Environmental Science and Pollution Research (2022) 29:67728–67750
https://doi.org/10.1007/s11356-022-22292-6

REVIEW ARTICLE

Knowledge mapping of planetary boundaries based on bibliometrics analysis

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Received: 29 March 2022 / Accepted: 25 July 2022 / Published online: 10 August 2022

Abstract

The planetary boundaries concept has triggered a vast amount of pure and applied scientific research, as well as policy and governance activities globally. Indeed, it has rapidly become a centerpiece of sustainability study. It is crucial to review the scientific state of the planetary boundaries (PB) concept systematically. However, there is a lack of research on drawing a scientific investigation map of planetary boundaries. Therefore, to clarify the spatial and temporal distribution characteristics, research hotspots, and frontiers of planetary boundaries, a scientometric analysis was performed based on 530 academic publications on planetary boundaries from 2009 to 2021. This paper conducted the analysis by visualizing the social network, dual-map overlay, co-cited references, structure variation article, and co-occurrence keywords with CiteSpace. The results show that as a new achievement and paradigm in sustainable development research, the planetary boundaries framework is gradually getting global attention and promotion, which has increasingly become an interdisciplinary hot research topic. The most productive authors and institutions are concentrated in England, the USA, Germany, and Sweden. Relevant articles were mainly published in journals focusing on ecology, earth, marine, veterinary, animal, economics, and politics. In addition, we summarized four predominant research themes by clustering keywords: the calculation of single boundary threshold and present value, the integration with assessment methods such as life cycle assessment and footprint families, the downscaling of planetary boundaries, and the expansion to economic and social domains. For scholars who are interested in this topic, this paper would be a useful reference and guideline.

Keywords Planetary boundaries · Bibliometric · CiteSpace · Absolute sustainability

Introduction

An important source of modern sustainable development is the reflection on the causes and solutions of environmental problems. As early as the eighteenth and nineteenth centuries, issues such as international equity, intergenerational equity, and natural resource conservation were already hotly debated by European philosophers (Shaler 1905; Kidd 1992). Then, since the United Nations Conference on the Human Environment held in Stockholm in 1972, sustainable development entered the conceptualization phase. Particularly in 1987, the concept of "sustainable development" was firstly used by the United Nations World Commission on Environment and Development (WCED) in United Nations' document, which was an important turning point. Following WCED, the United Nations Conference on Environment and Development held in Rio in 1992 effectively motivated a generation of scholars to pay greater attention to sustainable development. Since then, global programs such as the

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United Nations Millennium Development Goals (MDGs) and "Transforming Our World: The 2030 Agenda for Sustainable Development" were created to promote countries worldwide to effectively incorporate the Sustainable Development Goals (SDGs) into their global and national development strategies.

However, the understanding of sustainable development is distinguished from weak sustainable development and strong sustainable development. Weak sustainable development believes that one form of capital (man-made, human, social, natural) can be replaced by another form of capital, and the increase of one kind can compensate for the decrease of another. Regardless of whether the stock of natural capital decreases, it can be considered sustainable when the total capital remains unchanged or increases (Turner 1992; Pearce and Atkinson 1993; Arrow et al. 2012; Neumayer 2003; Irwin et al. 2016; Cohen et al. 2019), while strong sustainable development assumes that the stock of natural capital is irreplaceable, and human activities must remain within the carrying capacity of natural capital (Meadows et al. 2013; Devall 1990). Classical and neoclassical economists present their viewpoints on the relationship between natural capital and economic growth from the perspective of resource scarcity (Malthus 2013; Ricardo 1891). Different from neoclassical economics, ecological economics holds the view, which is consistent with the concept of strong sustainable development, that the economy is an open subsystem of the environment that encompasses the energy, material, and social systems (Daly and Cobb 1994) and meanwhile the natural capital is irreplaceable.

Early research on sustainable development was limited to an abstract theoretical framework that was difficult to adapt to the urgency of global sustainability. As a result, there has been an increase in the amount of quantitative research on sustainable development such as environmental carrying capacity (Brown and Ulgiati 2001; Singhal and Kapur 2002; Zhang et al. 2018), ecological footprint (Wackernagel and Rees 1998; Fan et al. 2017; Ahmed and Wang 2019; Zambrano-Monserrate et al. 2020), and eco-efficiency (Hoffrén and Apajalahti 2009; Rashidi and Saen 2015; Caiado et al. 2017). Especially in recent years, scientists and politicians are keen to measure the range and effects of human activities that may be carried by the ecosystem in response to the unpredictability and complexity of global environmental change. Thus "Planetary Boundaries" concept has emerged.

The planetary boundaries framework was proposed by a team of scientists led by Johan Rockström of Stockholm University. And it delineates a safe operating space for humanity. However, a great acceleration of the human population size, the use of resources, and emissions from their activities may cause the boundaries to be exceeded. The planetary boundaries framework holds the view that crossing the planetary boundaries may significantly reduce the possibility to maintain the Holocene-like status for humanity in the Anthropocene (Rockström et al. 2009a; Steffen et al. 2015). The framework contains 9 processes which were updated in 2015, including climate change, changes in biosphere integrity, stratospheric ozone depletion, ocean acidification, biogeochemical flows (P and N cycles), land-system change, freshwater use, atmospheric aerosol loading, and introduction of novel entities. Planetary boundaries are set by critical thresholds on a global scale. And thresholds are defined by the critical values of one or more control variables. These 9 processes are tracked through 16 control variables. The minimums within the uncertainty of biophysical thresholds are used to set the planetary boundaries, which give humans time to react to early warning signs that a critical value may be approaching (Steffen et al. 2015). The planetary boundaries framework quantifies human-caused environmental changes that risk destabilizing the long-term dynamics of the Earth system, which can help human beings prevent unacceptable environmental changes caused by human activities.

The planetary boundaries concept is not only a reflection of strong sustainability but a new achievement and novel idea in the field of sustainable development research, which has triggered extensive discussions in the international community (Barbier and Burgess 2017). Some scholars and policy communities have made many criticisms from the perspective of the boundaries setting, geologic politics, and social development (Molden 2009; Brook et al. 2013; Hughes et al. 2013; Mace et al. 2014; Clark 2014; Montoya et al. 2018; Lade et al. 2020). But some researchers think that the conceptual innovation and quantitative criteria that can reach the global consensus of planetary boundaries can provide a new paradigm for countries to promote sustainable development (Galaz et al. 2012a, 2012b; Rowan 2014; Brown 2017). Some scholars have focused on the improvement of the planetary boundaries framework, such as calculating the current status and threshold values of specific boundaries more scientifically (Running 2012; Gerten et al. 2013; Vries et al. 2013; Heck et al. 2018), adjusting the control variables and adding Earth system processes (Villarrubia-Gómez et al. 2018; Rounsevell et al. 2020; Zhang et al. 2021; Miraux 2022; Persson et al. 2022). And some scholars have conducted research on the implementation and application of planetary boundaries. They think that the planetary boundaries approach can be used to measure the environmental sustainability of global, countries, companies, and other activity subjects (Cole et al. 2014; Häyhä et al. 2016; Chandrakumar et al. 2019; Ding et al. 2020; Parsonsova and Machar 2021), combining with the life cycle assessment, footprint families, input–output approach, and other assessment approaches (Fang et al. 2015a; Bjørn et al. 2019; Algunaibet et al. 2019). Some scholars have also attempted to combine this approach with concerns regarding human rights, social justice, human health, and food security (Dearing et al.

2014; Lucas et al. 2020; Gerten et al. 2020; Donges et al. 2021; Zhang and Zhu 2022; Meijaard et al. 2022). Besides, planetary boundaries have the potential to enter the international political arena and contribute to global sustainable development (Galaz et al. 2012a, 2012b; Hajer et al. 2015). Indeed, such a situation is emerging. For example, the concept of planetary boundaries appeared several times in official documents (legal and non-legal), such as "Resilient People, Resilient Planet: A Future Worth Choosing," "The Road to Dignity by 2030: Ending Poverty, Transforming All Lives and Protecting the Planet," and "on a General Union Environment Action Programme to 2020 'Living Well, within the Limits of Our Planet.'".

With the extensive usage of the planetary boundaries framework in both the scientific community and political arena (Fernández and Malwé 2019), there is an urgent need to understand planetary boundaries research more systematically and intuitively. Although studies have been conducted to summarize the planetary boundaries research in a specific aspect, such as the critique of planetary boundaries (Biermann and Kim 2020), the downscaling of planetary boundaries (Ryberg et al. 2020), and the water boundaries (Bunsen et al. 2021). However, there is a lack of visual analysis of planetary boundaries using bibliometrics to combine and summarize the planetary boundaries studies systematically. Bibliometric analysis, compared to general reviews, is a data-driven analysis that can express the knowledge structure of a specific research field and its evolutionary history visually and clearly (Ellegaard and Wallin 2015; Geissdoerfer et al. 2017). We conduct bibliometric analysis with CiteSpace software based on the literature data in the field of planetary boundaries which are retrieved from the Web of Science. This study contributes to filling the gap in the literature study of planetary boundaries and will be beneficial to provide initial guidance and inspiration to interested researchers and practitioners in this field. And we attempt to address the following research issues: (1) investigation of the most influential and responsible authors, countries, and institutions for the progress of the field; (2) analysis of the milestones in this field, the internal logical connection, and the development path between these studies in planetary boundaries; and (3) from a sustainability perspective, what the major hot topics of research are at planetary boundaries and how they influence the dynamics of future research (such as how to further develop their role in global sustainability advancement and climate change management).

Materials and methods

Bibliometrics

The history of bibliometric analysis can be traced back to the twentieth century (Cole & Eales 1917; Bradford 1934). Bibliometric analysis is a research approach that uses bibliographic data as the object of investigation and bibliometrics as the theoretical foundation (Donthu et al. 2021). The development history, research focus, and future research direction of a certain academic field may be statistically revealed by econometric analysis of literature information such as title, keywords, authors, journals, year, literature content, and citation information (Zheng et al. 2017). In the early days, bibliometric analysis was mainly used by researchers in fields of the disciplines of intelligence, library science, and archives (Chen 2001). However, with the advancement of research and the emergence of cross-discipline, bibliometric analysis has been widely used as a research method to summarize the knowledge structure and explore the frontier dynamics of a discipline in the fields of economics (Marsilio et al. 2011; Nath and Chowdhury 2021), management (Zupic and Čater 2015; Guo et al. 2019), environment (Geissdoerfer et al. 2017; Mourao and Martinho 2020), energy (Omoregbe et al. 2020; Anuar et al. 2021), and medicine (Carter-Templeton et al. 2018; Manyangu et al. 2019).

