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Carbon Footprints

Review

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A review of multi-factor footprints: a bibliometric perspective

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Abstract

With the global concern for environmental issues, studies of footprints, especially multi-factor footprints, have received great attention worldwide. This study aims to offer an overview of this research domain of multi-factor footprints, based on a sample of relevant literature published from 1992 to 2023, and to analyze the research trends, basic characteristics, and research hotspots of multi-factor footprints through bibliometrics. This study not only sorts out multiple combinations of common objects of research and main research methods, but also analyzes the information on the countries and authors with a large number of publications by using VOSviewer and CiteSpace, and carries out keyword co-occurrence, clustering, and burst analyses to uncover the evolution of the research hotspots. Finally, this study concludes that multi-factor footprint research has great potential for development, the combination of carbon footprint and water, energy, and other footprints provides a more comprehensive and deep perspective for assessing environmental impacts, diverse research methods drive breakthroughs, and the research hotspots have been extended to interdisciplinary and multiple fields. This study offers scholars a literature review of research perspectives in the field of multi-factor footprints and provides a reference for future research directions.

Keywords: Multi-factor footprints, bibliometrics, VOSviewer, CiteSpace

INTRODUCTION

In 1980, the International Union for Conservation of Nature (IUCN) first proposed sustainable development[1]. In the second half of the 20th century, with the advancement of economic globalization and industrialization, the pressure of human activities on natural resources and ecosystems has increased significantly. In 2015, the United Nations formally put forward 17 global Sustainable Development Goals (SDGs)[2], which covered various environmental aspects, including water, land, climate, *etc*. It is in this context that the footprint has become an important indicator tool for measuring environmental sustainability, which can not only reflect a certain aspect of the SDGs independently but also examine the internal relationships that take multiple goals into account. It originated from the concept of the ecological footprint (EF-eco), which was formally introduced to the academic community in the 1990s, first by Rees, who explored the relationship between EF-eco and occupancy carrying capacity[3], which attracted widespread attention. Then, EF-eco was a measure of the area of land and water required to maintain the population's current levels of resource consumption and waste emissions[4]. Subsequent footprint studies have centered on quantitative analyses to assess the resource consumption and carrying capacity of a particular country, region, or individual, with a focus on sustainability[5].

After a literature search on the topic containing footprint, it was found that there were 60,162 papers or review papers about footprint from 1992 to 2023, which are divided by the final publication year [Figure 1]. It can be seen that the footprint research has shown a significant upward trend as a whole. Since the number of studies related to footprint exceeded 1,000 for the first time in 2009, this field has attracted increasing attention due to the convergence of global environmental challenges, advancements in research methodologies, policy changes, and increased public awareness. In 2023, the number reached 7,740, presenting a favorable development trend.

With the development of footprint studies, the footprint has expanded to more factors[6]. These include carbon footprint (CF), formally defined in 2008[7], which is employed to quantify the total amount of greenhouse gases (or carbon dioxide) emitted by humans during production and consumption activities. It encompasses both direct and indirect carbon emissions related to products or activities throughout their entire life cycle and assesses the impact of human activities on climate change[8]; water footprint (WF) measures the direct and indirect usage of water resources. Attention was first given to virtual water trade in 2002[9] and later expanded to water consumption in agricultural and industrial production[10,11]. The concept of the energy footprint (EF-energy) formally emerged in 2011[12], evaluating the influence of energy consumption on the environment and covering fossil fuels, renewable energy, *etc*.[13], followed by the methane footprint in 2009[14,15], the nitrogen footprint (NF) in 2012[16-18], the phosphorus footprint (PF) in 2012[19-21], the land footprint (LF) in 2013[22-24], and the material footprint (MF) in 2015[25], among others. The number of related studies on common footprints is presented in Table 1.

