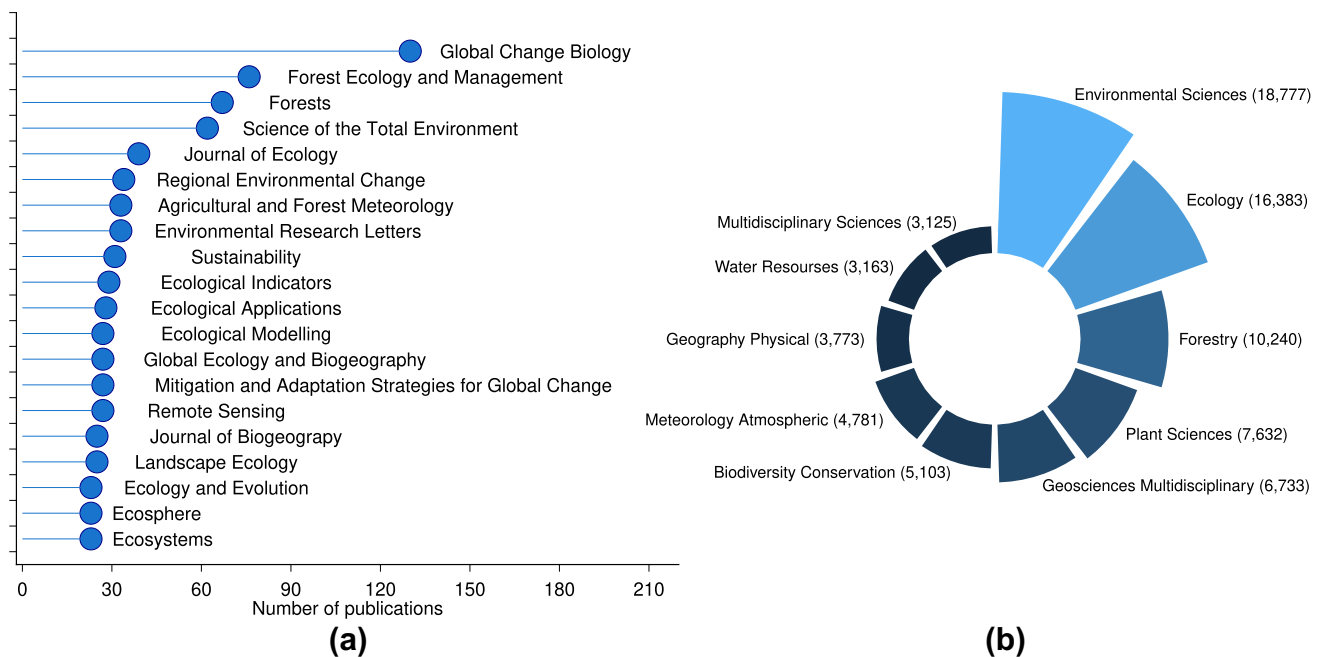


Fig. 3 Number of publications in the top 20 journals in the field (a), Top 10 disciplines in the total number of cited journals (b)

progress. Additionally, comprehensive journals covered a wide range of content, which could be a reason for the large number of the related publications in those journals. Moreover, the top 10 disciplines in this field were also identified based on their total citations (Fig. 3b). These categories were Environmental Science (18,777 citations), Ecology (16,383 citations), Forestry (10,240 citations), Plant Sciences (7,632 citations), Geosciences Multidisciplinary (6,733 citations), Biodiversity Conservation (5,103 citations), Meteorology Atmospheric (4,781 citations), Geographic Physical (3,773 citations), Water Resources (3,163 citations), and Multidisciplinary Sciences (3,125 citations). Environmental Science and Ecology received the most attention in our dataset.

3.3 Authors analysis

The cooperation network of authors who published at least 5 publications were grouped into 6 distinct clusters (Fig. 4a). The red cluster, represented by Piao S from Peking University, exhibited the highest level of cooperation with the other five teams. This group predominantly composed of Chinese scholars, underscoring the significant research activity among Chinese researchers in the related field of vegetation responses to climate change.