CiteSpace

CiteSpace is a citation visualization and analysis software that can be used for literature data mining and visual analysis (Chen 2004). It can sort out literature and present visually the quantitative patterns in the available literature sources. Specifically, based on the time slicing technique, it builds a time series of network models and synthesizes these individual networks to form an overview network. And it determines the basic knowledge and research frontiers in a specific field through analyzing literature co-citation and coupling, scientific research cooperation network, and theme contribution. This article uses CiteSpace software (Version 5.8.R3) to analyze the knowledge mapping of planetary boundaries.

Data

The data collecting process is divided into two parts. First, a reliable source of information was chosen: a reputable and large bibliographic database that allows broad access to high-quality refereed journal articles. In this study, the publications selected were identified in Web of Science (WOS), including the Social Sciences Citation Index (SSCI) and the Science Citation Index Expanded (SCI-E) databases. Both databases were created by the American Institute for Scientific Information. They contain a lot of literature information, such as research fields, institutions, and citations, which are reliable data sources for bibliometric analysis.

Next, the advanced search function of the WOS website was used to search and filter the articles needed for the study.

We used TS (TS: topic search) = ("planetary bound*") NOT TS = ("planetary boundary laye*"). The search type was selected as "article," and the time span was set from 2009 (the planetary boundaries framework was first introduced) to 2021. The content of the data includes all bibliographic information: author, title, source publications, abstractions, keywords, and references cited. As of November 8, 2021, the search yielded 530 articles.

Method

Five types of scientometric techniques provided by CiteSpace were applied in this study: social network analysis, dual-map overlay analysis, co-citation analysis, structure variation article analysis, and keyword cluster analysis. The process of using CiteSpace and the main functions of CiteSpace are presented in Fig. 1.

Social network analysis is an analytical method that evaluates the publication contributions and academic influences of authors, institutions, and countries. And it also reveals collaborative relationships (Liu et al. 2022).

A dual-map overlay of the science mapping literature can be used to analyze the relationship between cited and citing journals based on the global map of science generated from over 10,000 journals indexed in the Web of Science (Chen and Leydesdorff 2014). The Journal-level knowledge flow analysis on planetary boundaries was made to illustrate the correlation between disciplines in planetary boundaries research.

The co-citation analysis can determine the relationship between literature (Liu et al. 2021). Citation bursts, which refer to articles that have received sharp increases in the citation, can reflect the dynamics of a field. Articles with high cited frequency and strongest citation bursts are milestones and hotspots in the field of scientific research (Chen 2004). Based on co-citation analysis, this study analyzed these articles to identify the core research scholars in planetary boundaries and their classic literature.

Structural variation theory is a reorganization search in a high-dimensional common reference space. The main purpose of structural variation analysis is to detect unprecedented inter-cluster bridges or new types of remote connections and understand why specific connections are novel and valuable capabilities. The idea is to identify the potential of an article to establish extraordinary or unexpected connections across distinct clusters (Chen 2017).

Keywords are the high-level summary of the thesis, and their frequency and degree of relevance can reveal the research hotspots and internal connections in a certain field (Zhu et al. 2021). Keyword cluster analysis shown by timeline view was conducted to find the hot issues and research trends in planetary boundaries. The log-likelihood algorithm (LLR), which is one of the clustering algorithms provided by CiteSpace, was used in this part. Based on LLR, each cluster can be labeled by keywords of citing articles to the cluster.

The output figures in the results are generated based on 530 publications between 2009 and 2021. And the research was performed by setting years per slice to 1, Top $N = 50$. It means that the top 50 most-cited papers each year were merged to create synthetic networks that can deeply excavate the knowledge structure and development path of planetary boundaries framework, including social network, co-citation network, and keyword co-occurrence/cluster network. These networks consist of numerous nodes and links. And the type setting (such as country, author, reference, and keywords) determines the node's meanings. The size of the nodes is proportional to their frequency. The lines connecting the nodes are co-occurrence links, and the stronger the

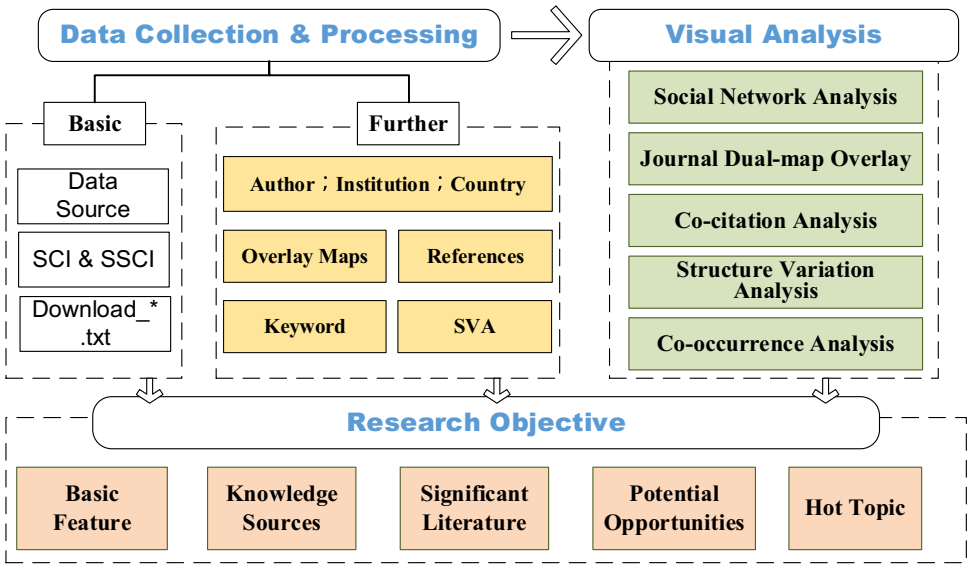

Fig. 1 The process of using CiteSpace

co-occurrence, the thicker the lines. Meanwhile, the color change from cool to warm was used to represent the evolution of time, with the cooler shapes representing earlier time than the warmer shapes. The parameters and functions selected for the research are shown in Fig. 2.

Results and discussion

Basic feature analysis

Trends in the total number of papers and time of publication

Figure 3 shows the distribution of 530 academic papers on planetary boundaries from 2009 to 2021. Although research history in this area is relatively short, the number of papers published about planetary boundaries frameworks has rapidly increased with articles increasing from 4 in 2009 to 107 in 2021. We searched for publications on other similar sustainability concepts, such as ecological carrying capacity, human appropriation of net primary productivity, eco-efficiency, and ecological limits. The results show that planetary boundaries have the most significant increase in the number of publications as well as the growth rate of publications compared to other concepts (presented by the red

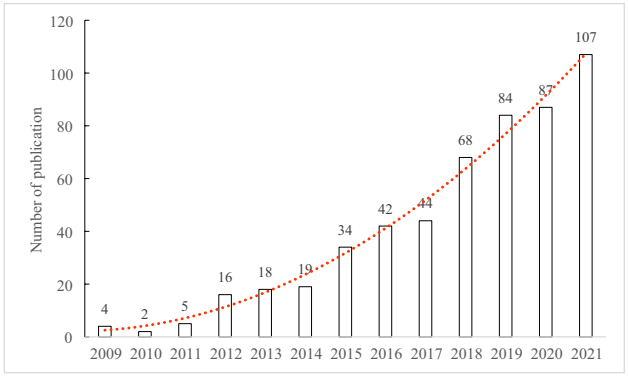

Fig. 3 The number of published papers on planetary boundaries (2009–2021)