The number of articles or review articles related to CF is more than 10,000, accounting for 20.89%, which indicates the key position of CF in footprint research. In addition to CF, the top three footprint studies are EF-eco, WF, and EF-energy, with the number of papers being 3,451, 2,982, and 583, respectively, indicating that the three are also the main research objects in footprint studies. The footprints of land, material, nitrogen, phosphorus, and methane, although accounting for a relatively small number of papers, are still a non-negligible part of footprint research. In fact, with the continuous expansion of the depth and breadth of research, as well as the changes in research hotspots, the original single-footprint research has become insufficient. It is crucial to understand resource use efficiency and sustainability from different perspectives by conducting multi-factor studies of footprint[26], which is essential to understand the resource consumption patterns of human activities and provide quantifiable evidence to support researchers and policymakers.

Table 1. The number of publications on common footprints from 1992 to 2023

#	Footprint	TP	PCT (%)
1	Carbon footprint	12,570	20.89%
2	Ecological footprint	3,451	5.74%
3	Water footprint	2,982	4.96%
4	Energy footprint	583	0.97%
5	Land footprint	233	0.39%
6	Material footprint	200	0.33%
7	Nitrogen footprint	154	0.26%
8	Phosphorus footprint	30	0.05%
9	Methane footprint	7	0.01%

TP: Total publications related to one footprint during 1992-2023; PCT (%): percentage of the number of one footprint publications to the total number of all footprint publications.

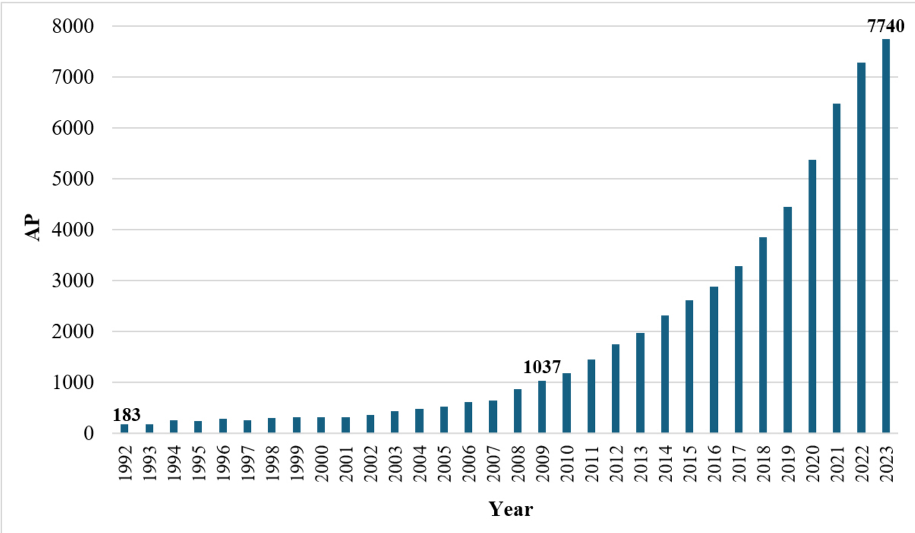

Figure 1. The number of annual publications on footprint studies from 1992 to 2023. AP: Number of annual publications.

Over recent years, there has been an increasing literature on cross-combination studies of multiple footprints. It involves the simultaneous consideration of multiple environmental elements (e.g., carbon, water, energy, land, *etc*.) or ecosystem services to provide a more comprehensive and integrated assessment of overall environmental impacts. Such integrated analyses provide strong support for global environmental governance and regional policy adaptation, promoting more coordinated sustainable development strategies. Although the research on multi-factor footprints is increasing, there is a lack of comprehensive review articles on multi-factor footprints, which is not conducive to subsequent scholars carrying out relevant research. Therefore, to fill the gap and provide convenience for scholars' research in the field of multi-factor footprints, this review article focuses on this research field - multi-factor footprint study. Multi-factor footprint research refers to relevant research that involves the combination of two or more single environmental factor footprints when assessing environmental impacts. By integrating multi-factor footprints, policymakers can avoid resource imbalances triggered by a single policy and better manage hidden resource consumption in global supply chains through the revelation of virtual flows.