Among the top five authors ranked by the number of research output, Scheller RM came in first with 17 publications, followed by Lindner M with 15 publications, Penuelas J with 14 publications, and Bugmann H and Iverson LR with 13 publications respectively (Fig. 4b). Scheller RM published the

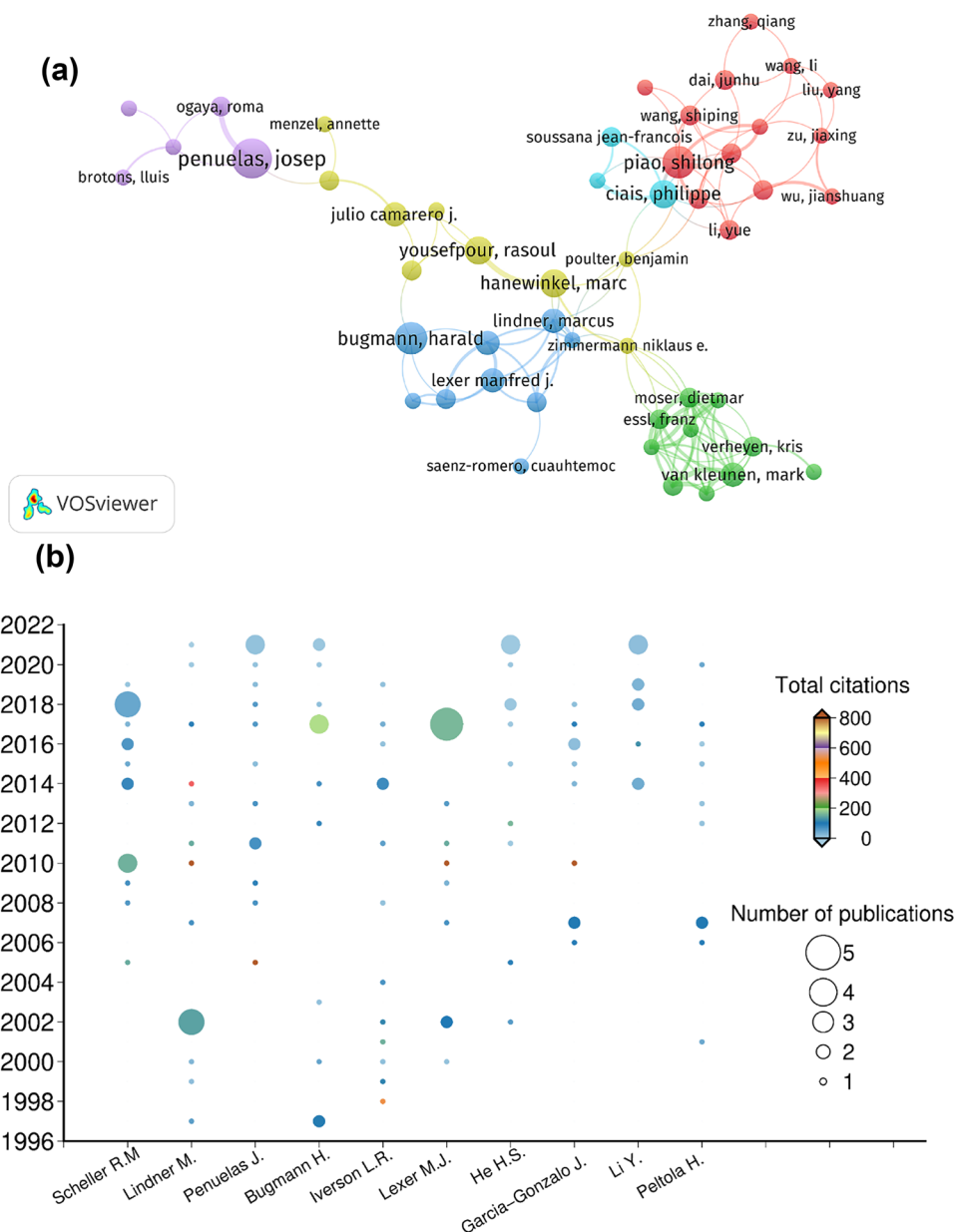
most publications with the first publication published in 2005 and had continued to produce at a steady pace, with three publications published in 2010 and four publications published in 2018. For the top 10 scholars, most of their research achievements were concentrated after 2010, except for Lindner M and Iverson LR, who both started publishing relevant publications in 1997 and have maintained a strong research presence. Notably, Li Y published his first research on vegetation under global change in 2014, but by 2021, his cumulative publications had placed him among the top 10 authors.