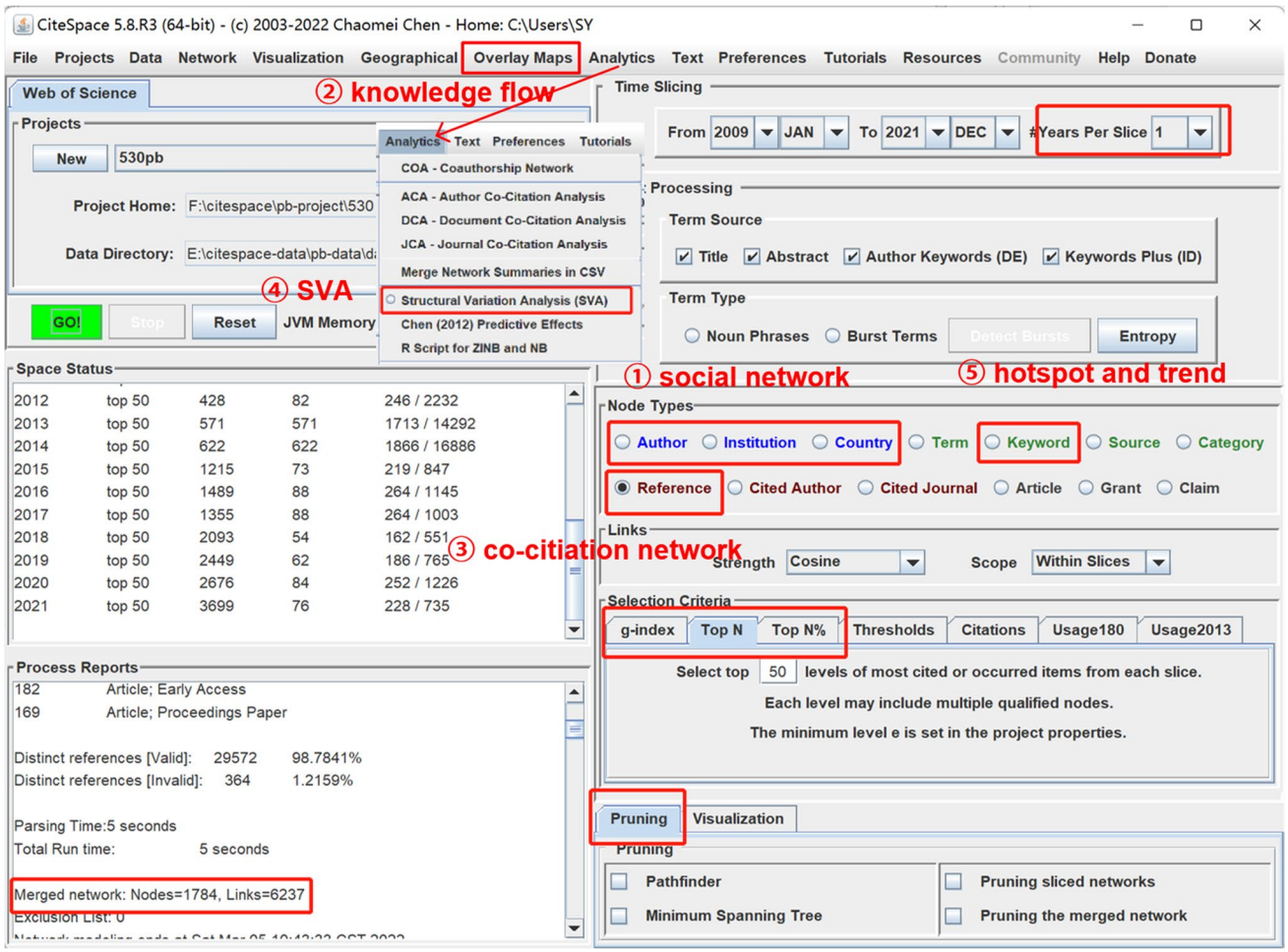

Fig. 2 The main user interface of CiteSpace

line in Fig. 4), followed by eco-efficiency and Environmental Performance Index. The planetary boundaries framework has become a subject of interest in the field of sustainable development (Brown 2017). At the beginning stage, the research on the planetary boundaries framework was more concentrated in the debate on this concept (Molden, 2009). And as the research progressed, more and more articles were published in this field. Furthermore, a growth trend model ($R^2 = 0.9859$) predicts 125 publications on planetary boundaries by 2022, demonstrating that academics' interest in this area is growing.

Author, institution, and country

As shown in Table 1, the research field is represented by Johan Rockström, Sarah E Cornell, Will Steffen, and Dieter Gerten. Most authors have backgrounds in natural sciences, ecology, and environmental sciences. Johan Rockström is the most frequently published author in the field of planetary boundaries, with 19 articles. He convened the workshop which consisted of 29 experts and published the "A safe operating space for humanity." Among the top ten authors in terms of publications, Will Steffen and Carl Folke are both key collaborators in this article. Sarah Connell (15), Will Steffen (11), and Dieter Getten (10) are behind Johan Rockström in the number of articles.

Figure 5 shows the institution collaboration network which consisted of 294 nodes and 639 links. The top 10 institutions that made major contributions to the outputs are presented in Table 2. Stockholm University ranked first with 55 articles, Potsdam Institute for Climate Impact Research (30) ranked second, followed by Commonwealth Scientific Industrial Research Organization (28), University of London (24). These institutions are mainly in Europe. Among

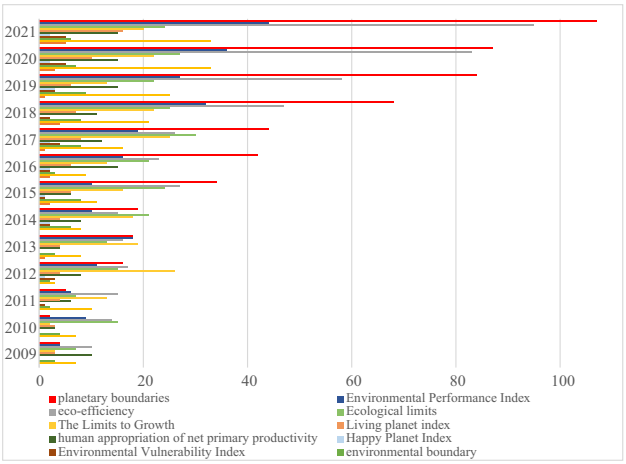

Fig. 4 The number of published papers of different sustainability concepts

Table 1 Top 10 authors of publications based on frequency

Author	Frequency	%/530	Author	Frequency	%/530
Rockström J	19	3.59	Guillen-gos-albez G	9	1.70
Cornell SE	15	2.83	Hauschild MZ	9	1.70
Steffen W	11	2.08	Donges JF	8	1.51
Gerten D	10	1.89	Folke C	8	1.51
Bjørn A	9	1.70	Lucht W	8	1.51

the 29 scientists who proposed the planetary boundaries framework, 15 scientists are from Stockholm University. In addition, a large number of scholars from Stockholm Environment Institute (represented by Johan Rockström and Åsa Persson), Australian National University (represented by Will Steffen), and Potsdam Institute for Climate Impact Research (represented by Hans Joachim Schellnhuber) are also in this expert team.

Table 3 shows the number and share of publications from the top countries. The address of the author determines the country and type of collaboration of an article. Articles, whether independent or collaborative, are allocated depending on the author's address (Li and Ho 2008; Zheng et al. 2017). England and USA both published 113 articles which is the largest number in this field, accounting for 21.32% of the total. Next, Sweden (97 articles) and Germany (94 articles) account for 18.30% and 17.73%, respectively. In particular, the 7th Environment Action Programme (EAP) adopted by the decision of the European Commission explicitly mentions "Living Well, within the Limits of Our Planet," which has played an important role in promoting the use of planetary boundaries. Therefore, it is not surprising that some European Union countries have more publications.

The network of collaborating countries consisted of 77 nodes and 294 links (Fig. 6). The size of the country nodes represents the number of the collaboration. The country has the greater contribution to the research field with larger nodes and denser connections. At the same time, the thickness of the connecting lines between nodes represents the closeness of cooperation between countries. In the early days, Denmark worked closely with several countries. In recent years, cooperation between the USA, Germany and the UK, and other countries has increased, with thicker and more warmly colored links between them (Fig. 6).

Periodical dual-map overlay

The scientific fields involved in the literature of the planetary boundaries framework are mainly distributed in Environmental Sciences (282 articles, accounting for 53.21%), Environmental Studies (164 articles, accounting

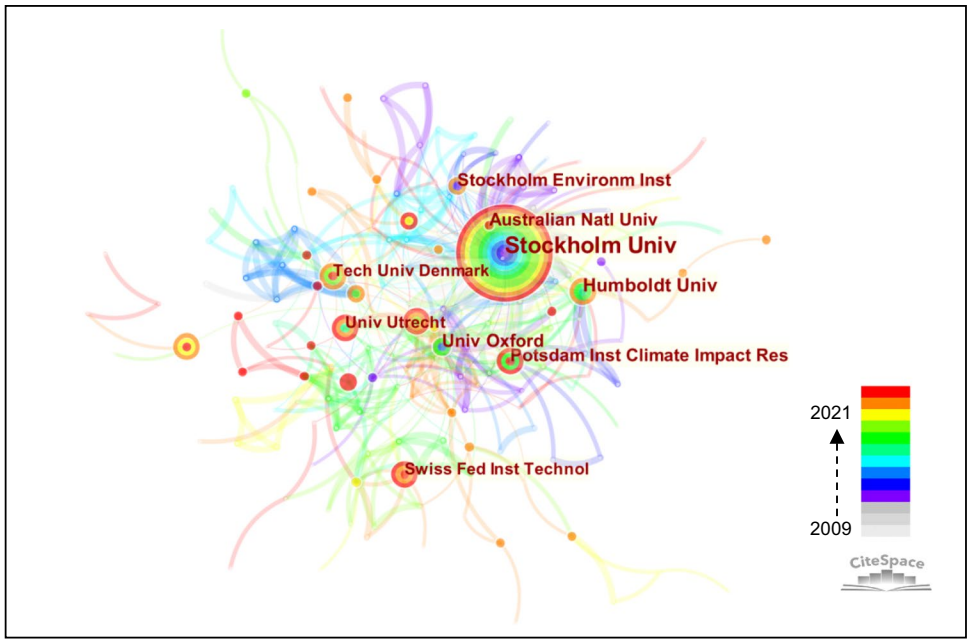

Fig. 5 A network map of institutions collaboration (The nodes represent the institutions. A larger node means that the institution has more products in the field of planetary boundaries. And the thickness of the curved connecting lines represents the strength of collaboration in the institutions. Collaboration between institutions in the gray line occurred earlier than in the red line.)

Table 2 Ranking of top 10 active institutions based on frequency in the field of planetary boundaries

Institution	Frequency	%/530
Stockholm University	55	10.38
Potsdam Institute for Climate Impact Research	30	5.66
Commonwealth Scientific Industrial Research Organization CSIRO	28	5.28
University of London	24	4.53
Stockholm Environment Institute	20	3.78
Humboldt University of Berlin	19	3.59
Technical University of Denmark	19	3.59
Australian National University	18	3.40
University of Oxford	17	3.21
Wageningen University Research	17	3.21

Table 3 Ranking of top 10 active countries based on frequency in the field of planetary boundaries

Country	Frequency	%/530	Country	Frequency	%/530
England	113	21.32	Netherlands	62	11.70
USA	113	21.32	Canada	45	8.49
Sweden	97	18.30	Denmark	38	7.17
Germany	94	17.74	Switzerland	35	6.60
Australia	87	16.42	Peoples R China	34	6.42

for 30.94%), Green Sustainable Science Technology (126 articles, 23.77%), Engineering Environmental (78 articles, 14.72%), Ecology (58 articles, 10.94%), Economics (46 articles, 8.68%), Meteorology Atmospheric Sciences (35 articles, 6.6%), and Geosciences Multidisciplinary (34 articles, 6.42%), according to the Web of Science.

Then a dual-map overlay of the science mapping literature was used to perform further analysis. On the left side of Fig. 7, the horizontal axis of the ellipse represents the number of authors, while the vertical axis represents the number of publications. The citing journals on the left side are the journals publishing the paper we searched, representing the frontier of the research results. On the right side, the horizontal axis represents the number of cited authors, while the vertical axis of the ellipse represents the number of times that the journal has been cited. The cited journals on the right side are the journals cited by the paper we searched, namely, their references, reflecting the knowledge base on which the research relies. The lines connecting the left and right sides of the map reflect the citation relationship between the journals. Thicker connecting lines indicate stronger knowledge flow relationships of journals in the cluster.

