Ecological Indicators 102 (2019) 650–665

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

A bibliometric analysis of comparative research on the evolution of international and Chinese ecological footprint research hotspots and frontiers since 2000

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ARTICLE INFO

Keywords:
Ecological footprint
Knowledge mapping
Research hotspots
Evolution of frontiers
Derek John de Solla Price curve
X index

ABSTRACT

The ecological footprint (EF) methodology, which is a tool for evaluating the natural resource use level and regional carrying capacity, has been extensively used to measure the capacity to reach both an ecological supply and demand balance and a level of sustainable development. In this study, to systematically sort and analyse the distribution of EF research, its hot areas and the evolution of its fronts, papers with "ecological footprint" as the subject term in the Web of Science Core Collection Database and the China Knowledge Resource Integrated Database Core Journals since 2000 are visually analysed using CiteSpace. The characteristics of these papers, including the quantity trend, quality, author group, affiliated institution type and journal type, are summarized, and keyword co-appearance and paper co-citation knowledge maps are produced. The results show the following: (1) Chinese researchers have been closely following international research fronts and steadily improving their research results. (2) Hotspots such as carbon dioxide emissions, the carbon footprint (CF), water footprint (WF) and sustainable use have been receiving attention both in China and internationally. International researchers focus on hot topics such as public satisfaction, land and resource use, spatial equity and policy analysis. In comparison, Chinese researchers prefer to modify and improve relevant methods, such as the three-dimensional EF (3D EF) and footprint family methods. (3) The research frontier of EF is based on improving the EF accounting method, which is aimed at assessing and monitoring the relationship between ecology and the economic society on a multi-scale basis, establishing an index system that can evaluate the demand for natural resources and environmental pressure, and explore the issues of mechanisms of regional ecology resource allocation fairness, and market-led and government-led ecological governance efficiency.

1. Introduction

In 1992, Rees (1992) first proposed the concept of the ecological footprint (EF), which was later improved by Wackernagel and Rees (1996). Rees and Wackernagel calculated the human demand for natural resources and the amount of resources that can be supplied by nature. In addition, they converted the consumption of various types of matter and energy into biologically productive land areas using a conversion factor. Whether regional economic development is within the reasonable carrying capacity was determined based on the balance between the ecological supply and demand. As a tool for evaluating carrying capacity, the EF methodology has received substantial attention thanks to international conventions. On June 4, 1992, the *United Nations Framework Convention on Climate Change* (*UNFCCC*) and the *Convention on Biological Diversity* (*CBD*) were adopted in Rio de Janeiro, Brazil. The *UNFCCC* (United Nations Framework Convention on Climate Change, 1992) was the first binding international convention to address climate warming, the comprehensive control of greenhouse gas (e.g., carbon dioxide) emissions, enhancing the adaptability of ecosystems to climate change, and ensuring grain production and sustainable development. The *CBD* (United Nations Environment Programme, 1992) was the first global convention related to biodiversity protection and sustainable use. On February 7, 1997, the United Nations (UN) Environment Programme passed the *Nairobi Declaration* and proposed the use of a comprehensive and unified method for environmental management and evaluation. For these, Charfeddine (2017) recommended using the EF as a new indicator of environmental degradation. In a paper co-authored by Butchart and 44 other researchers from 32 academic institutions and published in *Science*, the EF was proposed as one of the key indicators for describing global biodiversity

Abbreviations: EF, ecological footprint; CF, carbon footprint; WF, water footprint; 3D EF, three-dimensional ecological footprint

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https://doi.org/10.1016/j.ecolind.2019.03.031
Received 15 May 2018; Received in revised form 16 March 2019; Accepted 18 March 2019
Available online 24 March 2019
1470-160X/

(Butchart et al. 2010). Lubchenco (1998) noted that reducing the EF is a major challenge to each country's sustainable development. Ever since, the EF has been used and popularized on a global scale. Solarin and Bello (2018) proposed that using CO_2 emissions as an index for environmental degradation seems inadequate and stress the importance of the EF as an aggregate environmental indicator, they also mention that the lack of research on the random behaviour of EFs is increasing. The ecological price of economic growth is a controversial issue. Szigeti et al. (2017), through the relationship between EF and Gross Domestic Product (GDP), examine the trend of eco-efficiency in the first decade of the 21st century. The results show that the average EF intensity of countries has improved significantly during the given period.

Since the beginning of the 21st century, the importance of ecological, environmental, resource and sustainable development issues has been increasingly recognized worldwide. In 2005, 142 countries and territories signed the *Kyoto Protocol*, together promising to reduce greenhouse gas emissions before 2012. On December 7, 2009, during the Copenhagen Climate Change Conference, countries discussed follow-up plans for after the first commitment period of the *Kyoto Protocol*, clarified the central issue of "responsibility sharing", and proposed a long-term action goal of keeping the temperature from rising more than 2 °C above the pre-Industrial Revolution level. The *Paris Agreement* took effect on November 4, 2016, marking the third historical milestone after the *UNFCCC* and the *Kyoto Protocol* in enacting international laws to address climate change. The above-mentioned conventions not only lay the foundation for post-2020 global climate control but also point the way to a brand-new way of life and production. The EF methodology was proposed and developed in the same direction as these international conventions. The carbon footprint (CF), which was derived from the EF (Isman et al., 2018), has become a common indicator that measures the CO_2 emissions generated directly or indirectly during production and consumption processes (Chambers et al., 2007; Mancini et al., 2016). In 2012, Galli et al. (2012) first proposed a footprint family consisting of the EF, CF and water footprint (WF) for evaluating the impact of the consumption of biological and water resources and greenhouse gas emissions on Earth's environmental systems. In 2014, Hoekstra and Wiedmann (2014) comprehensively reviewed the EF, CF and WF and defined the concept of the maximum sustainable footprint, providing a reference for scientifically evaluating the sustainable level of human activity. This demonstrates that both that the academic and practical circles have reached a common understanding in the EF field and that the scientific term "footprint" has also gradually entered the public view.

In regard to issues that confront the entire world, such as sustainable development, coping with global warming and ecological construction, China is devoted to promoting the implementation of conventions and protocols and earnestly fulfilling its relevant obligations. In 1994, China prepared the *21st Century Population, Environment and Development* white paper, included a sustainable development strategy in their long-term national economic and social development planning for the first time. In 1997, China proposed sustainable development as a strategy that must be implemented in modernization construction. Of all the work that has been undertaken, desertification prevention and control is the most representative. For example, by establishing ecological economic systems in regions affected by desertification (Guang Ming Daily, 2001), the annual average desertified land changed from an expansion of 10,400 km^2 in the late 1990 s to a reduction of 2,400 km^2 (The state forestry administration of the People's Republic of China, 2017), realizing a comprehensive large-scale desertification prevention and control mechanism in which desertification prevention and control is led by the government, required by law, encouraged by policies, supported by science and technology, driven by engineering projects, stimulated by examples and involves public participation, which has received wide international recognition. In 2005, China passed the first *Renewable Energy Law*. By 2016, the consumption of clean energy (hydropower, wind power, nuclear power and natural gas) accounted for 19.7% of the total energy consumption in China (People's Daily, 2017), and the installed renewable power generation capacity in China surpassed 600 million KW, with the highest installed hydropower, wind power and photovoltaic power generation capacity in the world (Guang Ming Daily, 2017). In 2007, China enacted and implemented the *National Programme on Climate Change*, which was the first national law on climate change promulgated by a developing country. Later, China enacted and revised several laws and regulations, including the *Energy Conservation Law* and the *Circular Economy Promotion Law*, and gradually established a national legal system for ecological control. To reach the common "fixed goals" established in the *Paris Agreements* for all countries, China has proposed in the *Intended Nationally Determined Contributions* to reach peak CO_2 emissions, reduce carbon emissions per unit of GDP by 60%–65% compared to 2005 and increase the share of non-fossil primary energy consumption to approximately 20% by approximately 2030 (Policy Research Office of the National Development and Reform Commission of the People's Republic of China, 2015). Coal production in China has been on the decline every year since 2013. Coal consumption in China decreased for the first time in the 21st century in 2014 and registered a year-on-year decrease of 2.9%, 3.7% and 4.7% in 2014, 2015 and 2016, respectively (National Energy Administration, 2017). Green development practices in China place ecological civilization in the process of regional development. On October 2, 2017, the State Council of China issued the *Implementation Plan for a National Ecological Pilot Zone (Jiangxi Province)* and the *Implementation Plan for a National Ecological Pilot Zone (Guizhou Province)*, both of which regulate the regional ecological control mechanism. While reducing absolute carbon emissions, China is attaching greater importance to reducing greenhouse gases by increasing the ability of forests to store and sequester carbon. For example, China is currently implementing ecological rehabilitation projects, including the Three-North Shelterbelt Program in the Northwest, the North and the Northeast regions of China (He et al., 2017). In 2017, China implemented nationwide environmental inspections and used the inspection results both as part of the assessment of government officials and as an important basis for their appointment and dismissal. The program also pushed for responsibility systems across the country and established a water property rights system that clearly defines the ownership, rights and responsibilities as well as provides effective supervision. The *Environmental Protection Tax Law* that took effect on January 1, 2018, is not only conductive to building green production and consumption systems, but also help achieve ecological compensation between areas that provide and receive ecological benefits based on the determination of the ecosystem service value. Although ecological construction and environmental protection in China have received attention from the central government, there are still numerous issues as a result of the consideration given by sub-provincial-level governments to GDP growth performance. For example, the development of energy and chemical industries relies heavily on mineral resources such as coal and petroleum, accelerating urbanization lacks a "multiple rules merging into one" coordination mechanism, and population accumulation and the development of industrial enterprises in urban agglomerations accelerate pollutant emissions. These issues have attracted attention from Chinese researchers. On the one hand, the central government attaches full importance to ecological construction, ecological rehabilitation and environmental protection. On the other hand, ecological damage that conflicts with the will of the state occurs in some local areas, particularly ecologically vulnerable and sensitive areas. Hence, Chinese researchers have used the EF as a monitoring indicator for characterizing ecological conditions, examined the economic and social factors causing changes in the EF. Based on the Guanzhong-Tianshui Economic zone's EF from 2005 to 2014, the importance of various driving factors were compared by the Partial Least Squares (PLS) model (Yang and Zhu, 2017). Wang and Gao (2016) used the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model to analyse the social and economic drivers of the per capita EF of Baicheng