Furthermore, based on the number of citations, Allen CD, Breshears DD, and Running SW emerged as highly influential figures in this area, with citation counts of 5,913, 5,760, and 4,964, respectively. Notably, these three authors were not identified as the top productive authors, indicating the authors with the highest citation counts did not necessarily publish the most publications. Instead, researchers who collaborated with these highly cited authors often received more citations, even if they did not appear as the first authors or correspondents in the affiliation. This highlighted the importance of using representative works to accurately evaluate scholars' academic output.

3.4 Cooperation analysis of institutes and countries

The analysis revealed that Europe played a central role in this research field, with active and frequent collaborations with the USA and Canada, indicating their strong research capabilities and extensive international cooperation

Fig. 4 Author cooperation network of the research studies of vegetation responses to climate change (a), comparison of annual publications and citations of top 10 scholars in the research studies of vegetation responses to climate change (b)



(Fig. 5a). Meanwhile, the USA and Canada maintained close research cooperation with China and Australia, demonstrating a robust research network across continents. In total, 28 countries had published more than 25 publications in the field. The top-ranking countries were the USA (637 publications), China (510 publications), Canada (257 publications), and Germany (232 publications). The USA emerged as the leading country in terms of the number of publications published in the field, with China following closely behind in second place.

Additionally, 25 academic institutions which had published more than 20 publications in the field of vegetation responses to climate change research were also identified, which enabled them to be grouped into four distinct clusters

(Fig. 5b). The green cluster, represented by Chinese Academy of Sciences (228 publications), University of Chinese Academy of Sciences (81 publications), and Beijing Normal University (29 publications) had the highest number of publications and demonstrated the closest cooperation with other academic institutions or universities. The red cluster represented by United States Forest Service (74 publications), United States Geological Survey (37 publications), and Colorado State University (27 publications). The yellow cluster included the University of British Columbia (43 publications) and National Resource Centre of Canada (38 publications). Finally, the blue cluster is featured by Swedish University of Agricultural Sciences (29 publications) and University of Freiburg (25 publications).

Fig. 5 Network distribution of research cooperation between countries and regions in the research of vegetation response to climate change (a), cooperative distribution of institutions in vegetation research (b)