As shown in Fig. 8a and b, the knowledge carriers of planetary boundaries are mainly distributed in the clusters on the left side of the journal community, including 3#ecology, earth, marine, 7#veterinary, animal, science, 10#economics, economic, political. And the knowledge source (mainly cited journal source) falls on the right side (Fig. 8c and d), including 10#plant, ecology, zoology, 3#earth, geology, geophysics, 2#environment, toxicology, nutrition, 12# economics, economic, and political. The dual-map overlay shows that "2#environment, toxicology, nutrition" and "12# economics, economic, political" are the important knowledge-based journals of "7#veterinary, animal, science." The knowledge-based journals of 3#ecology, earth, marine occupy three

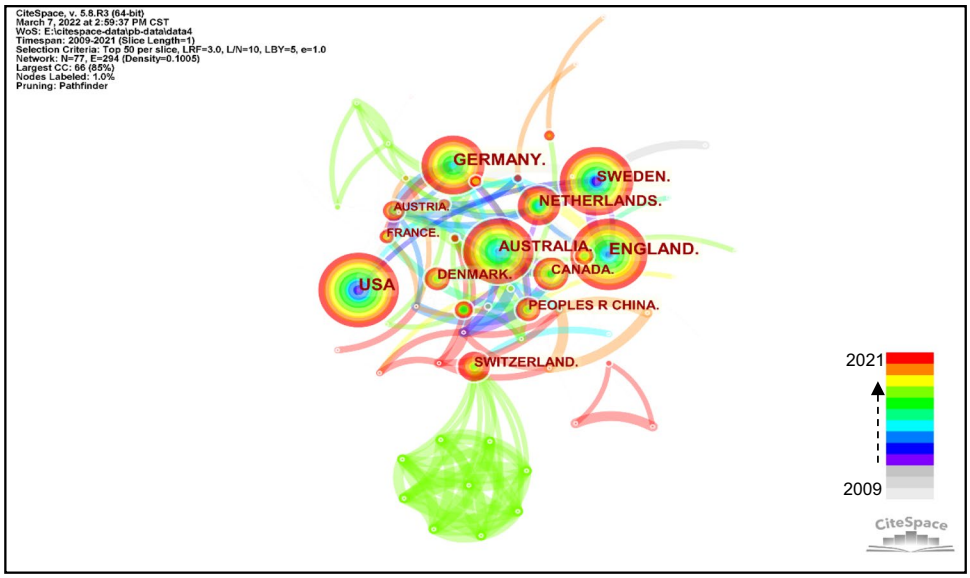

Fig. 6 A network map of countries collaboration

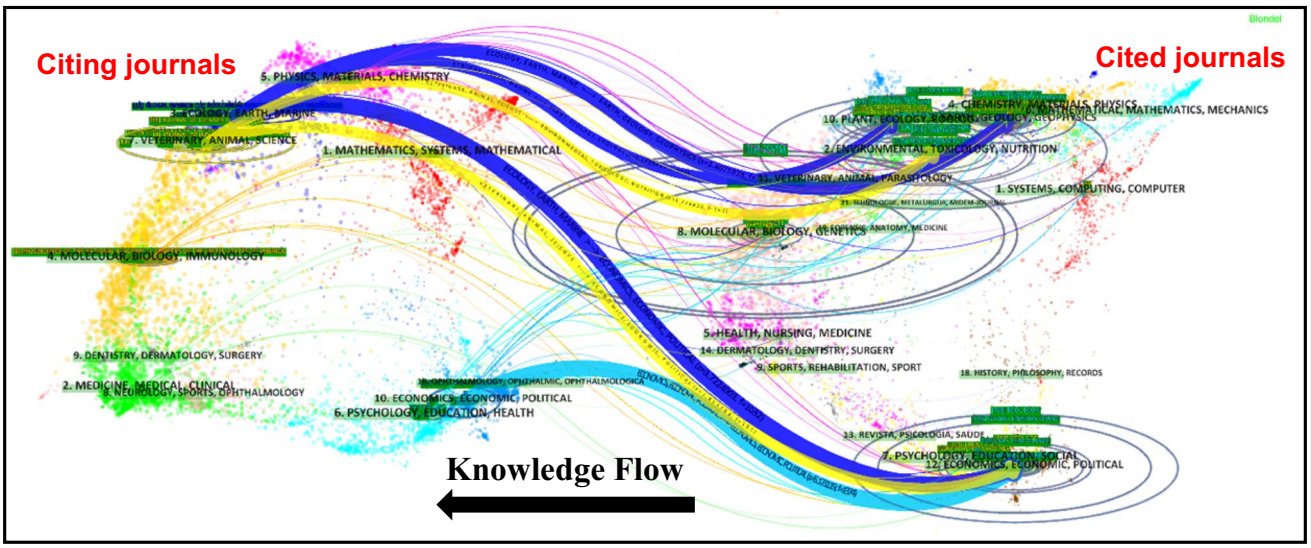

Fig. 7 Dual-map overlay graph of journals and disciplines regarding the planetary boundaries

journal groups, including 3#earth, geology, geophysics, 10#plant, ecology, zoology, and 12# economics, economic, political. The analysis of journal domain distribution and knowledge flow presented in the dual-map overlay graph shows that the early study of planetary boundaries developed from geography, ecology, and natural sciences and has branched out into the economy, society, policy, and management. This is a significant indication of the broad and diverse nature of planetary boundaries research, as well as the complexity and multi-discipline characteristics of sustainable development.

Some important journals in specific categories are identified in Fig. 8a and b, such as *Sustainability* with 46 citing articles, *Journal of Cleaner Production* with 31 citing articles (in the yellow circle), and *Ecological Economics* with 24 articles (in the blue circle). And there are some representative cited journals related to the planetary boundaries, such as Science (frequency = 1192, the frequency represents the number of papers published in this journal on the field of planetary boundaries), Nature (frequency = 1133), Proceedings of the National Academy of Sciences of the United States of America (frequency = 702), Ecology and Society (frequency = 363), Ecological Economics (frequency = 767), Global Environ Chang (frequency = 645), and Environmental Chemistry Letters (frequency = 329).

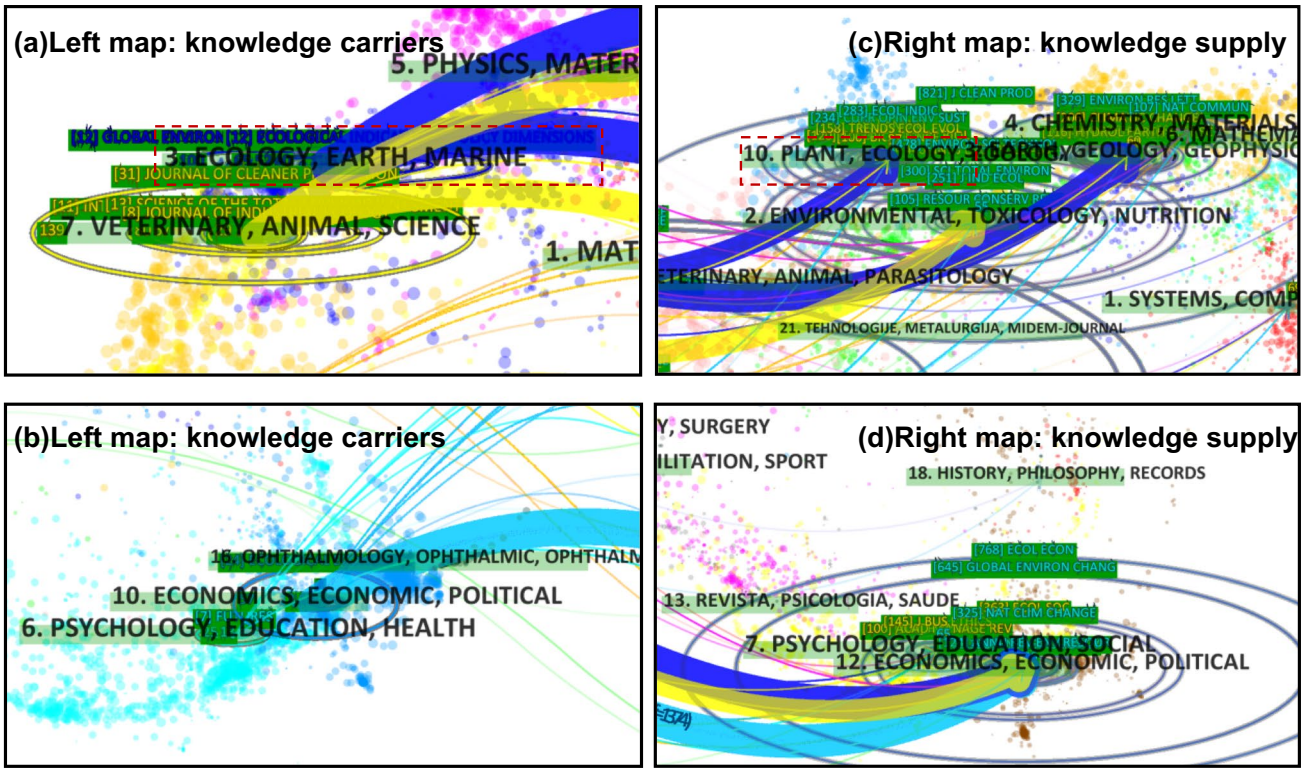

Fig. 8 Local amplification of planetary boundaries publication journal clustering (The size of the ellipse indicates the number of articles published by the journal in a particular field; the thicker the line indicates the main source of knowledge; the color of the line indicates the different subject areas). **a** Left map: knowledge carriers. **b** Left map: knowledge carriers. **c** Right map: knowledge supply. **d** Right map: knowledge supply

Cited literature analysis

Highly cited articles and references with citation bursts

Figure 9 depicts the time change of the cited references, with color change from cool to warm tones. There are 1782 nodes and 6231 links in the network. One node represents an article, and it is expressed by "author's name and year of publication." The node size indicates how many times the article has been co-cited. In the emergent analysis, the nodes where some circles turn red represent a sudden increase in the co-citation which indicates a shift in research direction.

We found some important articles in Fig. 9, such as "A Safe Operating Space For Humanity" (Rockström et al. 2009a), "Planetary Boundaries: Exploring The Safe Operating Space For Humanity" (Rockström et al. 2009b), "Planetary Boundaries: Guiding Human Development on A Changing Planet" (Steffen et al. 2015), "Development of A Life-Cycle Impact Assessment Methodology Linked to The Planetary Boundaries Framework" (Ryberg et al. 2018), and "Food in The Anthropocene: the EAT–Lancet Commission on Healthy Diets From Sustainable Food Systems" (Willett et al. 2019). Some of the articles were selected and are organized in Table 4, according to the different time phases of the emergent literature. Table 4 shows ten articles with high emergence intensity. We selected several representative articles for detailed analysis of the proposal, improvement, and application of the planetary boundaries framework.