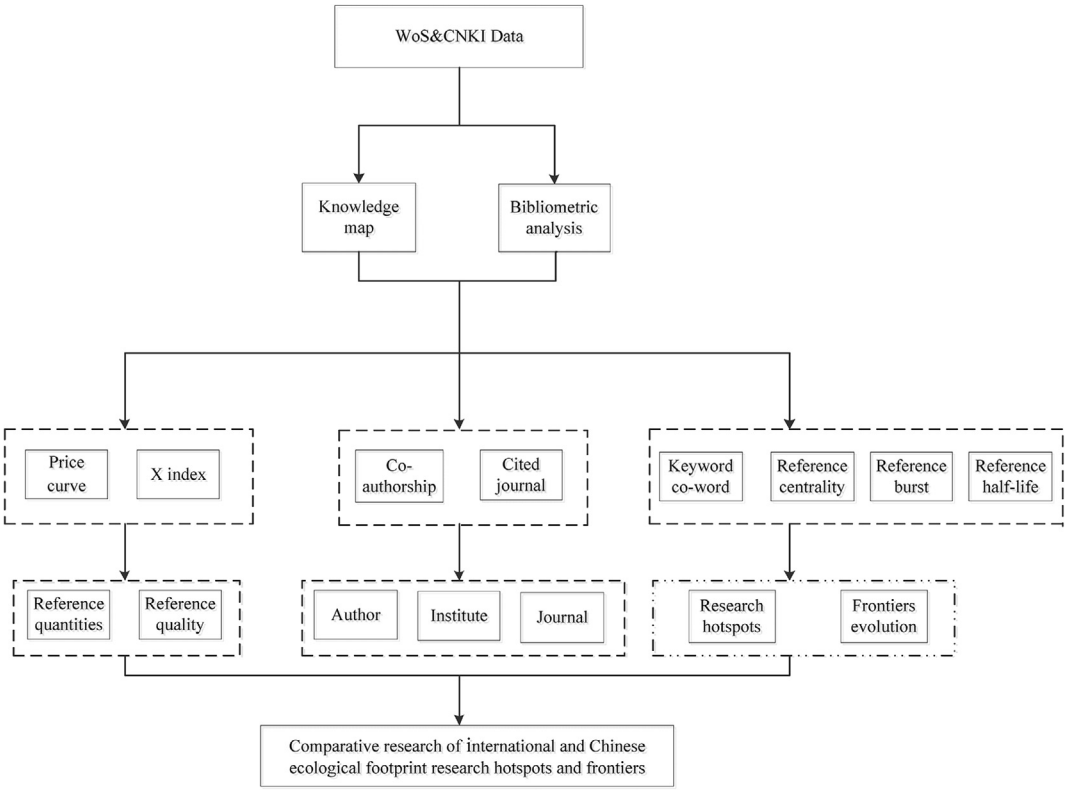

Fig. 1. Research framework.

City. The results showed that the population, comparable price per capita GDP, energy consumption per unit of GDP, ratio of secondary industry, urbanization rate and Engel coefficient were the drivers of the per capita ecology of Baicheng City. Regarding the social and economic drivers of the footprint, the driving force index values are 0.1575, 0.1647, 1.0500, 0.4719, 0.0206, and 0.5885.

All the existing review papers were essentially completed using subjective processing or *meta*-analysis. The reviews that rely solely on texts or numbers are less visual than graphs (Xin et al., 2014). In regard to information presentation methods, graphs are superior to tables, and tables are superior to texts. The CiteSpace information visualization and analysis software developed by Chen of Drexel University (US) has revolutionized conventional reviewing methods (Chen, 2006). Hence, in this study, based on the analysis results obtained using CiteSpace, knowledge-mapping methods are employed to reveal the knowledge basis of and hot topics in EF research, along with the evolution of its fronts by comparatively analysing the international and Chinese EF research (Fig. 1). This study not only systematically summarizes the development history, trend of EF research and lays a scientific foundation for conducting relevant research, but also has practical significance in that it encourages ecological managers to effectively use the EF methodology to design regional ecological control, natural resource management measures and provides relevant suggestions.

2. Methods and data

2.1. Methods

2.1.1. Knowledge-mapping analysis

A knowledge map produced based on all the papers in a certain field of research published within a certain time using the CiteSpace software developed in Java shows both hot research topics and advancement of the research fronts in a visualized form using functions such as co-citation analysis, co-occurrence analysis, and institution and author collaboration analysis (Chen et al., 2015). As the algorithms are being continuously optimized and the functions are being constantly improved, CiteSpace has been extensively used in more than 60 fields, including management, informatics, information science and medicine (Cui et al., 2018; Tho et al., 2017). When running CiteSpace, the thresholds of C, CC, and CCV are set to (2, 2, 20), (4, 3, 30), and (4, 3, 30), respectively, and the minimum spanning tree and pruning sliced networks are selected as the pruning method. Among, C represents the lowest cited or frequency of occurrence, CC represents the collinear or co-citation times in a particular time slice, and CCV represents the collinearity rate or co-citation rate. An analysis object is represented with a node. The larger the node, the more times it is cited within the selected time. The colour spectrum of the tree rings represents the citation history of an analysis object. The thickness of a tree ring reflects the number of citations of the analysis object within a given time. A line connecting two nodes indicates a co-citation relationship between the two nodes, its colour represents the first time that the two nodes are co-cited, and its length and thickness represent the strength of the link between the two nodes. A node encircled by a purple ring has relatively high (≥ 0.1) centrality (Liu, 2017), indicating an extensive connection with other nodes. This type of node is often the focus of concern in the knowledge domain and is of great significance to the node network analysis (Xin et al., 2014).

2.1.2. Spatio-temporal indicators analysis

By introducing the concept of the exponential growth of scientific literature proposed by Price, the quantity of scientific literature published in various years is plotted in a coordinate system, with the quantity of scientific literature as the y-axis and the year as the x-axis. A curve that reflects the exponential function relationship between the growth in the quantity of scientific literature and time, i.e., the Price curve, is obtained using a smoothing method (Price, 1983). The equation for calculating the quantify of scientific literature is as follows:

$$F(t) = a \cdot e^{bt} \quad (1)$$

where F(t) is the quantity of literature at time t. a is the quantity of

literature at the beginning of the statistical period. b is a time constant.

The X-index is the sum of the natural logarithm of the sum of the number of citations of each paper of an author and c and is calculated using the following equation (Xiao, 2015):

$$X = \sum_{i=1}^{N} \ln(Tc_i + c) \quad (2)$$

where N is the total number of papers. Tc_i is the number of citations of the i^{th} paper. c is a constant in the interval of [1, 2]. Because the impact of non-cited papers is not taken into consideration, $c = 1$.

2.2. Data collection

In this study, English literature data were collected from the Clarivate Analytics ISI Web of Science (WoS) website using the following procedure. First, the WoS website (http://apps.webofknowledge.com) was opened. Second, the "Web of Science Core Collection" that includes the Science Citation Index Expanded, Social Sciences Citation Index, Conference Proceedings Citation Index-Science, Current Chemical Reactions and Index Chemicus was selected in the "Select a Database" tab on the left side of the webpage. In addition, in the "Basic Search" tab, "ecological footprint" was entered in the "Topic" section and "2000–2017" was entered in the "Years Published" section. Then, by clicking the "Search" button, 2,380 search results were obtained from 2000 to 2017. Subsequently, the search results were refined using the "Refine Results" feature of the WoS Database by selecting "Paper", "Review" and "Proceedings Paper" in the "Document Types" tab. Overall, 2,322 effective records were obtained. Table 1 summarizes the acquired search results.

Chinese literature data were collected from the China National Knowledge Infrastructure (CNKI) database website. Currently, the CNKI database includes the largest and most up-to-date selection of journals in China. First, the CNKI database website (http://kns.cnki.net/kns/brief/result.aspx?dbprefix=CJFQ) was opened. A search in the "Core Journals" for papers published from 2000 to 2017 with the full Chinese term for "ecological footprint" as the "Topic" was performed. In addition, the obtained records were identified and sorted, and duplicate records, book reviews, catalogues and calls for papers were removed. Thus, 1,925 records were ultimately obtained. These references were then imported into CiteSpace, and "Refworks" was selected as the format. Table 1 summarizes the search results.

3. Results

3.1. The characteristics analysis of EF research

3.1.1. The characteristics of the quantity of selected publications

Overall, the number of EF-related papers in the WoS core database increased nonlinearly (Fig. 2). Fewer than 30 EF-related papers were published each year from 2000 to 2002. After 2006, the number of EF-related papers published each year began to increase at an increasing rate, and the annual average is 13.10%. In 2010, the Chinese government issued the first document of that year, namely, *Several Opinions on Strengthening Coordinated Urban and Rural Development and Further Laying a Foundation for Agricultural and Rural Development,* which clearly proposes to build a solid ecological safety barrier, to continue to advance ecological construction and to raise more compensation funds for ecological benefits. This document received considerable attention and strong reactions from various levels of government and in academic circles. In 2010, the number of EF-related papers published by Chinese researchers peaked. After 2012, the number of EF-related papers published by Chinese researchers began to decline.

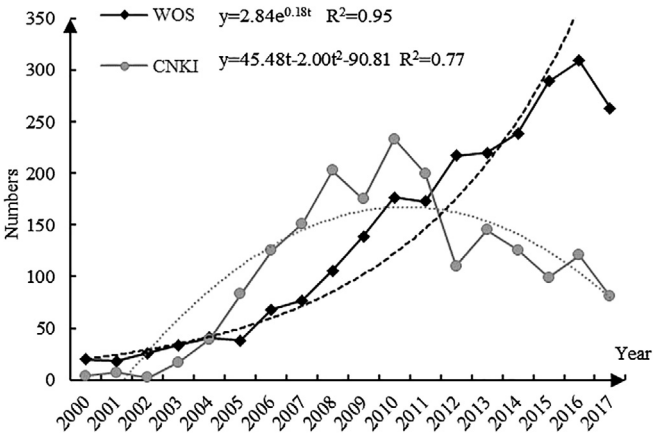

Fig. 2. Number trends in international and Chinese literature from 2000 to 2017.

The quantity data of EF-related papers included in the WoS core database and published in the CNKI core journals from 2000 to 2017 were subjected to a regression analysis using EViews, and the values of the coefficient of determination (R^2) were found to be 0.95 and 0.77, respectively. As demonstrated by the results shown in Fig. 2, the growth in the number of EF-related papers in the WoS core database matches the Price curve and conforms to the quantitative description of scientific growth by the first Price's law. In comparison, the trend curve of the number of EF-related papers published in the CNKI core journals exhibits an inverted U-shape. This is because after 2012, the number of case studies conducted in China in the EF field that focused on the CF and WF gradually increased, whereas the number of papers with EF as the subject term decreased.