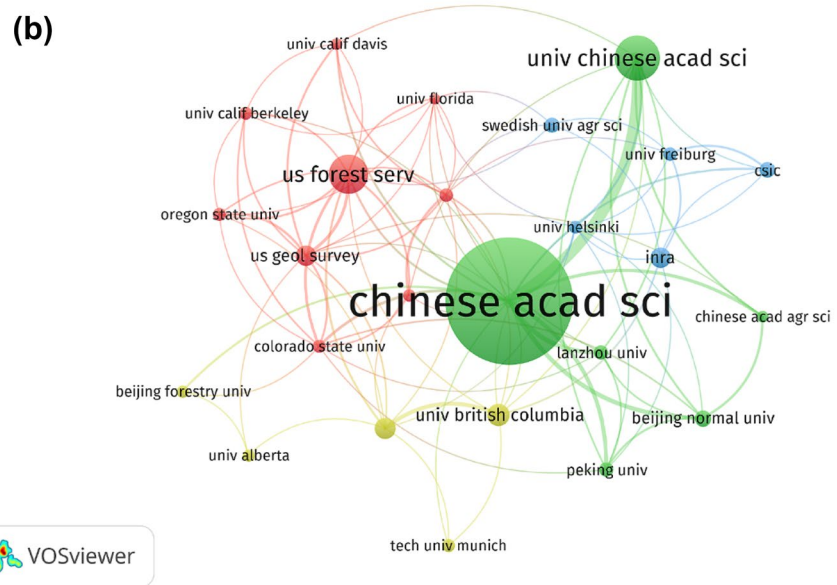
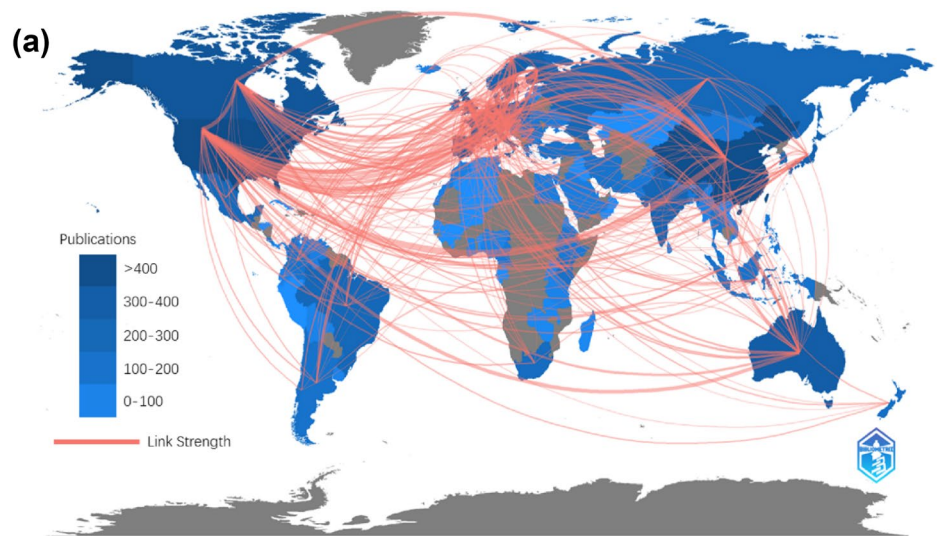
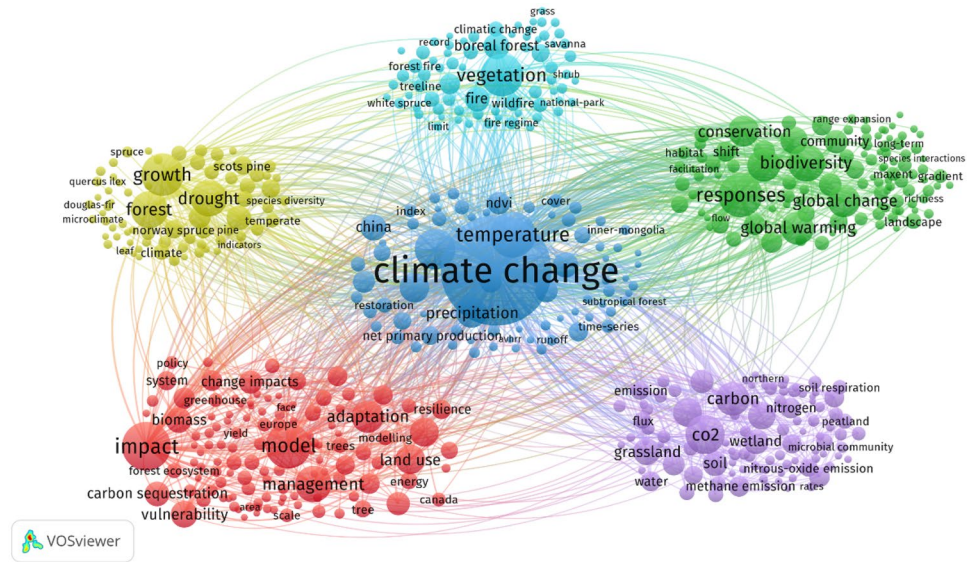


Table 1 Top 20 keywords in the field of the research of vegetation responses to climate change from 1991 to 2021

R	Keywords	O	C	TLS	R	Keywords	O	C	TLS
1	Climate change	1,493	5	7,084	11	Drought	179	4	1,052
2	Impact	312	1	1,865	12	Management	180	1	1,024
3	Temperature	276	5	1,601	13	Forest	181	4	1,020
4	Response	251	2	1,528	14	Diversity	150	2	950
5	Model	268	1	1,526	15	Carbon	156	3	928
6	Growth	239	4	1,367	16	Adaptation	143	1	811
7	Dynamic	217	5	1,299	17	Precipitation	132	5	798
8	Vegetation	238	6	1,281	18	Conservation	128	2	769
9	CO ₂	204	3	1,230	19	Global change	142	2	728
10	Biodiversity	185	2	1,220	20	Land use	121	1	707

R Ranking, O Occurrences, C Clusters, TLS Total Link Strength

Fig. 6 Keywords co-occurrence mapping for the research of vegetation responses to climate change