The concept for the planetary boundaries framework was originally introduced in 2009 by a team of scientists led by Johan Rockström. They published a paper entitled "A safe operating space for humanity" in the journal *Nature*. It has been cited approximately 12,000 times (according to Google Scholar in June 2022). This article produced the first burst, which occurred in the early stages of planetary boundaries studies, with the purple nodes. And this article has large emergent values (11.46) which was represented with red annual rings. The same year, a more extensive parallel 2009 paper entitled "Planetary boundaries: exploring the safe operating space for humanity" was published in *Ecology and Society* (Rockström et al. 2009b), which has been cited more than 6200 times. Subsequently, the planetary boundaries concept attracted great attention from the international scientific community. This article, which was responsible for the first structural mutation and has had a significant impact, described the planetary boundaries as a safe operating space for humans and measured them using 9 biophysical processes. The 9 biophysical processes include climate change,

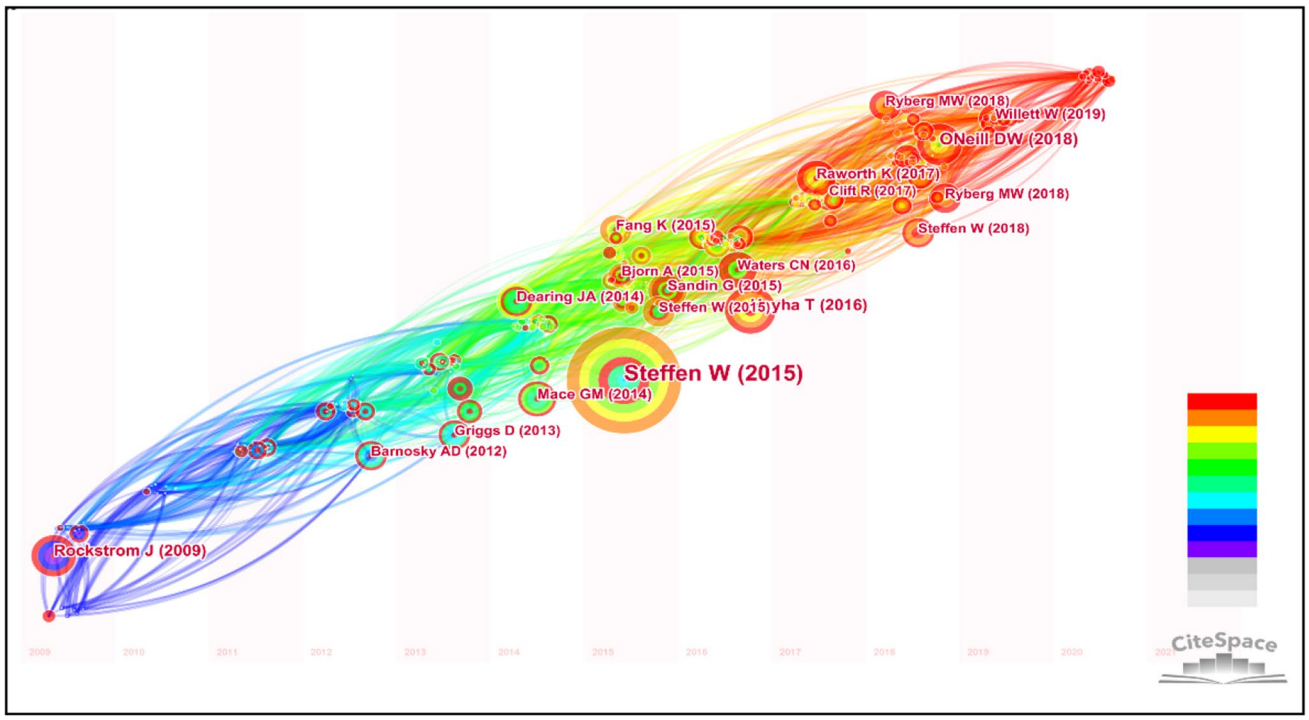

Fig. 9 Time zone view of the cited articles (The node represents articles; the lines connecting the nodes are co-occurrence links. The co-citation of the red line occurs after the co-citation of the purple line.)

rate of biodiversity loss (terrestrial and marine), interference with the nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, global freshwater use, change in land use, atmospheric aerosol loading, and chemical pollution.

Rockström et al. (2009a) quantified seven of these boundaries and discovered that the three of them were exceeded: climate change, rate of biodiversity loss, and nitrogen cycle. Since then, the concept of planetary boundaries has attracted the scientific community's interest. At the same time, the concept is also controversial. Some criticisms are targeted at the framework itself, such as different opinions on the measurement of threshold and present values (Gerten et al. 2013; Heck et al. 2018). Some scholars believe that not all boundaries have biophysical thresholds (Molden 2009; Lewis 2012), and those processes without threshold effects cannot set boundaries through scientific evaluation methods. Setting boundaries forcibly is an arbitrary behavior and may even aggravate ecosystem degradation (Montoya et al. 2018). The neglect of social justice by planetary boundaries is another controversial issue. Some scholars think that the implementation of the planetary boundaries framework may limit the economic growth and potential development prospects of underdevelopment regions (Biermann and Kim 2020).

Many disputes and discussions have provided space for the development and application of theories. The article "Planetary boundaries: Guiding human development on a changing planet" published by Steffen et al. (2015) in Science has been cited more than 9000 times, which produced the largest node in Fig. 8, shown in the blue, orange, and yellow regions. And it has the largest burst strength, which means this article has a significant structural impact on the study of planetary boundaries. This article is a revision and update of the research results in 2009. It supplemented and recalculated the control variables and thresholds, and then changed the rate of biodiversity loss into biosphere integrity which is composed of genetic diversity and functional diversity. In addition, chemical pollution was replaced by the introduction of novel entities. Nowadays, more and more scholars are conducting research on novel entities, such as the production of new substances in chemistry or engineering and the plastic pollution (MacLeod et al. 2021; Persson et al. 2022). Compared with the results in 2009, phosphorus cycles and land-use changes have also entered high-risk areas, in addition to genetic diversity and nitrogen cycles that are still in high-risk areas. The only good news is that the depletion of stratospheric ozone has been greatly improved. The publication of this article has had a huge impact on the research in the field of planetary boundaries and laid a solid foundation for subsequent research. Its influence continues today (Table 4).

Fang et al. (2015a) proposed a framework for the integration of environmental footprints and planetary boundaries.

Table 4 The important cited references in the planetary boundaries field

COF	CF	Author	Title	Source	BS	Begin-end	Range
42	6646	Rockström et al. (2009)	*A Safe Operating Space For Humanity*	Nature	11.46	2010-2014	
32	229	Dearing et al. (2014)	*Safe and Just Operating Spaces for Regional Social-Ecological Systems*	Global Environ Chang	11.82	2015-2019	
28	140	Mace et al. (2014)	*Approaches to Defining A Planetary Boundary For Biodiversity*	Global Environ Chang	10.33	2015-2019	
210	4230	Steffen et al. (2015)	*Planetary boundaries: Guiding Human Development on A Changing Planet*	Science	60.61	2016-2021	
28	88	Fang et al. (2015)	*Understanding The Complementary Linkages Between Environmental Footprints and Planetary Boundaries in A Footprint–Boundary Environmental Sustainability Assessment Framework*	Ecol Econ	8.97	2017-2021	
47	128	Häyhä et al. (2016)	*From Planetary Boundaries to National Fair Shares of The Global Safe Operating Space — How Can The Scales Be Bridged?*	Global Environ Chang	16.02	2018-2021	
32	114	Raworth (2017)	*Doughnut Economics: Seven Ways to Think Like A 21st-century Economist*	Lancet Planetary Health	10.85	2018-2021	
52	403	O'Neill et al. (2018)	*A Good Life for All Within Planetary Boundaries*	Nat Sustain	18.62	2019-2021	
27	52	Ryberg et al. (2018)	*Development of A Life-cycle Impact Assessment Methodology Linked to The Planetary Boundaries Framework*	Ecological Indicators	11.03	2019-2021	
27	848	Steffen et al. (2018)	*Trajectories of The Earth System in The Anthropocene*	Proceedings of the National Academy of Sciences of the United States of America	11.03	2019-2021	

(COF, CF, and BS represent the co-citation frequency (data from CiteSpace), the citation frequency (data from WOS, as of March 4, 2022), and burst strength, respectively. The range reflects the time evolution of the impact.)

They used the environmental footprints to calculate the current value of the planetary boundaries and measured the sustainability gap between the current magnitudes of human activities and associated capacity thresholds. That method is widely used (Zhang et al. 2021; Dong et al. 2022). In 2012, Raworth defined the safe and just operating space for humanity that integrates social wellbeing into the primitive concept of planetary boundaries. Then, Dearing et al. (2014) measured the social foundation and planetary boundaries of two rural Chinese localities, using paleoecological data and social survey statistics. This article expands the practical application of planetary boundaries while focusing on the economic development of developing countries. This is the second emergence, which has been co-cited 32 times. In 2018, O'Neill et al. published the article, named "A good life for all within planetary boundaries" shown in the orange region of Fig. 8. It emphasizes fairness and the need to ensure human well-being in a "safe and just space."

Analysis of article structure variation

The structure variation analysis of the cited article was used here to find literature with significant impact potential. The keyword clusters with different colors, including Cluster #0 Anthropocene, Cluster #1 nitrogen, Cluster #2 life cycle assessment, Cluster #3 pollution, Cluster #4 agriculture,

Cluster #5 global environmental change, Cluster #8 dietary guidelines, Cluster #10 post-growth, and Cluster #11 circular economy, are shown in Fig. 10a. The color-coded sections reflect the moment when co-citation links in those areas appeared for the first time. Areas in yellow were generated after the blue areas.

(1) The 7 papers by Bjørn created new dense and complex connections between Clusters #3 pollution, Clusters #2 life cycle assessment, Clusters #0 Anthropocene, Clusters #10 post-growth, and Clusters #8 dietary guidelines (Fig. 10b). Bjørn is committed to the practical application research of the planetary boundaries. In recent years, he has continuously tried to combine ecological footprint or life cycle assessment with planetary boundaries for absolute environmental sustainability assessment. In addition, the planetary boundaries framework was promoted and applied to the industry or company in the research of downscaling of the planetary boundaries framework.