3.1.2. The characteristics of authors

Academic circles have gradually approved of the use of citation frequency to evaluate paper quality (Zhang, 2010). Generally, the more frequently the papers of an author are cited, the higher the academic impact of that author. Tracking frequently cited papers in the EF field can facilitate the subsequent identification of research directions. Wackernagel and Rees (1996) and Rees (1992) are the authors with the highest X-index for EF-related papers in the WoS core database (Table 2), the concept of EF was proposed for the first time in their paper in 1992. In 1994, Wackernagel (1994) improved and developed the EF methodology. Wackernagel and Rees laid the foundation for EF research. Lenzen has the highest average number of citations per paper (127.67). Wiedmann et al. (2007) reviewed the environmental factors in international trade affecting the EF and noted that multiregional input-output models are the most suitable method for calculating the EFs of production, consumption and import and export. The environmental degradation accompanying human consumption is the most urgent global issue in today's world. Jorgenson (2003), who had an average number of citations per paper of 37.19, built a recursive indirect effects model to evaluate the effects of the world-system position, domestic inequality, urbanization and literacy rates on the EF per

Table 1
Retrieved results and strategies to acquire data.

Retrieval account	Retrieved results and contents	
Database	WoS core collection	CNKI core journal
Retrieval mode	TS = ("ecological footprint")	TS = ("ecological footprint")
Publication type	Article; Proceeding papers; Review	Article
Year	2000–2017	
Retrieval time	December 14, 2017	
Retrieved results	2322	1925

Note: TS- Retrieve the subject words, including the title, abstract, and keywords of the article.

Table 2
The X index and ACPP of the top ten authors.

Rank	WOS			CNKI		
	Author	X-index	ACPP[a]	Author	X-index	ACPP[a]
1	Wackernagel M	97.61	66.97	Wang Qing	119.66	32.6
2	Galli A	75.76	36.64	Gu XiaoWei	113.40	33.05
3	Lenzen M	58.73	127.67	Liu JianXing	88.79	39.36
4	Jorgenson AK	53.13	37.19	Xu ZhongMin	85.87	386.5
5	Narodoslawsky M	49.46	10.96	Zhang ZhiQiang	68.97	446.54
6	Niccolucci V	48.22	16.73	Lin ZhenShan	58.54	37.76
7	Herva M	35.61	23.08	Ren ZhiYuan	56.06	36.15
8	Moles R	35.21	23.75	Cheng ShengKui	54.18	28.44
9	Bastianoni S	30.74	15.17	Zhao XianGui	51.64	34.47
10	Shahzad K	19.65	7.25	Min QingWen	47.86	32.47

[a] ACPP: Average Citations Per Paper during the 2000–2017 period.

capita and found that the world-system position has the largest effect on the EF per capita, followed by the urbanization level, domestic inequality and literacy rates, i.e., countries with a high consumption level per capita require more biological resources. These results further clarify the meaning of EF in practice, reflect the academic value and application meaning of the EF methodology.

Wang has the highest X-index for EF-related papers published in the CNKI core journals (Table 2). In China, Gu et al. (2005) first built an urban EF calculation model with national hectares (NHA) as the unit of measurement and found that the EF of a region calculated using the NHA method could better reflect its ecological environmental stress as well as its current situation of sustainable development. Wang's study pioneered the research on the sinicization of EF. Later, Zhang et al. (2009) built a provincial hectare model, clarified both the meaning of the equivalence and yield factors and their calculation methods. In addition, they also, for the first time, introduced the concept of caloric values to overcome the technical difficulty in the direct summation of different types of biological products and realized the parallel comparison of small-scale study objects within a province. Zhang (average number of citations per paper is 446.54) and Xu (average number of citations per paper is 386.5) (2000) introduced the EF methodology to China, allowing people to realize that whether the EF is within the carrying capacity thresholds of an ecosystem is the core issue in measuring the level of sustainable development.

An author co-appearance analysis knowledge map can help find information on publications by the core authors in a certain subject or field and determine the intensity of their collaboration (Chen et al., 2017; Han et al., 2016). The more frequently an author appears, the larger the node in the map. Wackernagel and Galli published the most EF-related papers in international journals (29 and 28 papers, respectively). Globally, the following EF research groups closely collaborated with one another: the Niccolucci group from the University of Siena in Italy, the Wackernagel and Galli group from the Global Footprint Network (GFN), the Narodoslawsky, Kettl, Shahzad et al. group from Graz University of Technology in Austria, the Jorgenson group from Boston College in the US and the Clark et al. group from the University of Utah in the US (Fig. 3). As demonstrated in Fig. 4, Wang and Gu published the most EF-related papers in Chinese journals (42 and 40 papers, respectively). Eighteen authors each published more than 10 EF-related papers in Chinese journals. The author groups that published the most EF-related papers in Chinese journals primarily included the Gu, Wang, Liu, Li et al. group from the Resources and Ecology Research Center of Northeastern University, the Zhao, Ma, Xiao, et al. group from the School of Tourism and Environmental Sciences of Shaanxi Normal University, the Xu, Cheng, Zhang, Cheng, Min, Li et al. group from the Institute of Cold and Arid Regions Environmental, Engineering Research and Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences (CAS) and the Fang, Shen, Dong, et al. group from the College of Environment and Resources of Jilin University. In China, a research group generally consists of researchers from the same institution. The co-citation relationships between author groups and the academic links between different groups and authors are relatively weak.

Table 3 summarizes the top 10 authors that published the most papers in the EF field in international and Chinese journals. The EF-related papers published by these top 10 authors account for 12.0% and 8.0% of all the EF-related papers included in the WoS core database and published in the CNKI core journals, respectively. The EF-related papers published by authors that published more than 10 EF-related papers account for 12.6% and 12.0% of all the EF-related papers included in the WoS core database and published in the CNKI core journals, respectively. This suggests a relatively high author concentration and substantial basic contribution of the core authors.

3.1.3. The characteristics of different journals

Table 4 shows the top 10 international and Chinese journals that published the most EF-related papers from 2000 to 2017. Of the journals included in the WoS core search database, *Ecological Indicators,* with an IF[b] of 3.898, published the most EF-related papers in the study period, followed by *Ecological Economics* (IF[b] is 2.965). The objective of both the *Journal of Cleaner Production* and *Sustainability* is to help society become more sustainable. Of the CNKI core journals, *Acta Ecologica Sinica*, *China Population, Resources and Environment*, *Resources Science*, the *Journal of Natural Resources* and the *Chinese Journal of Applied Ecology* each have an IF[c] above 3.2 and represent the fronts and focuses of EF research in China, at least to some extent. The Chinese journals that published the most EF-related papers and were influential were all in the ecological and resource science fields, indicating that this type of journal attached importance to the publication of papers in the EF field. *China Population* and *Resources and Environment* are core journals that primarily report on the theories and practical applications of sustainable development. The *Journal of Natural Resources* and *Resources Science* are core journals in the resource and environmental fields. *Acta Ecologica Sinica* and the *Chinese Journal of Applied Ecology* are core journals in the ecological field. Clearly, EF research is an interdisciplinary field that involves numerous disciplines, including human geography, sustainable development, resources, ecology and the environment.

3.2. Comparative research on international and Chinese EF hotspots

The distribution and evolution of hot research areas can visually demonstrate the changes in research topics, perspectives and methods at various times. Keywords not only reflect the focuses of and the core issues discussed in the literature but also reflect the hot areas and topics of public interest in a certain time (Xia et al., 2017). Keyword co-appearance analysis (KCA) knowledge maps are a method that determines hot research areas based on high-frequency keywords (Hu et al., 2015). In this study, KCA knowledge maps were produced with 1a as the time slice and keywords as the node type. The WoS core database and the CNKI core journal data were imported into CiteSpace, and the node type was set to keywords. The KCA knowledge maps of WoS and CNKI contained 130 and 159 nodes, 209 and 149 links, respectively. Next, time-zone views were selected. CiteSpace was run to generate KCA knowledge maps for the EF field. The information on the key reference nodes in the KCA knowledge maps was integrated and extracted. A theoretical framework for EF research was established based on the literature and the corresponding keywords from the perspective of the comparison of international and Chinese research in the EF field (Fig. 5). Internationally, EF research focuses on meeting the demands of the public and enterprises for ecological services through the market-led enhancement of trading systems (e.g., carbon emissions). In comparison, in China, the government is the leader in the "government,