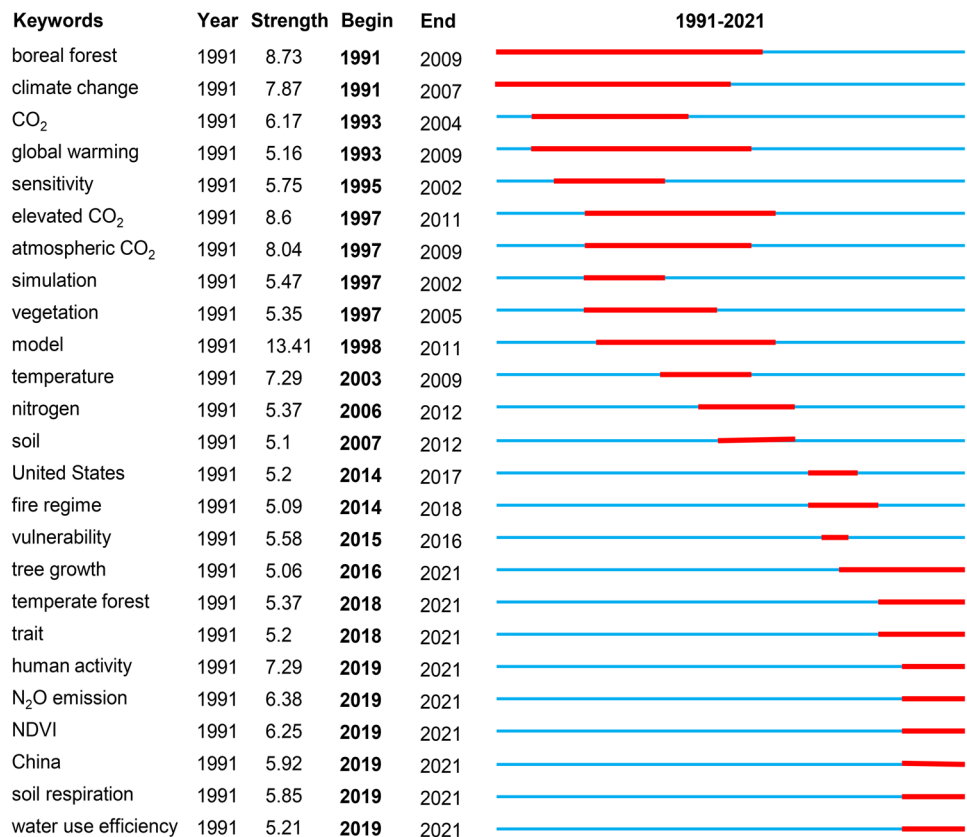
3.5 Keyword co-occurrence analysis

The dataset analyzed in this study included 2,310 publications and 10,502 keywords. Among the top 20 keywords, “climate change” had the highest frequency appearing 1,493 times with a total link strength of 7,084 (Table 1). “Impact”

and “temperature” ranked second and third in co-occurrence, appearing 312 and 276 times respectively, with total link strengths of 1,865 and 1,601. Furthermore, Fig. 6 depicts six major clusters in the keyword co-occurrence network: climate change, impact, responses, CO₂, growth, and vegetation. More detailed analysis can be found in section 4.2.

Fig. 7 Top25 burst keywords in the research field of vegetation responses to climate change from 1991 to 2021

Top 25 Keywords with the Strongest Citation Bursts



3.6 Burst analysis

The burst analysis illustrated the temporal evolution of publications of vegetation responses to climate change, which can be divided into the following three stages (Fig. 7):

1. From 1991 to 1996, the retrieved research shifted its focus to boreal forests due to its unique sensitivity to global warming (Prentice et al. 1991a; Burton and Cumming 1995; Sykes and Prentice 1995; Suffling 1995; Wang and Polglase 1995). Additionally, the burst keywords, “climate change”, “CO₂”, and “global warming” were included in relevant vegetation research as the background (Prentice et al. 1991b; Kasischke et al. 1995; Parton et al. 1995; Clark et al. 1996). Furthermore, this stage marked the beginning of research concerning the vegetation’s sensitivity to climate change (Hall et al. 1995).
2. During the period from 1997 to 2012, the research became more specific, and the background of climate change was no longer limited. For example, studies focused on the relationship among “elevated CO₂”, “atmospheric CO₂” and vegetation conducted by simulation models. These studies also included “nitrogen” and “soil” as important factors affected by climate change, since nitrogen is identified as a key component in nutrient cycling, while soil provides water and minerals to vegetation. Relevant studies through this period included those above conducted by Kellomäki and Väisänen (1997), Iverson and Prasad (1998), Flannigan et al. (2000), Kramer et al. (2000), Shaw and Harte (2001), Zavaleta et al. (2003), Woodward and Lomas (2004), Hamann and Wang (2006), Liu et al. (2009), Luo et al. (2009), Compant et al. (2010), Elser et al. (2010), and Lindner et al. (2010).
3. During the period of 2014 to 2021, the focus of the research had transformed to the analysis of the causes, impacts, and coping strategies of climate change on vegetation. The main factor causing global warming is recognized to be human activities, and thus the direct or indirect effects of human activities on vegetation have become a research hotspot (Cook et al. 2013). To quantify the impact of climate change, “tree growth”, “NDVI” and “vulnerability” were commonly used as criteria (Sperry and Love 2015; Sun et al. 2015; Zimmermann et al. 2015; Wu et al. 2015; Yang et al. 2017). Since 2018, microscopic studies related to vegetation have been using the high-frequency keywords “trait” and “water use efficiency” (Bussotti et al. 2014; Anderegg 2015; Camarero et al. 2015; Henn et al. 2018). In addition, climate factors such as rising temperatures and frequent droughts have led to increased fires, particularly forest fires. Thus, “fire regime” has become a crucial topic for researchers