(2) The 3 publications by Donges created new dense and complex connections between Clusters #1 nitrogen, Clusters #0 Anthropocene, Clusters #10 post-growth, and Clusters #8 dietary guidelines (Fig. 10c). Based on the supporting theories, such as the Anthropocene and Social-ecological resilience, Donges constructed models and analyzed the Earth System which is the study of the joint dynamics of biogeophysical, social, and technological processes on our planet. His research expands the study of planetary boundaries.

(3) The appearance of "From Planetary Boundaries to national fair shares of the global safe operating space — How can the scales be bridged?" created a new bridge between Clusters #4 agriculture, Clusters #3 pollution, Clusters #2 life cycle assessment, and Clusters # 0 Anthropocene (Fig. 10d). Häyhä et al. developed a framework that includes biophysical, socio-economic, and ethical dimensions. They proposed how to transform planetary boundaries into a fair share of national-level Earth's safe operating space. It plays an important role in making decisions on sustainable development pathways at the national level.

(4) In 2021, Lucas et al. published the article "Optimising diets to reach absolute planetary environmental sustainability through consumers," which made novel connections between Cluster#0 Anthropocene, Clus-

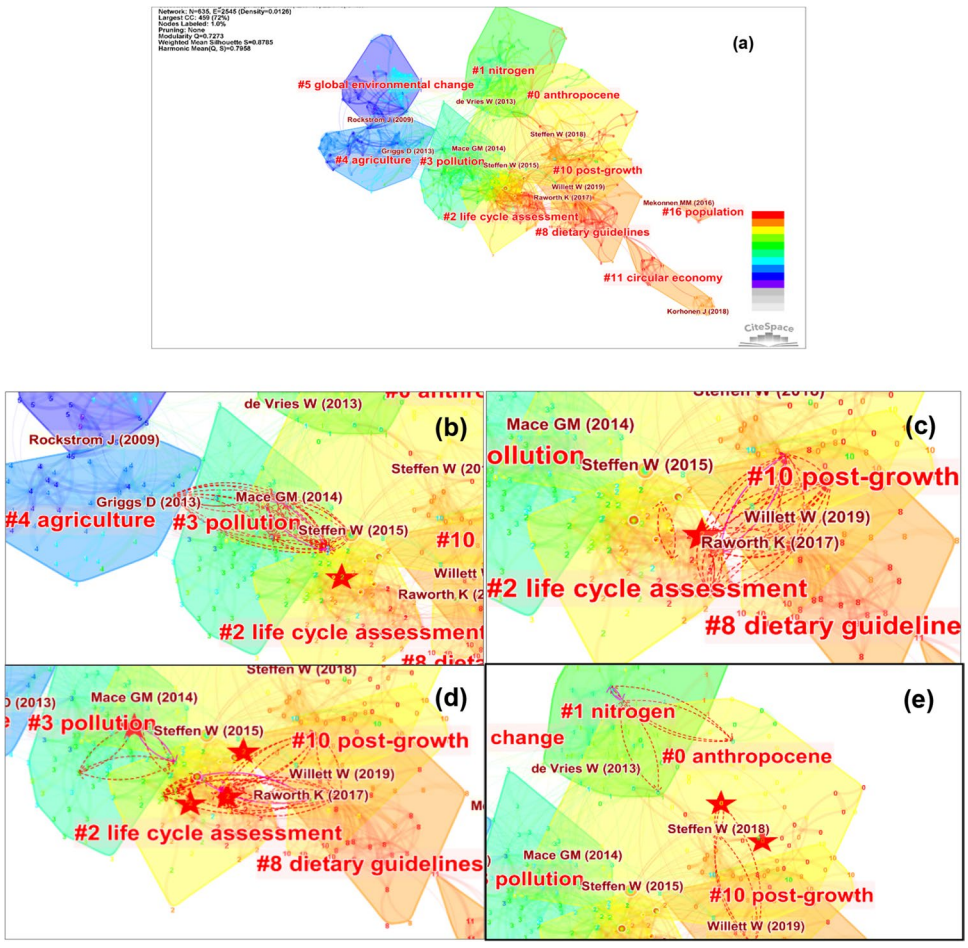

Fig. 10 Keyword clusters of cited articles (**a**); novel co-citations made by Bjørn (**b**), Donges (**c**), Häyhä (**d**), and Lucas (**e**). (The five-pointed star in the figure indicates the turning point, the dotted line is the clustering trend that may exist now or in the future and the emergence of bridges between clusters.)

ters #2 life cycle assessment, Clusters #10 post-growth, and Clusters #0 Anthropocene (Fig. 10e). This article used UK food consumption as a case and discussed the impact of diets on planetary boundaries. They found that more sustainable dietary patterns are not currently incentivized by the relative prices of food items in the UK and made a breakthrough in the research direction of planetary boundaries.

Research hotspots and trend analysis

A co-occurrence visualization of high-frequency keywords was performed based on CiteSpace. The results revealed that the top ten keywords include climate change (frequency = 93), planetary boundaries (frequency = 84), safe operating space (frequency = 61), impact (frequency = 53), framework (frequency = 38), sustainability (frequency = 35), life cycle assessment (frequency = 29), Land use (frequency = 28), systems (frequency = 28), biodiversity (frequency = 26), consumption (frequency = 26), water (frequency = 25), discharge (frequency = 25), and management (frequency = 25), footprint (frequency = 25). Then the log-likelihood algorithm (LLR) was used to extract the noun terms as cluster names shown in Fig. 11. Labels in the vertical direction indicate different clusters. The different colors indicate that the time when the co-citation link first appeared in the research area is different. Node size indicates the frequency of keywords. The flow of knowledge between clusters follows a distribution from dark to light, and from cold to warm. At present, Cluster #0 absolute sustainability, Cluster #2 Anthropocene, Cluster #4 model, Cluster #6 income, Cluster #7 demand, and Cluster #8 governance function still keep a high co-citation rate. These fields still maintain a high degree of research enthusiasm.

Cluster #0 focuses on the assessment of absolute sustainability. The average year of publication was 2017. The research objective of this cluster is to measure the carrying capacity of the Earth system and the impact of human activities on the Earth system. This cluster reflects the integration of planetary boundaries with footprint and life cycle assessment. Cluster #1 focuses on studying the relationship between biodiversity, scarcity, global carbon cycle, international trade, and planetary boundaries. Cluster #2 focuses on the study of the fundamental theory of planetary boundaries. The average year of publication was 2015. Cluster #3 focuses on the impact of agriculture such as the livestock industry, as well as biophysical processes like freshwater use and CO_2 emissions. This cluster emphasizes improving production efficiency and promoting the green transformation of industries. The average year of publication was 2017. Cluster #4 focuses on constructing system models to discuss the effects of changes in energy or climate on planetary boundaries. The average year of publication was 2013. Cluster #5 focuses not only on theoretical understanding of the concept of boundaries but also on the assessment of the safe operating space using a system of indicators on the other hand. The average year of publication was 2015. Cluster #6 focused on the impact of income levels and dietary habits on planetary boundaries. This clustering emphasizes the need for future diet optimization. The average year of publication was 2017. Cluster #7 focuses on human consumption within the framework of planetary boundaries. Green consumption is the future trend. Cluster #8 focuses on how governance actors, such as the state and government, use planetary boundaries

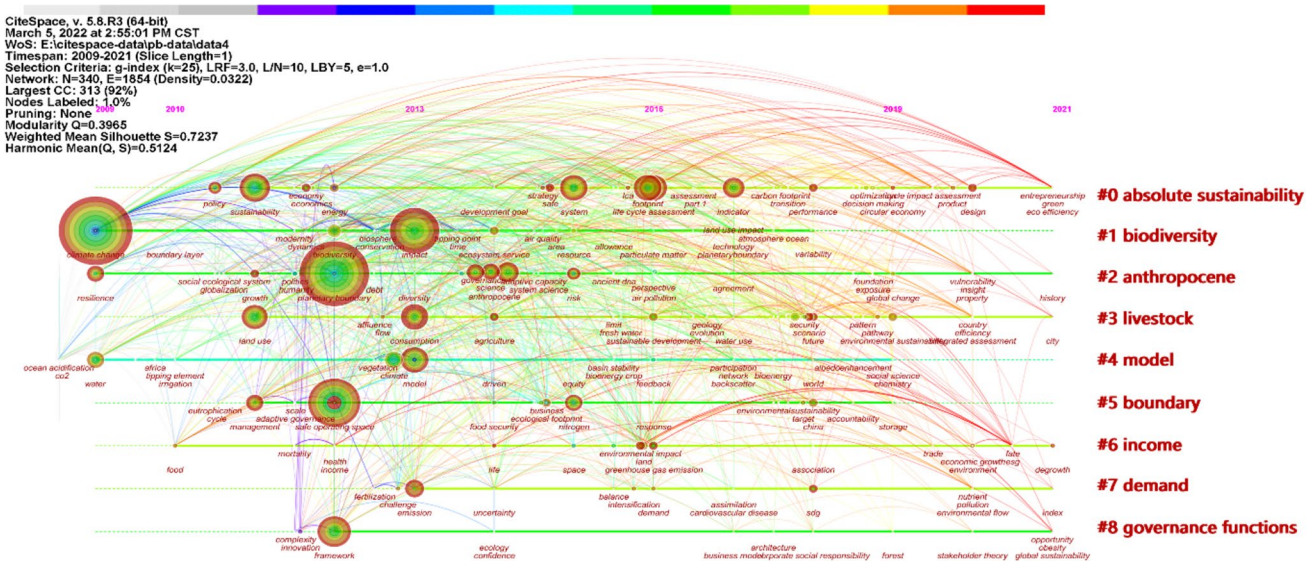

Fig. 11 Timeline map of research hotspot (The nodes represent the keywords; connecting lines indicate co-occurrence. The appearance of 9 clusters at various time periods and temporal spans is depicted in this view.)

to promote sustainable development; and how corporations can assume social responsibility.

As shown in Figs. 11 and 12, the network linked by these keywords has a large time span and a complex structure, involving multiple biophysical processes, government governance systems, economic and social development, and so on, which indicates the diversity of perspectives and research content of planetary boundaries. The hot issues of planetary boundaries were analyzed based on the frequency and timeline map of keywords.