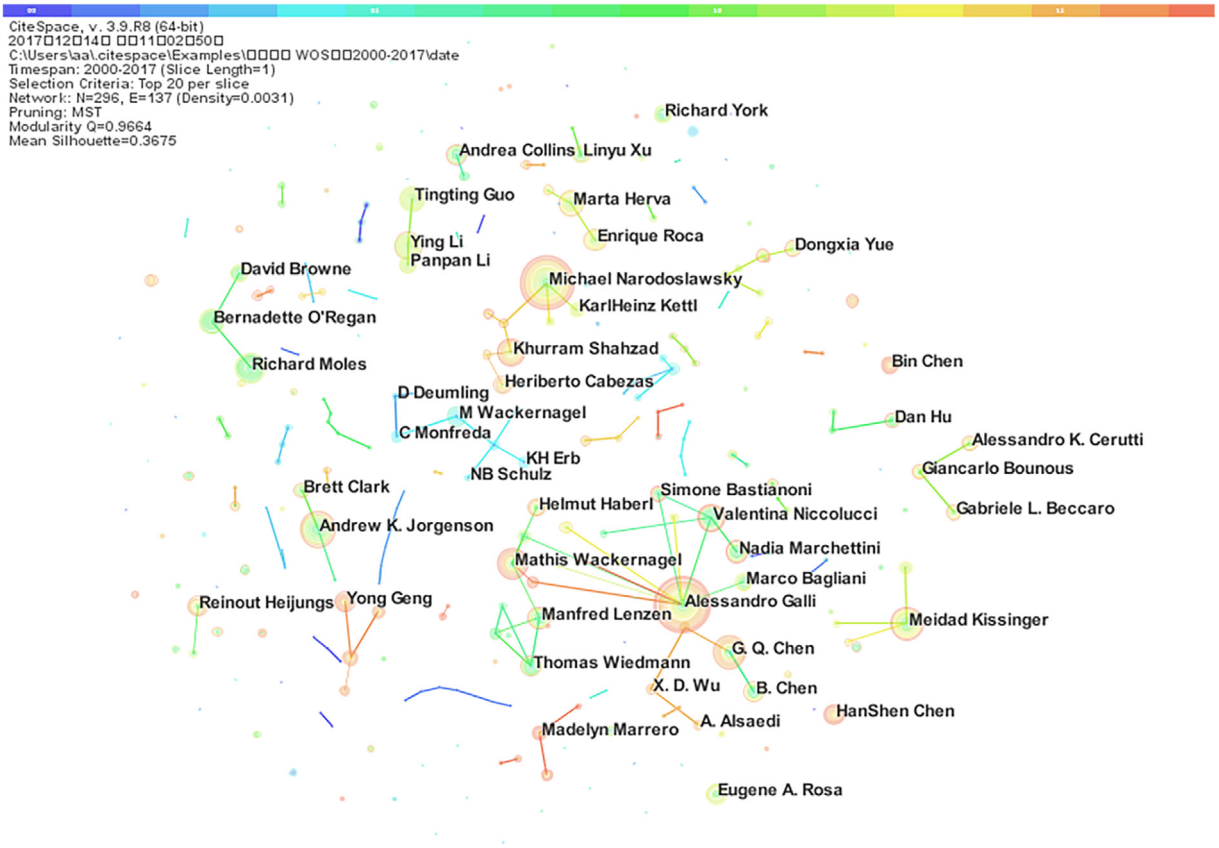

Fig. 3. Authors of international ecological footprint research from 2000 to 2017.

industry, academic and research circles" research system, and a government-led market participation model is adopted. The EF research in China focuses on policy supply with national ecological construction and sustainable development strategies as the targets.

3.2.1. International hotspots

The analysis of the hot keywords associated with international EF research (Fig. 6 and Table 5) shows that there were several hot keywords for each year from 2000 to 2017, except for 2015. There was only one hot keyword, which was CO_2 emissions, in 2016. The results shown in Fig. 6 demonstrate the following. (1) EF research exhibits significant regional characteristics. For example, Huang et al. (2016) evaluated the levels of sustainable development in 10 megacities in China from 1978 to 2014 using a set of sustainability indicators, including the EF, and provided suggestions for improving the environmental quality in megacities. (2) The attention paid to policies, behaviour patterns and transportation demonstrates that the EF research exhibits noticeable characteristics of behavioural sciences. For example, Charfeddine (2017) analysed the environmental conditions in Qatar from 1970 to 2015 using a Markov switching equilibrium correction model. The EF and ecological CF (ECF) as new indicators, they found not only that trade openness and urbanization resulted in an increase in the EF, but also that electricity consumption and financial development were positively correlated to the EF, negatively correlated to the ECF and CO_2 emissions. (3) The attention paid to individuals, households and wealth demonstrates that the EF research exhibits characteristics of human sciences. For example, Song et al. (2015) analysed the carbon, water, and EFs of 17,110 members of Chinese households associated with food consumption and waste generation, concluded that the generation of food waste was highly correlated to the consumption of various groups of food, e.g., vegetables, rice and wheat were consumed the most, consequently, contributed the most to each type of footprint. In addition, pork and aquatic products contributed significantly to the footprints. (4) CO_2 emissions, land, resource use and WF are the new hot areas of EF research. For example, Mi et al. (2016) calculated the CO_2 emissions generated by energy consumption in 13 Chinese cities in 2007 using an input-output model, found that a city's energy consumption not only led to CO_2 emissions within its own territory, but also induced CO_2 emissions in other regions through interregional trade. In addition, researchers have been paying increasing attention to such issues as public satisfaction (Verhofstadt et al., 2016) and spatial equality (Teixidó-Figueras and Duro, 2015). It is worth noting that policy analysis has garnered attention from international researchers. The term "policy" has even become a high-frequency keyword in the hot areas of international EF research in recent years, triggering a change in the direction of "public policies" in multiple areas of EF research. Policies have become a new trend in EF research (Baabou et al., 2017; Ulucak and Lin, 2017). For example, Charfeddine and Mrabet (2017) included economic development, social and political factors, including real GDP, energy use, urbanization level, average life expectancy at birth, fertility rate and social and political system variables. An EF estimation system was based on the panel data of 1975–2007 for 15 Middle Eastern and North African countries, used them as possible factors causing environmental degradation in an extended description of the Environmental Kuznets Curve relationship. They found inverted U-shaped relationships between the real GDP per capita and the EF of the oil-exporting countries. In addition, for the non-oil-exporting countries, they found a U-shaped relationship between foreign-exchange reserves and economic growth, that variables such as the urbanization level, average life expectancy at birth and fertility rate were long-term factors causing environmental changes, and that improving the political system did not help reduce environmental stress.

3.2.2. Chinese hotspots

As demonstrated in Fig. 7 and Table 5, the high-frequency hot keywords that appeared in Chinese EF research from 2000 to 2004

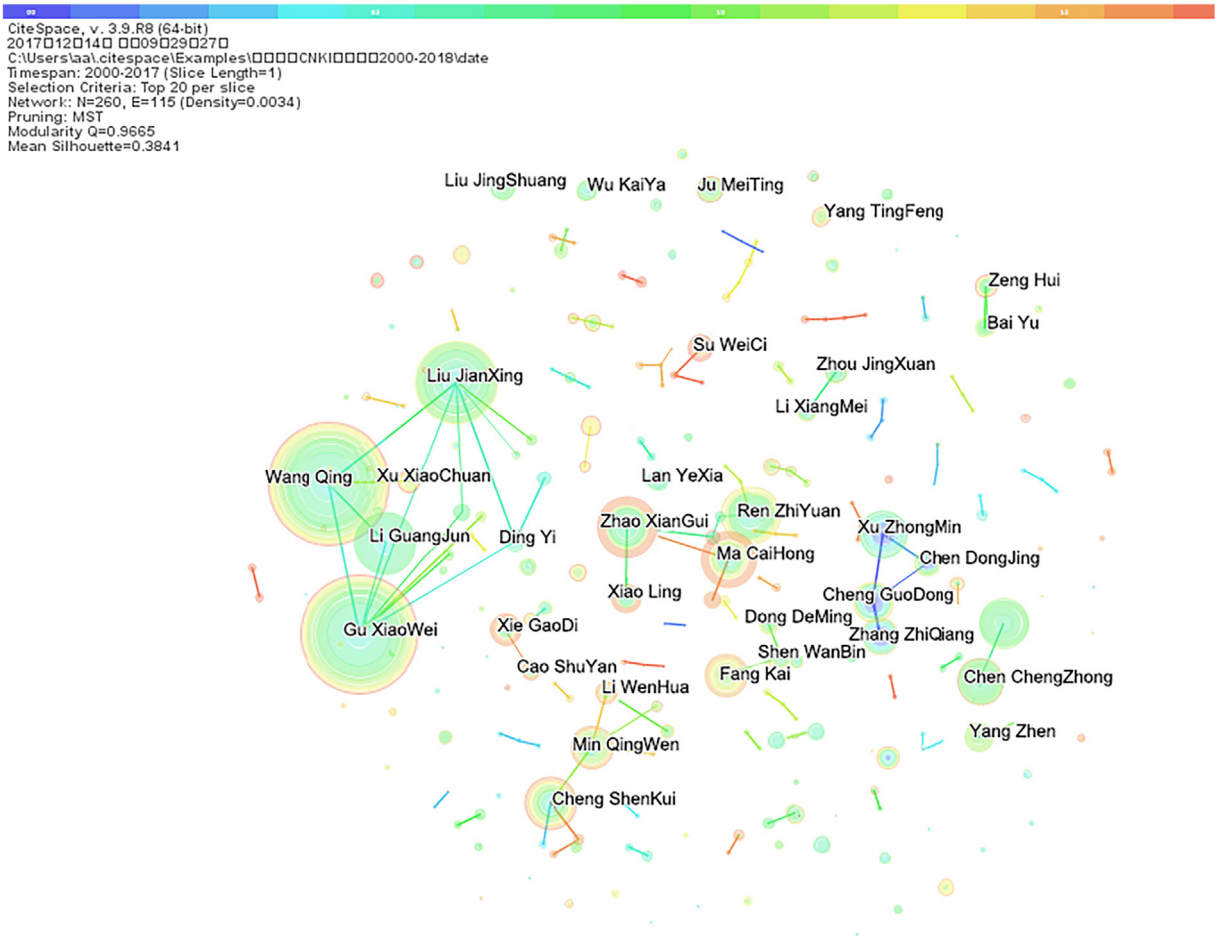

Fig. 4. Authors of Chinese ecological footprint research from 2000 to 2017.

Table 3
The performance of top 10 most productive authors.

Rank	TP[a]	,International Author	TP[a]	Chinese Author
1	29	Wackernagel M	42	Wang Qing
2	28	Galli A	40	Gu XiaoWei
3	24	Narodoslawsky M	28	Liu JianXing
4	22	Niccolucci V	21	Li GuangJun and Zhao XianGui
5	18	Bastianoni S	20	Ren ZhiYuan
6	16	Jorgenson AK	18	Cheng ShengKui
7	15	Lenzen M	17	Lin ZhenShan
8	13	Kissinger M	16	Xu ZhongMin
9	12	Haberl H	15	Min QingWen
10	11	Bagliani M	14	Cheng GuoDong

[a] TP: The total publications of one author during the 2000–2017 period.

included EF, sustainable development, indicator system, ecological deficit, ecological carrying capacity (ECC), ecological surplus, ecological economics, China, evaluation, research progress, urbanization, region, etc. The EF research in this period was characterized by the use of the EF methodology to determine whether the development of a region is within its ECC. For example, Xu et al. (2000) calculated the EFs of Gansu Province in 1998 and 12 provinces in Western China in 1999, found that, except for Yunnan Province and Tibet, where there was an EF surplus per capita, the production and living intensity in all the provinces exceeded the ECC and the regional ecosystems were unsustainable (Zhang et al., 2000). Guo et al. (2003) calculated the dynamic changes in the EF of Guangzhou from 1995 to 2000, found that the EF and ECC per capita in Guangzhou were 25 ha and 2 ha in 2000, respectively. The EF per 10,000 *yuan(CNY)* of GDP decreased year-to-year in the five-year period and the EF per capita increased slightly. In addition, they also provided policy suggestions for improving resource use efficiency, promoting conservation-oriented modes of production and domestic consumption. The high-frequency keywords that appeared from 2005 to 2009 included EF model, the EF of tourism, ecological compensation and capacity, ecological safety and efficiency, dynamic analysis, water EF, biological carrying capacity, environmental and ecological stress, sustainable use, emergy analysis, water resources, etc. EF research in this period was characterized by improving the EF methodology and models to increase their guiding value in practice. The high-frequency hot areas that appeared from 2010 to 2014 included economic growth, driving factors, yield factor, the STIRPAT model, low-carbon economics, farmland and land use, ecological civilization, etc. It is worth noting that after 2010, China's GDP growth rate fell from above 10% to 7%-8% and its economy entered a "new normal" characterized by a transition from high-speed growth to medium-to-high speed growth, continuous optimization and an upgrade of the economic structure, a transition from a factor-driven and investment-driven economy to an innovation-driven economy. Hence, the economic factors driving the growth of the EF attracted attention from Chinese researchers. For instance, Zhang and Zhang (2014) estimated the EF of Minqin county from 1978 to 2012 and employed the STIRPAT model to analyse the factors driving the growth of the EF. In addition, they calculated the coupling and coordinated relationship between economic development and the ecological environment using the ridge regression and partial least squares methods, respectively. Liu et al. (2014) constructed a comprehensive relative indicator of three indicators, namely, ecosystem services, EF and GDP per capita, and used it to evaluate the level of ecological civilization construction in

Table 4
The performance of the top 10 most productive journals.