studying management strategies in recent years (Cai et al. 2018; Huang et al. 2021). It is noteworthy that certain keywords, such as “human activities”, “N₂O emissions”, “NDVI”, and “soil respiration” have burst as high-frequency keywords since 2019. Following the typical pattern, it is anticipated that these keywords will remain the focus of research in this field of the coming years.

4 Discussion

4.1 Publication citation burst analysis

The frequency of citations is a crucial indicator of a publication’s influence. As referenced in section 3.1, the total frequency of publication citations exhibited an abrupt shift in 2010. Here we will further analyze and discuss the publication citation burst situations. The three pieces of publications published in 2010 with the highest citation frequencies are as follows: (1) “A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests” (Allen et al. 2010) with 4,294 citations, provided the first global assessment of tree mortality due to drought and heat stress, emphasizing that global forests would become more vulnerable to tree mortality in a changing climate; (2) “Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems” (Lindner et al. 2010) with 1,392 citations, which introduced in detail the impacts of climate change, adaptability, and vulnerability of European forest ecosystems; and (3) “Biological stoichiometry of plant production: metabolism, scaling and ecological responses to global change” (Elser et al. 2010) with 504 citations, which summarized the latest research progress in the field of plant ecology and global change. Thus, high-frequency citations of publications above resulted in an apparently abrupt change of total citations of publications in 2010, which suggested that these three publications had a greater influence and were highly regarded in this field. Therefore, the popularity of a certain research can be distinguished through the changes in the number of references cited. Furthermore, when evaluating scholars’ scientific research outputs, more emphasis should be placed on the citation of their representative works.

4.2 Keyword co-occurrence analysis

The occurrence of specific keywords indicates an interest in a particular subject. Analyzing the co-occurrence of keywords over a long period reveals research hotspots in recent years and guides researchers in selecting topics for future studies. In this study, 10,502 keywords retrieved were grouped into six major clusters in the keyword co-occurrence network (Fig. 6). To further understand the responses of vegetation to

Table 2 Six clusters of keywords co-occurrences in the research of vegetation responses to climate change from 1991 to 2021

ID	N	C	L	Top 10 keywords
1	122	Red	Impact	Impact, model, management, adaptation, land use, forest management, vulnerability, carbon sequestration, biomass, future
2	110	Green	Response	Response, diversity, conservation, biodiversity, global change, global warming, community, distribution, plant, nitrogen deposition, species distribution model
3	102	Purple	CO ₂	CO ₂ , carbon, greenhouse gas, elevated CO ₂ , wetland, soil, grassland, nitrogen, methane, nitrous oxide
4	74	Yellow	Growth	Growth, forest, drought, Scots pine, climate, temperate, spruce, Norway spruce pine, species diversity, leaf
5	73	Blue	Climate change	Climate change, temperature, dynamic, precipitation, variability, trend, ecosystem, NDVI, China, sensitivity
6	73	Cyan	Vegetation	Vegetation, boreal forest, disturbance, fire, vegetation change, wildfire, succession, environmental change, climatic change, tundra

ID serial number, *N* number of keywords in the cluster, *C* node color in the cluster, *L* cluster label

climate change, the publications with the keywords of each cluster will be further discussed with a summary subtitle of the main content (Table 2).