(1) The in-depth research on one of the nine boundaries. Scholars conduct multi-dimensional research on each boundary. Some of them analyze nitrogen and phosphorus cycles from the perspective of consumption (Springmann et al. 2018; Willett et al. 2019), or assess and calculate local or global planetary boundaries of climate change (Beard et al. 2021), freshwater use (Gerten et al. 2013; Falkenmark et al. 2019; Gleeson et al. 2020), change in land use (Shaikh et al. 2021), and nitrogen and phosphorus cycle (Carpenter and Bennett 2011; De Vries et al. 2013; Sinha et al. 2022). At the same time, research on biodiversity has also begun to emerge (Mace et al. 2014; Rounsevell et al. 2020). And some scholars strengthen their research on ocean systems and novel entities (Nash et al. 2017; Villarrubia-Gómez et al. 2018). Among them, the climate boundary has received the most attention.

Climate change has appeared 93 times, with the highest frequency. According to Fig. 13, the keyword of "climate change" has appeared since 2009. It is due to the continuous concern of human beings on climate change. Especially at this stage, it is already in a dangerous position (Dong et al. 2022). The international community has been calling for mankind to control carbon emissions. The linkage on climate change still extends today and generates multiple linkages in Clusters #0 absolute sustainability, Clusters #3 livestock, Clusters #6 income, Clusters #7 demand, and Clusters #8 governance functions. Questions about climate change management permeate various areas of research. For example, Clusters #3 livestock, Clusters #6 income, Clusters #7 demand, and climate change research focuses on issues of green economy, green consumption, and circular economy. The research on climate change and Clusters #8 focuses on discussing how to formulate policies and plans for the green transformation of production and lifestyle. Research on Climate change has surged from 2015 to 2016. The reason is that the Paris Climate Conference was held in 2015 and the Paris Agreement was signed in 2016. This agreement puts forward a long-term goal to keep the global average temperature rise below 2 °C compared with the pre-industrial period, and strives to limit the increase in temperature to less than 1.5 °C. The climate boundary in the planetary boundaries also puts forward strict requirements on carbon emissions, which is in line with global requirements (Brown 2017). Planetary boundaries have attracted more attention from academic and political circles because of the quantitative requirements in the boundaries of climate change (Engström et al. 2020; Pincheira et al. 2021). Therefore, the number of using planetary boundaries to deal with climate change issues has increased after 2015.

(2) Evaluation of absolute sustainability. Several common environmental sustainability assessment methods, such as life cycle assessment (LCA), environmental

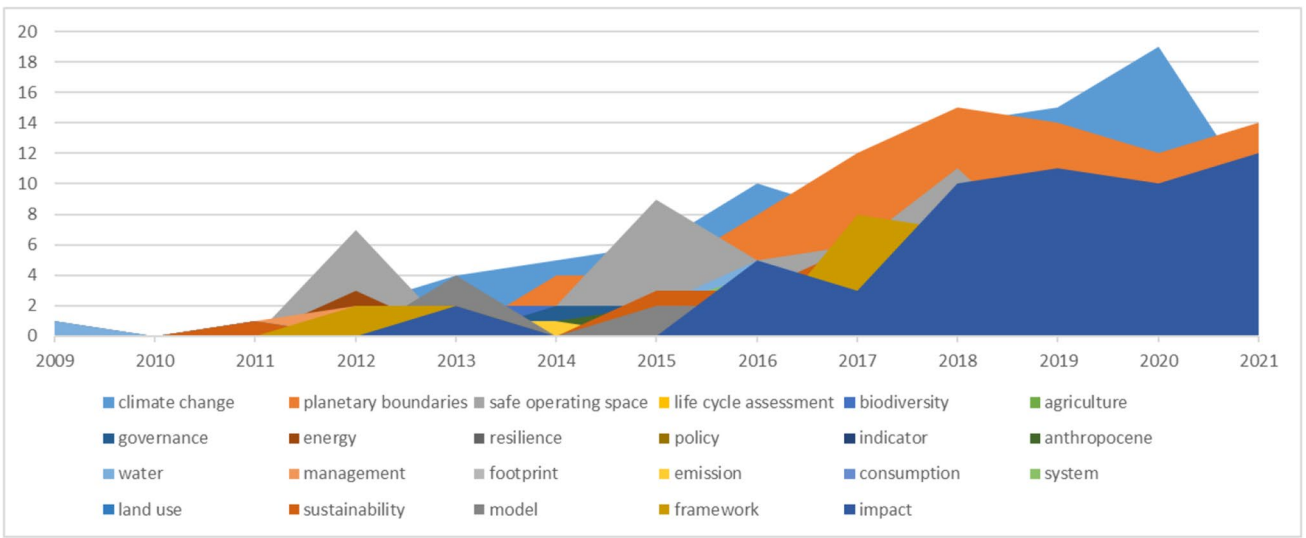

Fig. 12 Yearly distribution of the frequency of keywords

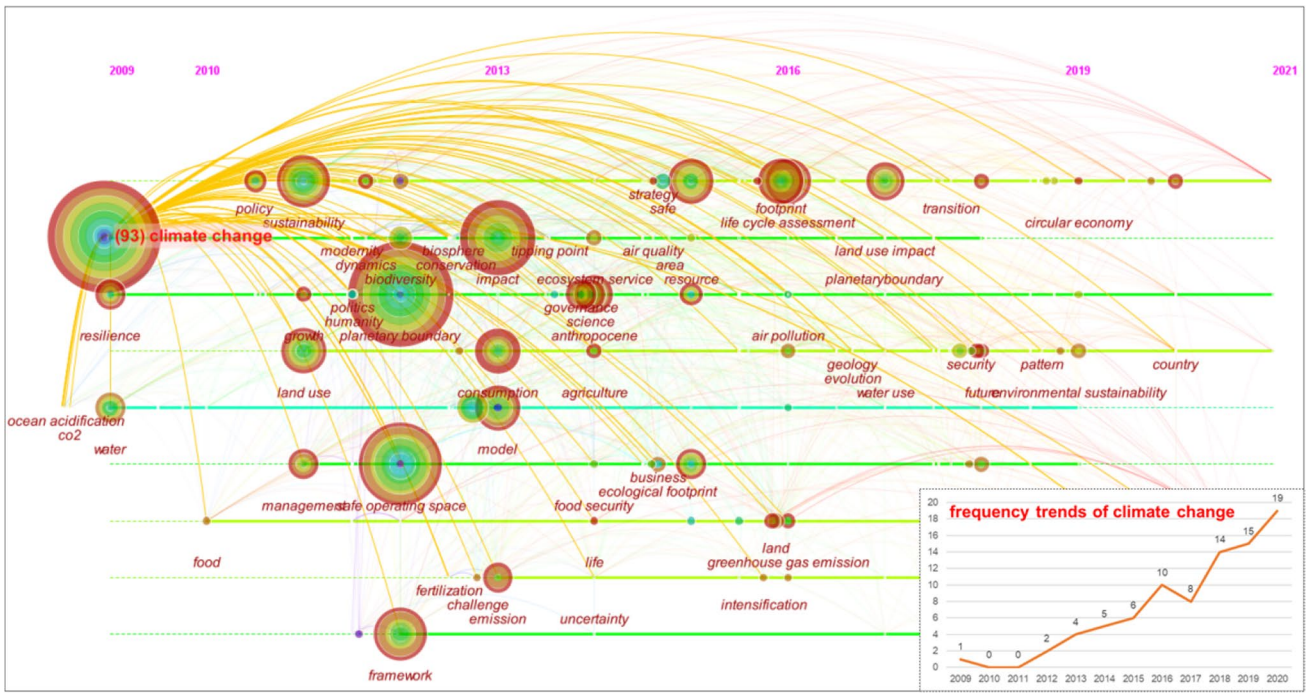

Fig. 13 A timeline map of the keywords (representative node "climate change")

impact assessment (EIA), and ecological footprint family (EFs), can quantify the environmental impact of the studied system, provide stakeholders with information on the level of environmental sustainability, and promote sustainable development plans. Scholars combine life cycle assessment, footprint family, and planetary boundaries, and then evaluate the level of absolute sustainability by quantifying the present value (Bjørn et al. 2015, 2017; Chandrakumar and McLaren 2018).

Scholars use life cycle assessment to transform the planetary boundaries framework into a product-related decision scale (Sandin et al. 2015). Based on the principle of fair sharing, they assess the absolute environmental sustainability of human activities by comparing the environmental impact value of the life cycle assessment with the safe operation space allocation value under the planetary boundaries framework (Moldan et al. 2012; Tuomisto et al. 2012; Sala and Goralczyk 2013; Roos et al. 2016; Wolff et al. 2017; Bjørn et al. 2020a, b; Guinée et al. 2022). There are two methods of integrating life cycle assessment and the planetary boundaries framework: the development of a new PB-LCIA model in the life cycle assessment (Ryberg et al. 2016; Algunaibet et al. 2019) and the integration of the planetary boundaries concept into the life cycle assessment in a standardized and weighted manner (Bjørn and Hauschild 2015).

The footprint family is mostly used to quantify the level of resource consumption or the intensity of the environmental impact caused by human activities, and it is one of the important means of environmental sustainability assessment. Scholars believe that the current value of the planetary boundaries can be measured by the ecological footprint (Fang et al. 2015b). With the help of the "footprint-boundary" environmental sustainability assessment framework, the sustainability gap between the scale of the activity and the relevant capacity threshold is measured. Fang et al. (2014) used the global per capita carbon emission space, 40% of the country's renewable water resources, and biocapacity to characterize the carbon boundary, water boundary, and land boundary respectively, and then they calculated the 30 major countries in the world using the range method and target distance method. Some scholars use the ecological footprint to quantify the planetary boundaries at the provincial level and link planetary boundaries of different scales with final consumption (Li et al. 2020; Wang et al. 2022; Suárez-Eiroa et al. 2022). In this way, we find the scale and spatial scope beyond the boundaries intuitively, which is conducive to the adjustment of policy objectives.

(3) Downscale the planetary boundaries. The planetary boundaries framework delineates a safe operating space that takes the world as a whole (Biermann and Kim 2020). Allocating the full safe operating space to actors or activities (i.e., downscaling) is necessary to

better align the framework with decision-making scales (Ryberg et al., 2020). And the transgression of regional boundaries may not cause the transgression of global planetary boundaries, but it also leads to irreversible environmental degradation and affects social sustainability. How to use the planetary boundaries framework to constrain the behavior of objects of different scales such as countries, localities, social organizations, and enterprises has attracted academic attention (Galaz, 2012; Whiteman et al. 2013; Bjørn and Hauschild 2015; Barker 2017).

① National and regional scales. The downscaling of planetary boundaries to a national or regional scale mainly adopts two methods: "top-down" based on the global security operation space allocation and "bottom-up" based on the local resource endowments and environmental capacity.