Rank	TP[a]	The International Journal	IF[b]	PP[d](%)	TP[a]	The Chinese Journal	IF[c]	PP[d](%)
1	133	*Ecological Indicators*	3.898	5.73	129	*Journal of Anhui Agricultural Sciences*	0.423	6.70
2	129	*Ecological Economics*	2.965	5.56	108	*Acta Ecologica Sinica*	3.540	5.61
3	109	*Journal of Cleaner Production*	5.715	4.69	84	*Ecological Economy*	1.193	4.36
4	66	*Sustainability*	1.789	2.84	79	*China Population, Resources and Environment*	4.530	4.10
5	40	*Advanced Materials Research*	/	1.72	68	*Resources Science*	3.541	3.53
6	30	*International Journal of Sustainable Development and World Ecology*	1.864	1.29	63	*Journal of Arid Land Resources and Environment*	1.939	3.27
7	28	*Plos One*	2.806	1.21	55	*Research of Soil and Water Conservation*	1.329	2.86
8	26	*Science of The Total Environment*	4.900	1.12	52	*Journal of Natural Resources*	3.250	2.70
9	25	*Journal of Environment Management*	4.010	1.08	46	*Resources and Environment in the Yangtze Basin*	1.815	2.39
10	21	*Energy Policy*	4.140	0.90	26	*Chinese Journal of Applied Ecology*	3.267	1.35

[a] TP: The total publications of the journal during the 2000–2017 period.
[b] IF: The international journal's impact factor is from the respective official website in 2016.
[c] IF: The Chinese journal's impact factor is from CNKI in 2017.
[d] PP: percent point.

each province of China in 2010. From 2015 to 2017, results concerning the CF (Wang et al., 2015), three-dimensional EF (3D EF) (Du et al., 2016), WF (Wu et al., 2017) and footprint family (Fang, 2015a) emerged. For example, Liu et al. (2017) calculated the dynamic trend of natural capital in Shenyang from 1995 to 2014 based on the improved three-dimensional (i3D) EF. The i3D EF model was first used to calculate the natural capital utilization of different land types and then the integrated utilization. Eliminating the errors in the previous overall calculation process, which more specifically tracks the movements of stocks and flows of natural capital, Fang et al. (2018) integrated the EF, WF and corresponding ability indicators into an i3D model to study the use of water and land as an important natural capital resource in Guiyang. The results show that i3D is able to track the structural and characteristic dynamics of both flows and stocks while avoiding burden shifting across various components within single forms of natural capital from a strong sustainability perspective. Zhao et al. (2016) improved the footprint family and constructed an evaluation index system for ecological civilization construction to assess the level of ecological civilization construction in Xinjiang from 1990 to 2013. The results show that the Xinjiang ecological text is restricted. The main factors restricting the ecological civilization construction in Xinjiang are high greenhouse gas emissions and high pressure on water resources, which suggests that energy conservation, emission reduction and water conservation are the future directions. In addition, the EF, ECC and sustainable development, topics that appeared earlier, still appeared in the middle and later parts of the period examined in this study, suggesting that they were enduring topics in the EF field.

3.3. The evolution of the frontier on EF research

The research fronts of a field are reflected by the academic papers actively cited by researchers and can be used to describe the dynamic nature of the field (Xu and Guo, 2012). The literature downloaded from the WoS core database was subjected to a co-citation analysis using

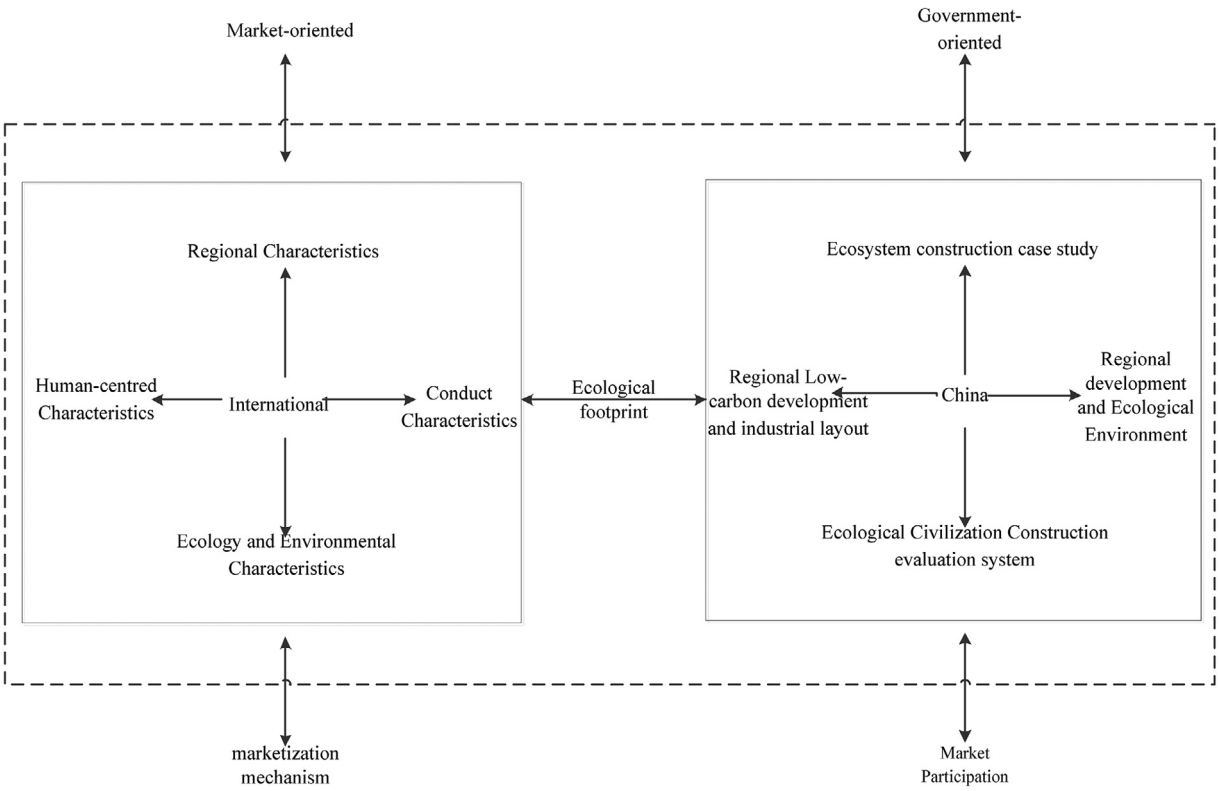

Fig. 5. Theoretical framework of ecological footprint research from international and Chinese perspectives.

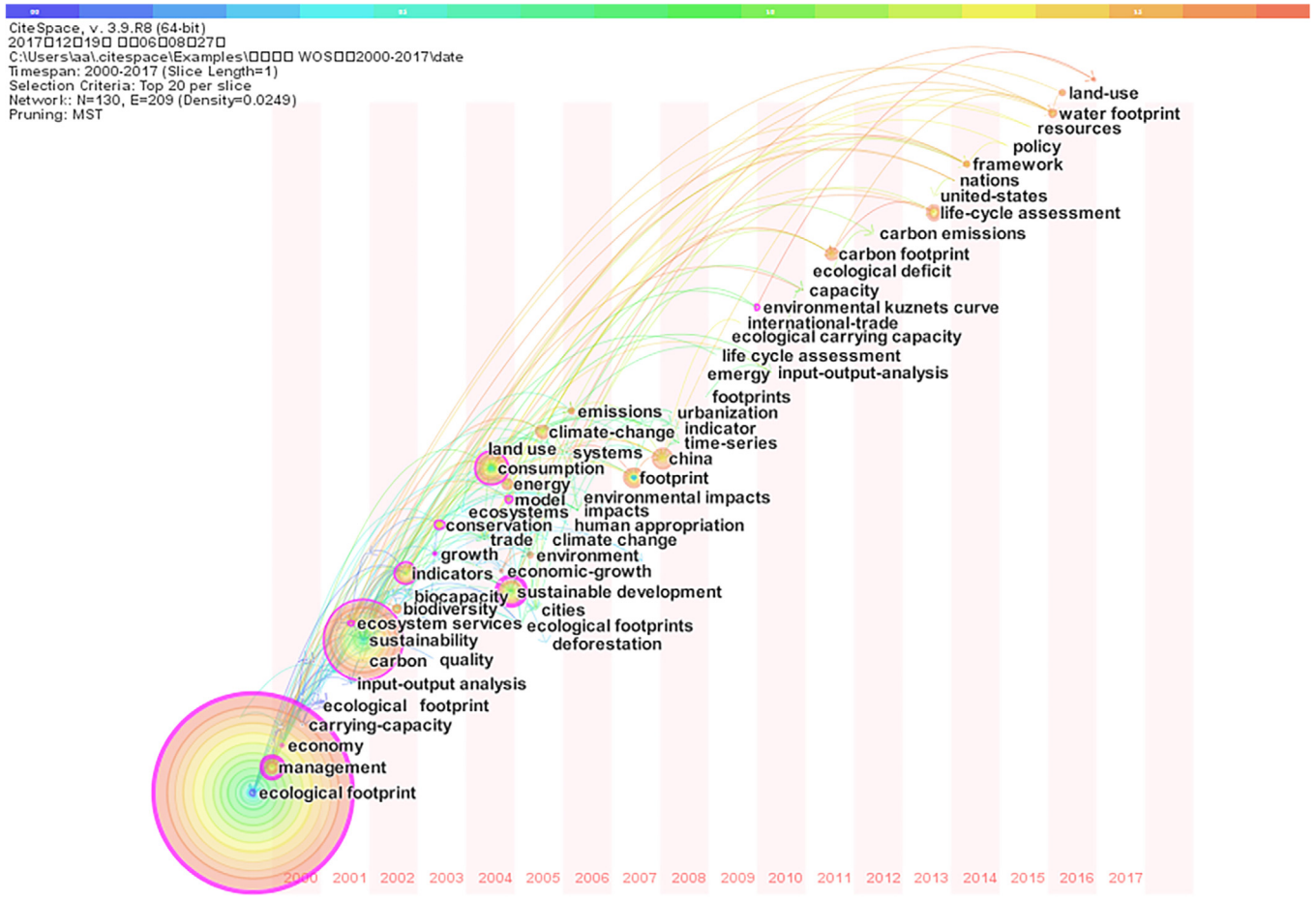

Fig. 6. The time-zone view of WoS ecological footprint hotspots keywords from 2000 to 2017.