4.2.1 Impacts of climate change to vegetation

Climate change can trigger a range of effects on vegetation, leading to alterations including individual physiology function, species distribution, and community composition (Saxe et al. 2001; Thomas et al. 2004; Groffman et al. 2012; Anderegg 2015). These impacts have been already investigated and will occur continuously in the future (Walther et al. 2002). Thus, exploring the impacts of climate change on vegetation has become a hotspot in recent ecological research (Sun et al. 2022a, b). The studies in this field revolved around three main aspects, the current state of vegetation after being affected (Allen et al. 2010; Elmendorf et al. 2012), the causes and mechanisms of the impact exerted by climate change (Thompson et al. 2011; Liu et al. 2009; Shi et al. 2020), and the corresponding coping measures (Lindner et al. 2014; Thébault et al. 2014; Keenan 2015). Generally, the methods involved observations (i.e., in situ observations and remote sensing) (Shen et al. 2015; Huang et al. 2016), experimental manipulations (Dunne et al. 2003; Cornelissen et al. 2007), and modeling stimulations (Dale et al. 2010; Wu et al. 2015). Moreover, the arid and semi-arid areas, the Tibetan Plateau, and Northern Hemisphere particularly become the popular research area in this field where they are more sensitive to climate change (Niu et al. 2008; Liu et al. 2009; Shen et al. 2015; Sun et al. 2015; Li et al. 2023).

4.2.2 Responses of vegetation to climate change

Climate exerts a selective force in natural populations, so it is important for vegetation to respond such a rapid climatic change. The most common response of vegetation species is migration (Jump and Peñuelas 2005). Climate is a key factor in determining species distributions, so the local vegetation

migrates to adapt to the current climatic conditions. Moreover, the genetic composition of vegetation is likely to be altered to response climate change. Therefore, a series of unpredictable changes could be induced, including the risk of extinction, the biological diversity, and the capability of resistance and resilience (Zavaleta et al. 2003; Booker et al. 2009; Alfaro et al. 2014; Wang et al. 2016). Notably, the responses to climate change will be intensified with longer exposure time and an increased number of affected factors, hence the corresponding variations could be strengthened (Komatsu et al. 2019). To further understand the responses vegetation triggered, the physiological analysis may also provide insights into the mechanisms to explain them (Ezquer et al. 2020).

4.2.3 Effects of elevated CO₂ on vegetation

The atmospheric CO₂ concentration increased from 315.7 ppm in March 1958 to 418.90 ppm in July 2022, an increase of 32.69% in 65 years (<https://keelingcurve.ucsd.edu/>), which has resulted in climate change, particularly global warming (Fu et al. 2015; Solomon et al. 2009). Vegetation plays an important role to mitigate greenhouse gas emissions by storing carbon in its cell walls, with each plant cell contributing to carbon storage and sequestration (Ezquer et al. 2020). It is thereby facilitating the achievement of carbon emission reduction targets (Sun et al. 2022a, b). It was estimated that scientific management of grassland grazing or increasing grassland productivity would mitigate 150,000 tons of global CO₂ emissions by 2030 (O'Mara 2012). Additionally, elevated atmospheric CO₂ has beneficial effects on vegetation, such as enhancing disease resistance and promoting its growth (Compant et al. 2010; Lindner et al. 2010). Except for CO₂, as one of the greenhouse gases, the atmospheric abundance of other greenhouse gases such as nitrous oxide (N₂O) and methane (CH₄) has also increased in recent years (IPCC 2001). Hence, the interaction between the greenhouse gas fluxes and vegetation changes becomes a research focus (Jones et al. 2005; Johansson et al. 2006; Ward et al. 2013).

4.2.4 Changes in vegetation growth

Climate change could exert the double-edged sword effect on vegetation growth. Due to the extreme weather events, the vegetation growth shows a continuous reduction both in productivity and biomass, which may induce an increase of the mortality, especially in arid regions (Allen et al. 2010; Tei et al. 2017). However, increased mortality has positive implications to promote evolutionary adaptation of vegetation to climate change (Kuparinen et al. 2010). Based on the physiological process of vegetation, CO₂ concentrations can be one of the factors which is regarded as an influential element of the vegetation growth (Sun et al. 2022a, b). Rising CO₂ concentrations contribute to an expansion of vegetation coverage and its greening (O’ishi and Abe-Ouchi 2009; Luo et al. 2020). Recent research also found that vegetation grew synchronously in different areas, responding to climate change and reflecting the temporal and spatial adaptability of vegetation growth (Shestakova et al. 2016). Thus, tree growth networks can be an effective tool to study multi-species co-growth (Dorado-Liñán et al. 2019). Moreover, Norway spruce and Scots pine become two of the common research materials of the experiments of exploring the vegetation growth (Lebourgeois et al. 2010; Temperli et al. 2012; Nothdurft et al. 2012). This is because Norway spruce is sensitive to arid environments, while Scots pine is a drought-tolerant but vulnerable species (Zlatanov et al. 2017).