In traditional physical flow studies, the main focus is on resource use and environmental impacts that occur directly at the place of production or consumption. However, with the expansion of global trade networks, the physical consumption of resources is often separated from the place of consumption of the final product, and this spatial dislocation of resource and environmental impacts makes it necessary for footprint studies to be revisited from the perspective of the global supply chain[27]. At this point, the concept of virtual flows becomes particularly important. Virtual flows refer to resource use and environmental impacts implicit in goods and services, such as virtual water[28], virtual carbon emissions[29], virtual land use[30], *etc*. With the continuous deepening and expansion of global trade and supply chains, the “virtual flow” of multi-factor footprints is more academically valuable and more in line with practical needs than a single-factor footprint.

In terms of research methodology, footprint analysis has expanded from a single-factor to multi-factor and dynamic models, such as Environmentally Extended Multi-regional Input-Output Analysis (EE-MRIO)[31], Hybrid Life Cycle Assessment-Input Output Analysis (Hybrid LCA-IOA)[32], *etc*. By integrating different types of footprint, the researchers can combine data to systematically quantify the overall impact of resource consumption[33], in addition to other research methods such as Structural Decomposition Analysis (SDA)[34] and machine learning[35]. Footprint studies also rely on advanced data acquisition and analysis techniques, including Remote Sensing[36], Geographic Information Systems (GIS)[37], *etc*. These tools not only improve the accuracy of multi-factor footprint measurements but also enable the tracing of pathways of virtual flows on a global scale, revealing the environmental cost hidden behind trade.

It is necessary to quantitatively analyze the basic features of existing literature, mine research hotspots, and identify the current research progress and future research direction with the help of bibliometrics, which not only helps to sort out the theoretical models and the knowledge system but also provides references to the future multi-factor footprint research. This paper, inspired by the research motivation, makes the following marginal contributions: (1) Uncovering the common combinations of research objects in the domain of multi-factor footprints; (2) Systematically summarizing the principal research methods applied in this field; (3) Conducting a detailed analysis of the publications of various countries and authors; and (4) Delving deep into the research hotspots and emerging frontiers in the field of multi-factor footprints, providing fresh perspectives and in-depth insights for future research endeavors. To figure out the above parts, this paper analyzes the literature related to multi-factor footprint research published during 1992-2023. The paper is organized as follows: After the introductory section, Section "METHODS AND DATA SOURCE" describes the methods and data source. Section "STATE OF THE ART" analyzes the state of the art of the multi-factor footprint study, including publication trends, research objects, and research methods. Section "RESULTS" presents the research results involving country and author influences, keyword co-occurrence, clustering, time zone evolution, and burst analysis. Finally, we draw research conclusions and prospects for future research in Section "DISCUSSION".

METHODS AND DATA SOURCE

Methods

Bibliometrics has been widely used to carry out review analysis in various fields due to its advantages in quantitative systematic analysis[38]. In this study, Microsoft Excel is used to draw annual publication volume histograms to analyze the situation of published papers and the overall research trend. VOSviewer has a strong advantage in co-occurrence analysis, with clear data presentation and significant visualization[39], so VOSviewer is used to complete the co-occurrence analysis in terms of countries, authors, and keywords. CiteSpace is good at clearly displaying the research hotspots and frontier trends in the field of multi-factor footprints with timeline diagrams and emergence diagrams, realizing the function of explaining the current situation and foreseeing the prospects of the field[40]. Based on the CiteSpace, keyword clustering, evolution, and emergence analyses are carried out with the Log-Likelihood Ratio (LLR) algorithm and a two-year time slice to complete the exploration of the hotspots of the research on the multi-factor footprints.