CiteSpace. The time span was set to from 2000 to 2017. The top 20 highly cited papers for each time segment were selected. By selecting the "Clustering" function in the "Cluster" menu, a co-citation overall integrated network clustering time evolution knowledge map was generated (Fig. 8). The half-life, burst and centrality of a node characterize its "solid", "striking" and "critical core" positions in the citation network, respectively (Xu and Guo, 2012). The longer the half-life of a paper, the more solid is its position in the research field. A paper that is cited increasingly within a certain time has a relatively high burst value, which may become both a central paper and a hot topic for subsequent research. The higher the centrality of a paper, the more likely it may be to become the key to the transition of the fronts in the

Table 5
The information related to the Keywords from 2000 to 2017.

The International				The China			
Frequency	Centrality	Key Word	Year	Frequency	Centrality	Key Word	Year
859	0.31	ecological footprint	2000	1361	0.04	ecological footprint	2000
395	0.2	sustainability	2001	543	0.09	ecological carrying capacity	2001
195	0.12	consumption	2005	482	0.24	sustainable development	2000
184	0.28	sustainable development	2003	205	0.1	ecological deficit	2001
160	0.17	indicators	2001	71	0.1	ecological security	2006
140	0.05/0.21	China/management	2006/2000	57	0.23	ecological footprint model	2005
139	0.05	footprint	2006	44	0.07	tourism ecological footprint	2005
124	0.05	energy	2004	35	0.05	emergy analysis	2008
119	0.09	climate-change	2006	33	0.03/0.02	ecological compensation/China	2005/2002
108	0.01	life-cycle assessment	2011	30	0.04	ecological efficiency	2006
103	0	carbon footprint	2010	28	0.07	eco-civilization	2013
82	0.1	environment	2003	27	0.05	ecological surplus	2001
80	0.06	biodiversity	2002	26	0.01	ecological pressure	2008
79	0.01/0.05	emissions/ trade	2006/2003	25	0.02/0.13	biocapacityecological economy	2007/2001
78	0.03	framework	2012	23	0.01	sustainable utilization	2009
77	0.03	systems	2006	22	0	natural capital	2013/2010
76	0.03	water footprint	2014	21	0	carbon footprint water resource EF	2014/2013
75	0.11	model	2004	20	0	ecological environment	2006
74	0	impact	2010	19	0	plowland	2012
74	0.11	conservation	2002	18	0	energy footprint	2012

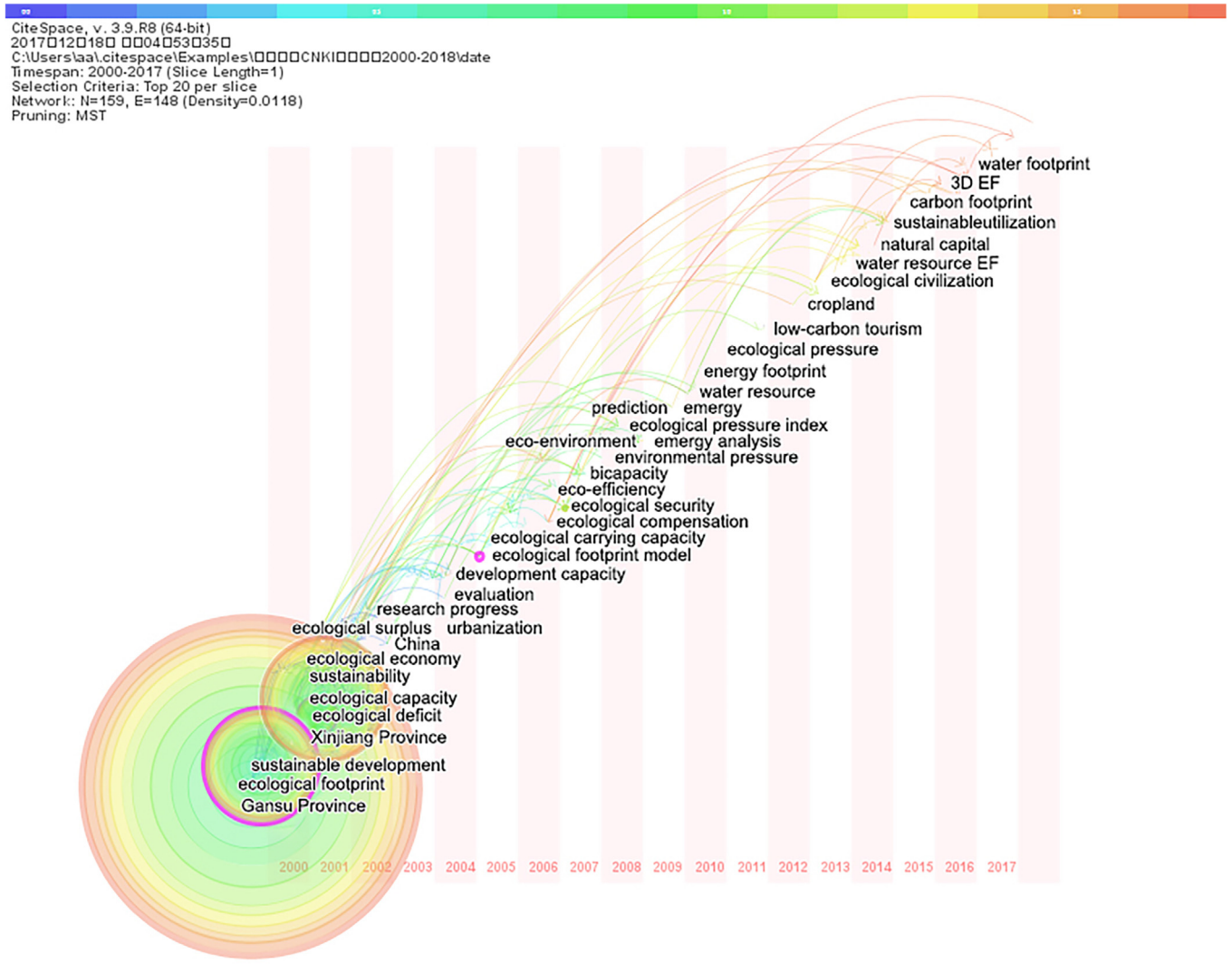

Fig. 7. The time-zone view of CNKI ecological footprint hotspots keywords.

network. To highlight the evolution of research fronts, 24 key papers with a centrality value above 0.11 were extracted, of which those with a long half-life and a high burst value were selected.

3.3.1. *The analysis of centrality and burst*

The centrality analysis results (Table 6 and Fig. 9) show that Kitzes et al. and McDonald et al. each have one of the highest centrality values. Kitzes et al. (2009) reviewed the development history of the nation-level EF accounting method, summarized the central issues of the academic debates, and improved the 2006 version of the nation-level EF accounting method. McDonald and Patterson (2004) proposed an input-output methodology-based model for analysing regional EFs, which could facilitate developed countries to periodically prepare and compare input-output tables according to an internationally approved classification. During the 10th *CBD* Conference of the Parties held in Nagoya, Japan in October 2010, new biodiversity targets and new indicators for the period of 2011–2020 were agreed on. The EF methodology was included in the related measurement and monitoring systems (Galli et al., 2014). Naturally, it has been a common occurrence for researchers to criticize the theoretical basis of EF and its methodology, question the reasonableness of its assumptions, debate policies and practices. For example, Mancini et al. (2017) noted that EF accounting failed to reveal the level of use of the stocks and flows of natural capital. Accordingly, Niccolucci et al. (2011) proposed a 3D EF model and used footprint depth and footprint size to characterize the appropriation of capital stocks and the level of use of capital flows, respectively, advancing EF research in depth. Fang (2013) improved the 3D EF model by introducing two new indicators, namely, the appropriation rate of capital flows and use ratio of stocks to flows, performed a validation analysis based on Chinese data for the period from 1961 to 2006. These results demonstrate that the frontier research in the EF field not only pays attention to theoretical and methodological innovations, but also focuses on actively exploring methods for guiding practice.