4.2.5 Climatic factors affecting vegetation change

Significant climate events, such as extreme temperature and heavy precipitation, have become more frequent and severe (Huang et al. 2016; Zhang et al. 2018; Wang 2021), particularly affecting the vegetation growth (Kato et al. 2004; Wu et al. 2021). To examine the vegetation change and its possibly driving meteorological factors, correlation analysis, trend analysis, and principal component analysis (PCA) are frequently used (Zhou et al. 2007; Li et al. 2020; Duan et al. 2021; Xue et al. 2021). Besides, remote sensing, based on long time series, is commonly used to monitor vegetation growth using the vegetation index (such as NDVI, NPP, SIF), identifying the distribution and characteristics of vegetation (Shen et al. 2015; Zheng et al. 2019). Temperature and precipitation are widely regarded as the two primary controls of vegetation research under climate change (Saxe et al. 2001; Boisvenue and Running 2006; Wu et al. 2015; Piao et al. 2019).

4.2.6 Effects of disturbances on vegetation dynamics

Vegetation is subjected to undergo intensifying natural disturbances prompted by climate change. Fire is one of the dominant disturbances (Flannigan et al. 2000). Climate

change affects the fire regimes through direct effects such as changes in temperature, seasonal precipitation patterns, wind behavior, and atmospheric stability, altering fire behavior, fire seasons, and fuel moisture (Huang et al. 2021). The research primarily investigated the vegetation changes after the fires, including the current status (Bergeron and Flannigan 1995; Krawchuk and Cumming 2011; Cassell et al. 2019; Heidari et al. 2021), the succession of vegetation (He et al. 2002; Brncic et al. 2009), and potential coping managements (Raftoyannis et al. 2014; Halofsky et al. 2016; Williamson et al. 2019). The popular study area of this field is boreal forest (Amiro et al. 2001; Lindner et al. 2010; Luo et al. 2020), since the influence of climate change on fire may become more dramatic in this region (Liu et al. 2012). The uncertainty owing to climate change requires novel approaches to improve the ability of vegetation ecosystems to rapidly respond to disturbance events (Mina et al. 2021). For instance, to reduce the likelihood of fires, one strategy is to plant deciduous species, while another approach is to employ resistant management techniques by reducing intra-species competition (Huang et al. 2021).

5 Conclusion

A bibliometric analysis was conducted using HistCite, Vosviewer, CiteSpace and R (Bibliometrix package) based on the WOS Core Collection to examine research publications on vegetation responses to climate change over the past 30 years. The analysis revealed the following key findings:

Firstly, the number of publications in this field had grown exponentially over time, with a slow growth rate of 2.2 publications per year before 2010, and an average of over 100 per year with a growth rate of nearly 10 after 2010. Secondly, *Global Change Biology* was the leading journal in publishing publications, and Environmental Science and Ecology were the two disciplines that showed the greatest interest in this research area. Thirdly, the most highly cited scholars in this field were Allen CD, Bresears DD, and Running SW. Europe served as the geographical center of this research field. Research teams from the USA and China made the most significant contributions and exhibited a high impact in this field. The Chinese Academy of Sciences, University of the Chinese Academy of Sciences, and the United States Forestry Service published the highest number of research publications. Fourthly, the keyword co-occurrence analysis revealed six clusters: impact, response, CO₂, growth, climate change, and vegetation. The development of this field could be divided into three stages: macro-level responses of vegetation to climate change, investigation of the relationship between specific climate change indicators and vegetation activity, and in-depth analysis of

the phenomenon, mechanism, and responses strategy of how climate change affected vegetation.

Although this study provides a valuable theoretical support and important data for future investigations of the impact of climate change on terrestrial ecosystems, there are certain limitations that could be improved upon. Specifically, the study only focused on natural vegetation, potentially overlooking the impact of climate change on artificial vegetation such as farmland and orchards. Additionally, the publication retrieval was limited to the WOS Core Collection and only included English publications, potentially excluding relevant studies from other databases and languages. Despite these limitations, this study offers a new perspective for understanding the research dynamics and future trends of vegetation responses to climate change and serves as an essential reference for researchers to identify current research hotspots in this field. Future studies could incorporate artificial vegetation and publications from multiple databases and languages to provide a more comprehensive analysis.

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Declarations

Consent to participate All participated in the design of this manuscript and consented for submission.

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