Data sources

The comprehensiveness and authority of the Web of Science Core Collection (WoSCC) can provide reliable support for academic analysis of multi-factor footprints. Compared with other databases, although Google Scholar has a wide range of covered literature, the quality of its literature varies greatly, and its retrieval accuracy is relatively low. While Scopus covers multiple fields, it is not as comprehensive as WoSCC in collecting some regional or specialized literature. So, we choose WoSCC as the database. The search starts from the publication year of the first paper on footprint formally[3]. The search terms cover the common types of footprints in Table 1, which have accounted for a considerable proportion of the literature on footprint study. It is common to select Article or Review Article as the sample types because this can combine the innovation of the original research with the comprehensiveness of the review article. The specific search settings and results are shown in Table 2.

Based on the initial 19,089 articles searched on September 1, 2024, the papers whose topics contain two or more factor footprints were manually selected, totaling 1,079 papers. Specifically, the manual selection criterion is that in the preliminary retrieval of articles, if the title, keywords, or abstract of the article involves the relevant content of two or more types of footprints, it shall be taken as the literature review samples in the field of multi-factor footprints. The overall process is illustrated in Figure 2.

STATE OF THE ART

Tendency of selected publications

To know the overall trend in the field of multi-factor footprint research, 1,079 multi-factor footprint papers were divided by the year of final publication in Figure 3.

Since 1998, academia began to focus on the study of multi-factor footprints, and since then, the number of papers related to this has been on a slowly fluctuating upward trend until 2016, when there was a research peak of 59 papers, which may be related to the promulgation of global environmental goals and constraints, such as SDGs and the Paris Agreement[41] in 2015, indicating the importance of multi-factor footprint study in helping to solve environmental problems.

The overall development of multi-factor footprints is favorable, and interest in this area of research continues to grow. Since 102 relevant studies were published in 2020, it reached 206 in 2022 and remained around 198 in 2023, which shows that academia has paid more and more attention to the combined research of multi-factor footprints. It may be related to many phenomena such as the prominence of global environmental problems, the enhancement of the public's environmental awareness, the advancement of quantitative technology, and the craze of cross-disciplinary research nowadays, which makes multi-factor footprint research an emerging hot field.

Analysis of common research subject combinations

To gain a deeper understanding of the research object in the field of multi-factor footprints, common multi-factor footprint combination information is shown in Table 3.

EF-eco, as a measurement indicator of human demand for natural resources, is not a single-factor footprint but an aggregation of a basket of environmental factor indicators[42]. Ecological+ footprint denotes the

Table 2. The search settings and results for data collection

Search settings	Search results
Database	Web of Science Core Collection (WoSCC)
Collections	Science Citation Index Expanded (SCI-EXPANDED) Social Sciences Citation Index (SSCI)
Search method	((((((((TS=("carbon footprint$")) OR TS=("ecological footprint$")) OR TS=("water footprint$")) OR TS=("energy footprint$")) OR TS=("land footprint$")) OR TS=("material footprint$")) OR TS=("nitrogen footprint$")) OR TS=("phosphorus footprint$")) OR TS=("methane footprint$")
Document types	Article or Review Article
Range	1992-2023
Records	19089

Table 3. Statistics of common multi-factor footprint combinations

#	Footprint combination	TP	PCT (%)
1	Ecological + footprint	491	45.51%
2	Carbon + water footprint	426	39.48%
3	Carbon + energy footprint	94	8.71%
4	Water + energy footprint	48	4.45%
5	Carbon + water + energy footprint	28	2.59%
6	Carbon + material footprint	22	2.04%
6	Carbon + nitrogen footprint	18	1.67%
7	Nitrogen + phosphorus footprint	8	0.74%

TP: Total publications belonging to one footprint combination during 1992-2023; PCT (%): percentage of the number of this footprint combination to the total number of samples in the multi-factor footprint field.