The burst analysis results (Table 6 and Fig. 9) show that the results published by Wackernagel et al. in *Ecological Economics* were cited 404 times in Science Citation Index journals. This reference has one of the highest burst values. Wackernagel et al. (1999) were the first to build a national and global natural capital accounting framework based on the concept of EF. Using Italy as an example, they converted national energy and resource outputs into the biologically productive land areas required to produce these resources and conducted a comparison between different countries, thereby verifying the applicability of the proposed accounting framework. Results of Wackernagel et al. opened up a new field in which the EF methodology is employed in national and global natural capital accounting. Monfreda et al. (2004) provided more meaningful comparisons of the final consumption or production of countries by clarifying the assumptions and choice of data sources on which the accounts were built, using more comprehensive data sources and accounting methods, distinguishing between primary and

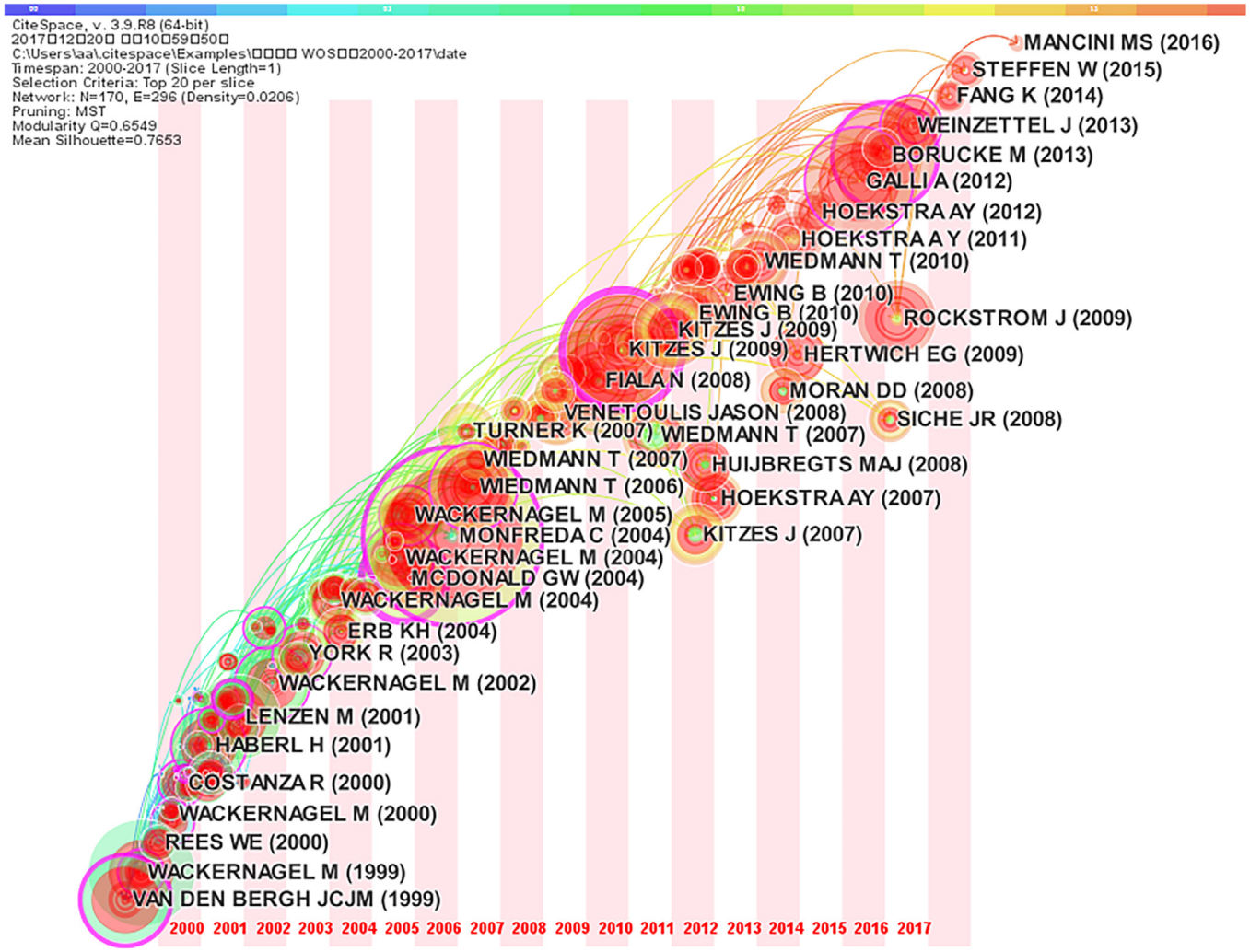

Fig. 8. Forefront of international ecological footprint research time-zone view of the evolution knowledge map from 2000 to 2017 for the co-cited references.

secondary product accounts, which could help analyse the EF embodied in trade and evaluate the economic sectors of production. Later, the generalization of regions in which the EF is applicable, the specialization of study objects enriched the meaning and extension of EF, covered a number of research directions, including provincial regions (Xun and Hu, 2019), urban agglomerations (Muñiz et al., 2016) and the construction industry (Martínez-Rocamora et al., 2017). In addition, researchers realized that single indicators could not comprehensively monitor the impacts of human activity on the environment. Thus, the focus of EF research gradually evolved to the integration of footprint indicators (Fang, 2015b). Galli et al. (2012) noted the need for the EF, CF and WF to be complementary to one another to be suitable for use in a multi-angled, multi-layered assessment of the level of sustainable development. Fang et al. (2014) systematically compared the meanings of EF, CF, WF and the energy footprint, the application conditions for their methodologies from a footprint family perspective, analysed the potential advantages of and obstructions to the integration of these four types of footprint. Ewing et al. (2012) integrated existing methods for calculating EF and WF within a multi-regional input-output (MRIO) modelling framework that has already been successfully applied for CF estimation, and the model offers significant improvements in EF and WF accounting through harmonization of methods with CF accounting. Bello et al. (2018) used four different measures of environmental degradation, including EF, CF, WF and CO_2 emission as target variables, while controlling for GDP, GDP square and urbanization for the period of 1971 to 2016. The results show evidence of an inverted U-shaped relationship between environmental degradation and real GDP. It is found that hydroelectricity can significantly reduce environmental degradation, and urbanization causes no particular harm to the environment except for the impact of air pollution. Wu and Liu (2016) combined the EF and CF with an environmentally extended multi-regional input-output model to analyze the imbalances, inequities and pressures of the EFs of China's 30 provinces in 2007. The result shows that the CF in the secondary sector is the main embodied EF of the flows among the provinces responsible for inequities. Moran et al. (2008) analysed the levels of sustainable development in 93 countries from 1975 to 2003 based on the EF in conjunction with the human development index (HDI). They found an overall trend in high-income countries that the improvement to the HDI led to a significant increase in the EF. In contrast, they found that some low-income countries achieved a relatively high level of development without a corresponding increase in the per capita demand on ecosystem resources. Morse and Vogiatzakis (2014) tested the relationship between the Townsend index of deprivation (TID) and the EF for English regions, using fine scaled data derived from the UK Census and the Stockholm Environment Institute, respectively. The results show that the relationship between EF and deprivation in most UK regions is significantly linear. As EF increases, the degree of deprivation decreases. Yang and Xu (2017) analysed the relationships between ecological efficiency, environmental efficiency and resource efficiency in the southern Qinling Mountains in Shaanxi province from 2005 to 2014 based on the EF combined with the City Development Index (CDI). Overall, the calculation of the EF alone

Table 6
Summary of crucial references.

No.	Year	Author	Title
1	2009	Kitzes J	A research agenda for improving national ecological footprint accounts
2	2004	Mcdonald GW	Ecological footprints and interdependencies of New Zealand regions
3	1999	Van den Bergh JCJM	Spatial sustainability, trade and indicators: an evaluation of the 'ecological footprint'
4	2013	Borucke M	Accounting for demand and supply of the biosphere's regenerative capacity: The National Footprint Accounts' underlying methodology and framework
5	1997	Wackernagel M	Perceptual and structural barriers to investing in natural capital: economics from an ecological footprint perspective
6	2004	Monfreda C	Establishing national natural capital accounts based on detailed - ecological footprint and biological capacity assessments
7	2000	Van Vuuren DP	Ecological footprints of Benin, Bhutan, Costa Rica and the Netherlands
8	1999	Buitenkamp M	National natural capital accounting with the ecological footprint concept
9	2004	Wackernagel M	Calculating national and global ecological footprint time series: resolving conceptual challenges
10	1996	Wackernagel M	Our ecological footprint: reducing human impact on the earth
11	1999	Lewan L	Evaluating the use of natural capital with the ecological footprint - applications in Sweden and subregions
12	2001	Haberl H	How to calculate and interpret ecological footprints for long periods of time: the case of Austria 1926–1995
13	2014	Galli A	Ecological footprint: Implications for biodiversity
14	2003	York R	Footprints on the earth: The environmental consequences of modernity
15	2000	Costanza R	The dynamics of the ecological footprint concept
16	2002	Ferng JJ	Toward a scenario analysis framework for energy footprints
17	2013	Weinzettel J	Affluence drives the global displacement of land use
18	2009	Hubacek K	Environmental implications of urbanization and lifestyle change in China: ecological and water footprints
19	1998	Bicknell KB	New methodology for the ecological footprint with an application to the New Zealand economy
20	2012	Galli A	Integrating ecological, carbon and water footprint into a "Footprint Family" of indicators: definition and role in tracking human pressure on the planet
21	2002	Wackernagel M	Tracking the ecological overshoot of the human economy
22	2004	Wackernagel M	Calculating national and global ecological footprint time series: resolving conceptual challenges
23	2006	Wiedmann T	Allocating ecological footprints to final consumption categories with input-output analysis
24	2001	Andersson JO	Ecologically unsustainable trade
25	2004	Erb KH	Actual land demand of Austria 1926–2000: a variation on Ecological Footprint assessments
26	2007	Wiedmann T	Examining the global environmental impact of regional consumption activities-Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade

cannot explain the relationships between the ecosystem and economy and society. The EF analysis framework is gradually transitioning from the improvement of single footprint models to the integration of the footprint family, the scale of EF research is also transitioning to provinces, urban agglomerations, industries and individuals to provide a multi-layered, systematic EF application method.