The "top-down" approach applies to planetary boundaries processes that have clear global thresholds and systemic environmental issues (Fang et al. 2015a; Huang et al. 2020), such as the problem of climate change and ozone depletion. This method calculates environmental goals, based on the principle of equal shares or the principle of equal shares per capita compatible with intergenerational equity (Dao et al. 2018), and downscales the global scale to the national or regional level (Cole et al. 2014; Ryberg et al. 2018). Some scholars have expanded the simple "average share per capita" (Butz et al. 2018; Ehrenstein et al. 2020) by assessing the size and growth rate of the country's population to solve the problem of fairness among the past, present, and future populations (Kim and Kotzé 2021; Parsonsova and Machar 2021). This method is beneficial to balance the division of environmental impact responsibilities and future ecological resource distribution caused by development patterns, wealth accumulation, and resource endowments in developed and developing countries in the process of sustainable development.

The "bottom-up" approach focuses on compound environmental issues which need to consider spatial heterogeneity, such as the problem of the use of land, nitrogen pollution, and freshwater utilization. Fang et al. (2015b) set 40% of each country's renewable water resources as the freshwater use boundary (Cole et al. 2017). Regional-scale planetary boundaries delineation is often more targeted and operational in the implementation and practice of sustainable development goals. But at present, it is still dominated by theoretical research, and the technical operation level is in the exploratory stage. Policymakers should not only actively consider the planetary boundaries process in development planning and decision-making, but also expand the boundary to the three dimensions of biophysics, society, and politics (O'Neill et al. 2018; Li et al. 2021). Then they transform the national or regional scale boundaries into the normative standard which includes local population, land area, economic output, resource efficiency, the historical share of resource use, emissions, environmental impact.

② Enterprise and industrial scale. Scholars believe that, to successfully strive for a safe and fair space for mankind, companies must participate in a sustainable transition (Sjåfjell 2020; Jiang and Li 2020). Integrating the concept of planetary boundaries into enterprise development can improve the environmental awareness of enterprises (Antonini and Larrinaga 2017; Ding et al. 2020; Burch and Bella 2021). Due to factors such as funding and non-resource efficiency, at present, this framework plays a relatively small role in the strategic decision-making of enterprises and departments (Haffar and Searcy 2018). Especially, climate change is the most concerned issue (Bjørn et al. 2017).

Some scholars also discussed how to achieve sustainable industrial development within the boundaries. At present, most researches mainly focus on the primary industry, such as tomato planting (Bjørn et al. 2020a, b), sugarcane ethanol industry (Wheeler et al. 2021), and animal husbandry (Leng and Hall 2021). Discussing the impact of specific industries on freshwater, land, and other ecological boundaries can determine the best combination of technology and network layout, and then minimize the impact on the planetary boundaries. The discussion of the industrial planetary boundaries should include global trade factors, because the potential environmental impact might be felt even far from the producing location. Research on the primary industry can continue to extend to a wide range of supply chain issues such as chemicals and fuel production, energy systems and agricultural planning industries, and heavy industry, so as to promote the adjustment and upgrading of the industrial structure.

(4) Attention to human economy and society. Sustainable development is a collection of complex systems based on the principles of fairness, sustainability, and commonality. It is the result of the interaction of economic, social, and environmental systems. To achieve sustainable development, we must dialectically understand and handle the relationship between development and population, resources, and the environment.

Scholars believe that the planetary boundaries framework has an important guiding role in the sustainable use of natural resources, while the social economy, human impact, and public participation are ignored (Raworth 2012; Baum and Handoh 2014). This may have negative effects on human

rights (Ensor and Hoddy 2021), social fairness and justice (Raworth 2012; Hughes et al. 2013; Leach et al. 2018; Steffen and Smith 2013; Hickel 2019), power politics (Lewis 2012; Brook et al. 2013), global governance (Biermann et al. 2010), democratic legitimacy and so on(Downing et al. 2019; Montoya et al. 2018). Such defects do not meet the requirements of the sustainable development. Some scholars think that the biophysically defined framework should be more integrated with socioeconomic and geopolitical factors. Economist Kate Raworth developed the famous "doughnut" theory, which combined 9 planetary boundaries system processes with 11 basic social indicators, including water, income, health, resilience, employment, voice, gender equality, energy, education, food security, and social equity. This theory is a deepening of the inclusion model, including two boundaries, social and environmental, and the structure of three zones that create a "safe and just (operating) space." It is necessary to ensure human well-being in a "safe and just space" (Cole et al. 2014; Dearing et al. 2014; Galaz et al. 2016; Raworth 2017; Hickel 2020; Coote 2021; Dillman et al. 2021).

Conclusions

This paper conducted a bibliometric analysis of 530 articles on planetary boundaries research which were published between 2009 and 2021 in the Web of Science database. We used the knowledge map analysis method and CiteSpace visual analysis software for this analysis process. The main findings are described below:

(1) We analyzed the basic characteristics such as volume, trends, authors, countries, institutions, and journals with the co-occurrence network of the citing literature. The concept of planetary boundaries and the terminology developed around it are now gradually gaining attention in the discussion of sustainable development. The number of planetary boundaries research papers continues to increase. The England and USA have the highest number of publications in the 530 documents. Johan Rockström, Sarah E Cornell, and Will Steffen from Stockholm University are some of the most influential scholars in the planetary boundaries research. Based on the knowledge flow analysis performed by the dual-map overlay, we found that planetary boundaries become a multidisciplinary cross-fertilized research field, expanding from ecology and natural science to economic and social fields continuously.

(2) The development path of planetary boundaries studies was analyzed using co-citation networks and the structure variation analysis. Rockström et al. (2009a) triggered the first emergent node—the planetary boundaries framework was proposed. The planetary boundaries framework was subsequently updated by Steffen et al. (2015). This article which has the highest co-citation frequency and emergent intensity, has been the main reference for subsequent scholarly research. Although the parallel article (Rockström et al., 2009b) sets out the scientific approach more fully, scholars mainly applied the framework updated by Steffen et al. (2015) in the recent research. They have a fundamental impact on the research and development of planetary boundaries. Research in the field of planetary boundaries framework has gone through proposals, controversies and developments, and is now being widely used. These studies by Lucas et al. (2021), Häyhä et al. (2016), Bjørn, and Donges provide important references for future directions of planetary boundaries research, such as studies on food consumption and cross-border integration issues of planetary boundaries.

(3) Research hotspots in the field of planetary boundaries were studied by keyword co-occurrence and cluster analysis. We summarized the current research hotspots into four themes, including in-depth studies of single boundaries, evaluation of absolute sustainability, downscaling of planetary boundaries, and expansion of economic and social domains. These studies are centered on the refinement of the planetary boundaries framework itself and the application of this approach. Among the in-depth studies targeting a single boundary, the climate change boundary is currently attracting the most attention. Combining planetary boundaries with methods such as life cycle assessment and footprint families to explore how to allocate safe space to subjects at different scales such as countries, companies, and industries is another research issue. Meanwhile, a large number of scholars began to focus on the use of planetary boundaries in economic, social, and political domains. These issues will continue to receive a great deal of attention in subsequent studies.

Unlike previous research, this study analyzes the research dynamics of the planetary boundaries more systematically and comprehensively using scientometric methods, which provides an in-depth analysis of the internal logical connections and development paths of research in this field. The findings of this study can help scholars and institutions in this field to strengthen communication and cooperation, and can provide a reference for the direction of future planetary boundaries research.

The future research potential of planetary boundaries was summarized given the current development trends of the studies. Firstly, in the summary of research hotspots, although we found that a large number of scholars have explored the methods of measuring environmental

sustainability of different subjects under the planetary boundaries framework, most studies have chosen specific research subjects that are not suitable for generalization so far. The measurement models for assessing planetary boundaries at different scales with global adaptability should be explored in the future. And the available data are the key in the measurement. So a big data system for the Earth should be established in the future.

Secondly, expand the application domain of planetary boundaries. In the structure variation analysis section of the article, we listed several research hotspots that may continue to be investigated in the future, such as the use of planetary boundaries to guide human food consumption and dietary habits. Food systems are a major driver of climate change, land-use change, freshwater depletion, and pollution of aquatic and terrestrial ecosystems through excessive nitrogen and phosphorus inputs. In-depth research in this field will be very important. And there are many controversies in the application of the planetary boundaries, especially in the field of social equity. Future research should start with how to better deal with equity issues, and combine descending scale research to set constraints on subjects of different scales within the "doughnut."

Finally, integrate the planetary boundaries framework with global sustainable development policies. On the one hand, future research needs to promote the planetary boundaries in the international community and explore the possibility of integrating it with SDG indicators and incorporating it into international law. As we found in our research hotspots, the early warning function of the danger zones defined by the planetary boundaries is particularly important in such a critical situation of climate change. Continuous attention to the role of planetary boundaries in the global climate change governance process is an important research direction in the future. On the other hand, promote the integration of planetary boundaries with the top-level design of national policies. With the global promotion of planetary boundaries, some developing countries (for example China, which ranks 10th in the output) have gradually started to research planetary boundaries. In the future, we should strengthen international cooperation, actively participate in global governance, and explore the development path suitable for countries based on the international community's experience exchange.

However, this study also has some limitations. One is the data source. The literature was obtained from the WOS database, excluding other databases such as Scopus. And the type of literature was "article" (published in peer-reviewed journals). Therefore, some data may be missed. The analysis of knowledge bases and classic documents omits significant achievements in books. Besides, CiteSpace also has some limitations. It can only form country co-occurrence networks through the author's territorial information. And defining the geographical sources of published articles is not an easy task. However, given the availability of data, this paper chose to assign countries based on the addresses of the authors. Although such a choice introduces some limitations to the analysis, it can still reveal the status of the co-occurrence network between countries and institutions to some extent. Further research can be conducted by expanding the database sources, adding key information manually, and combining other scientometric software.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Siying Chen and Jingwei Han. The first draft of the manuscript was written by Siying Chen. Supervision, funding acquisition, and review were performed by Zhixiong Tan, Maozhi Chen, and Demin Chen. And all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding The authors declare that the fund support was received from the Fundamental Research Funds for the Central Universities of Chongqing University (2018CDYJSY0055, 2022CDJSKJC26, 2021CDSKXYGG013) and from the Science and Technology Research Project of Chongqing Education Commission (KJQN202001602).

Data availability These data were derived from the following resources available in the public domain: https://www.webofscience.com/wos/alldb/basic-search.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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