3.3.2. The analysis of half-life

The results in Table 6 and Fig. 9 show that results of Hubacek et al. have the longest half-life. Hubacek et al. (2009) employed an input-output method to analyse the EF and WF of Beijing, described the course of changes in urbanization and lifestyle. They found that compared to other cities in China, Beijing had a per capita EF of 4.99 gha, which was 2.8 times the national average. In addition, they found that in cities, agriculture made a very small contribution to the EF. Whereas the manufacturing industry and energy production contributed to 60% of the total EF and the transportation and service industries contributed to nearly 20% of the total EF. In 2012, Beijing had a total water supply of 3.59 billion m^3 and a per capita amount of water resources of 191 m^3 (Beijing Water Authority, 2012), whereas its WF and per capita WF

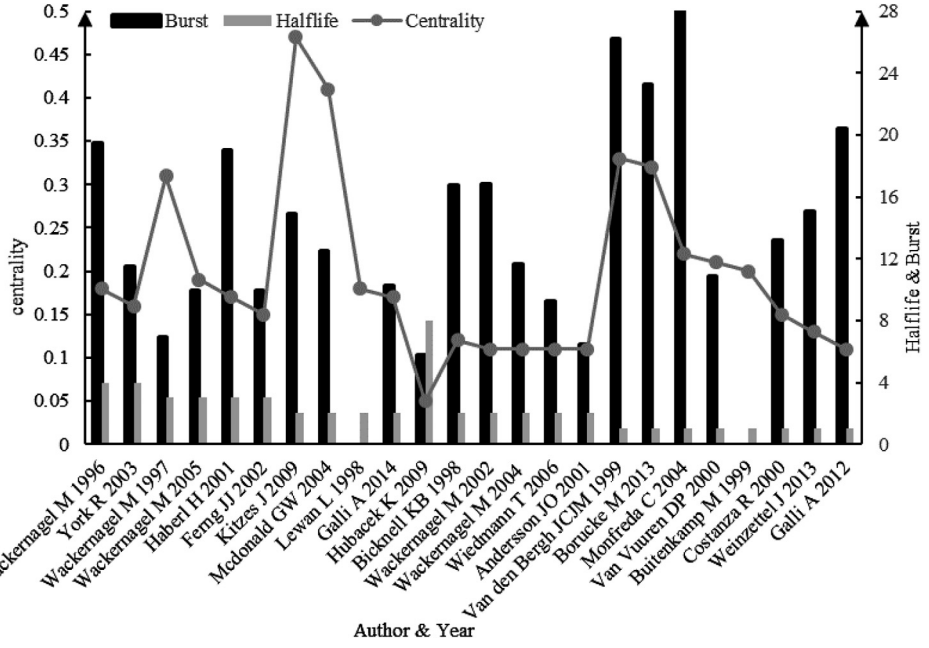

Fig. 9. The centrality, burst and half-life of crucial references.

reached 35.26 billion m^3 and 1,704 m^3, respectively (Sun et al., 2015). This suggests that the water resources supplied by the South-to-North Water Transfer Project were unable to meet the water demand in Beijing. Based on the research results of Hubacek et al. (2009), Lu and Chen (2017) established a system dynamics model based on Markov chain and measured the EF of Beijing from 2001 to 2020. The results show that Beijing's footprint has remained stable for a long time due to stable consumption patterns and environmental protection policies. Energy consumption is considered to be a major contributor to Beijing's footprint. Su et al. (2018) measured the water EF of Beijing and Tianjin. The results show that the per capita water ecological surplus in Tianjin only occurred in 2012, while the water resources in other years were severe. Moreover, Beijing's water resources utilization has reached an unsustainable state, suggesting that the water conservation efforts of Beijing and Tianjin should follow the principle of unified planning, total volume control, planned water consumption, comprehensive utilization and emphasis on benefits. Chu et al. (2017) calculated the ecological tension index (ETI), the ecological occupancy index (EOI) and the ecological economic coordination index (EECI) for the Beijing-Tianjin-Hebei (BTH) region from 1995 to 2010. They found an increase in the EF and a decrease in the biocapacity of the terrestrial ecosystem in the BTH region, which led to a 1.77-fold increase in the ecological deficit of the region. The ETI level of the region was found to be very risky. The EOI level fluctuated from poor to moderately poor, indicating that the stress on the ecosystem resulting from rapid economic development led to a decrease in the EECI level, which further demonstrated that the existing mode of development was unsustainable. Indeed, addressing ecological environmental problems is no longer one city's task but involves regional ecological resource distribution and equality issues. Thus, 10 Chinese government agencies, including the Ministry of Environmental Protection, and six provinces or municipalities, including Beijing, Tianjin, Hebei, Shanxi, Shandong and Henan, jointly issued the *Action Plan for Comprehensive Control and Tackling of Air Pollution in the BTH Region and its Surrounding Regions in the Fall and Winter of 2017–2018* in 2017 (Ministry of Environmental Protection of the People's Republic of China, 2017), requiring that the task of replacing coal with electricity and gas be comprehensively completed, that clean coal, such as coal briquettes and semicoke, be actively popularized to replace bulk coal in areas incapable of replacing bulk coal with clean energy during the heating season from November 15, 2017 to March 15, 2018. All the 44,000 coal-fired boilers included in the 2017 elimination list be "cleared". Even so, insufficient heating and natural gas supply shortage problems still occurred in the regions surrounding the BTH region. Addressing ecological environmental problems should not cause public discontent. As a branch of EF research, the relationship between people's livelihood and the ecological environment has garnered continuous attention from both academic circles and the government. In addition, the question of whether a radical or progressive solution should be adopted has also attracted public attention.

In 2008, the United Nations Development Programme (UNDP) released the 2007–2008 human development report, calling for international solutions to climate change in the 21st century. If rely only on market forces to solve environmental problems and it is difficult to cope with the increasingly severe global climate change situation, the global climate change problem may become the "largest and most widespread market failure in human history". Therefore, it is necessary to meet this challenge to adopt effective policies to reduce GHG emissions and correct market failures (Betts, 2008). The world must not only reach a consensus agreement on the limits of GHG emissions, but must also establish a national restriction strategy and detailed carbon emission reduction paths (UNDP, 2008). Since the UNDP report, the world has paid great attention to climate change and has promoted a low-carbon economy. Achieving global sustainable development through low-carbon economic models and low-carbon lifestyles (Zhang, 2008). Therefore, the use of EF as a monitoring indicator for the characterization of climate change has become the focus of scholars. For example, Isman et al. (2018) takes 15 Canadian cities according to census metropolitan areas as an example to show the applicability of the EF and focuses on the CF subcomponent of the EF in census metropolitan areas. The research results show that the largest contributor to the EF of the census metropolitan areas is the CF. Meanwhile, the actions needed to achieve the goal of global sustainability, as measured through the EF, overlap with and are indeed highlighted by the Paris Climate agreement at the 2015 United Nations Climate Change Conference, COP (Conference of Parties) 21, which emphasized the need for climate change mitigation through the reduction of CO_2 emissions.

The application of EF results in carbon emissions trading systems has received attention from various countries, particularly China. In 2017, the National Development and Reform Commission of China issued the *Program for Establishing a National Carbon Emissions Rights Trading Market (Power Generation Industry)*, marking the formation of a national carbon emissions trading system (National Development and Reform Commission of the People's Republic of China, 2017). However, no separate CF standards were established in this programme. Internationally, the European Union Emission Trading Scheme was first launched in 2005. In 2008, the British Standards Institution (2008) issued the Publicly Available Specification (PAS) 2050: Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services. In 2011, the International Organization for Standardization formulated the first product CF standard in the world, the International Standard ISO 14067. Bureau Veritas calculated the CFs of starch products manufactured by China National Cereals, Oils and Foodstuffs Corporation (CNCOFC) according to the accounting standard stipulated in the PAS 2050 specification. CNCOFC became the first enterprise in the Mainland China food industry to implement the PAS 2050 specification (Tong et al. 2018). Localization based on the characteristics of carbon emissions in China, and according to international standards, has become the basic task in the operation of the carbon emissions trading system. Europe and the US were able to rapidly popularize the CF and carbon labelling, primarily because of their market-oriented economies and the active participation of enterprises. Therefore, formulating a market-oriented accounting standard that covers all products and services. General applicability is crucial to low-carbon development in China and will simultaneously allow the footprint results to be widely recognized internationally. This will become the EF research front in China.

4. Conclusions

The formation and development of the concept of EF has a certain historical background. The challenges to sustainable development, the changes in the global climate pattern and the increase in the level of scientific research are the main factors affecting EF research. In this study, CiteSpace information visualization and analysis is employed to analyse the EF research results obtained since the beginning of the 21st century from various perspectives, including publication trends, literature quality, author group, organization type and journal type. The hot areas and fronts of EF research are determined and sorted. In addition, an EF research framework is established from the perspective of a comparison of international and Chinese EF research, which shows the basic approach in this field.

First, China has produced relatively few EF research results at the international level but is steadily improving its research in this field. China's ecological problems have been receiving increasing attention from researchers around the world. The manner in which China addresses ecological problems in accordance with the "innovative, coordinated, green, open and sharing" development concept is continuously receiving international attention. China is the largest developing country in the world. Coordination of the population, resources and the environment and economic development will be an important topic for China for a very long time to come.

Second, future hot topics in EF research will involve breaking

through the single description of the EF, improving the interpretation capacity for the EF and its application level, e.g., using residents' lifestyles as one of the factors affecting the EF to explain and apply temporal and spatial ecology–economy–society processes and in urban planning, transport design and the construction of smart cities. There are noticeable differences and links between the hot topics of the international and Chinese EF research that are reflected in the difference in interdisciplinarity, which involves perspectives such as economic geography, sustainable development, resources and ecological environment. In terms of the connecting relationships between the hot topics of EF research, the topics studied in developed countries were investigated early and have good continuity. In comparison, EF research started late in China. Some topics studied in China overlap those investigated in developed countries. Because of the special state system and conditions of countries, EF research conducted in developed countries has multiple perspectives and focuses on improving the ecological environment by exploring the market mechanism. In contrast, most EF research conducted in China is led by national policies and centres around a dynamic analysis of the economic and social systems at the national, provincial and municipal levels or in special zones and their driving factors.

Third, EF research frontiers focus on improving specific methods, such as multiregional input–output analysis (IOA), life cycle assessment (LCA) and 3D EF methods, e.g., combining the LCA method with the IOA method to reduce computational errors and simplify computation subjects. Combining emergy analysis with the net primary productivity (NPP) method and embodying the stability advantage of the emergy parameters in the NPP can help reflect the differences in biological emergy productivity between different land types. An indicator system composed of complementary indicators (e.g., EF, WF, CF and CDI) needs to be established and used to comprehensively evaluate the relationships between the ecosystem and the economic and social systems. China's low-carbon economy and green development will become a typical global EF research sample. Led by the government, China will formulate strategic ecological plans, e.g., plans for ecological compensation, ecological restoration, equitable distribution of regional ecological resources and natural resource management, using the market mechanism based on its situation as a developing country.

CiteSpace requires the same citation ratio for papers published at different time points. As a result, the most recent papers will not be included in the study sample, which, together with the time lag resulting from the publication cycle of papers, will reduce calculation accuracy, causing errors in the results.

Acknowledgements

This work was supported by the National Social Science Foundation of China Western Project (15XJL009), Science and Technology Planning Project of Xi'an (2017109SF/RK003-(5)), Soft Science Research Program of Shaanxi-Joint Project (2018KRLY07).

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