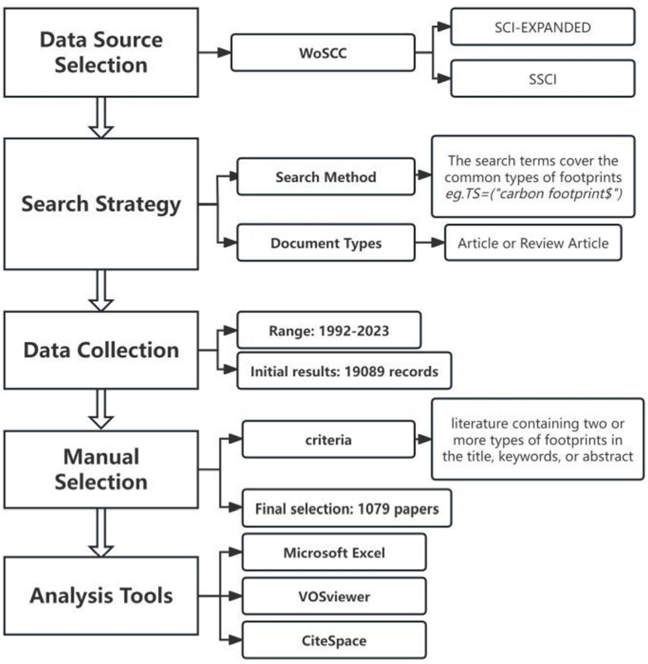

Figure 2. The flowchart of data selection and analysis.

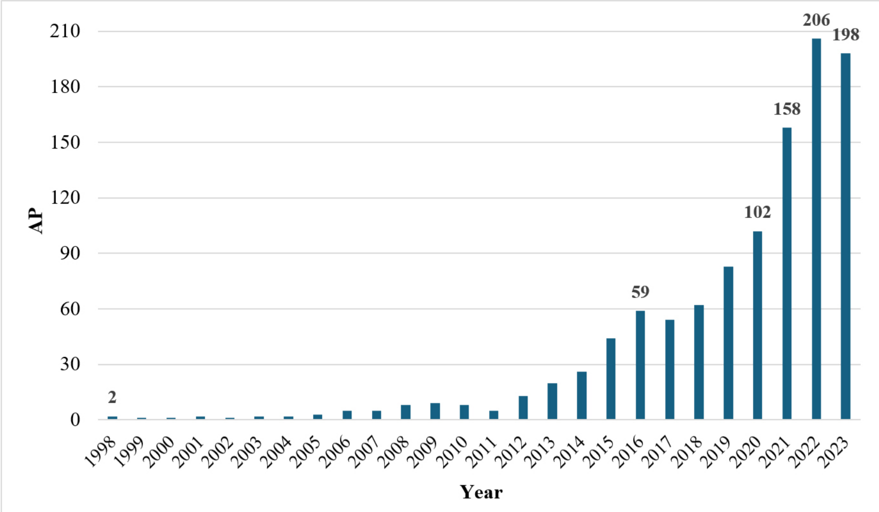

Figure 3. The number of annual publications on multi-factor footprint studies. AP: Number of annual publications.

portion of EF-eco literature containing two or more factor footprints by manual selection, and there are a total of 491 papers that satisfy the condition, which accounts for nearly half of the total of multi-factor footprints papers. Wang *et al.* conducted a three-dimensional spatial-temporal evolution analysis and deep-learning inversion of water-carbon-ecological footprints in the central plains urban agglomeration[43], and Jin *et al.* focused on environmental and urbanization issues to achieve sustainable development[44]. Scholars also explored the relationship between technological innovation[45], financial development[46], renewable energy[47], CF, and EF-eco in an attempt to mitigate environmental problems in all aspects.

Another common combination of multi-factor footprint studies is the research of combining CF and WF, which accounts for nearly 40%, with a total of 426 papers. Ridoutt and Pfister first attempted to combine WF with CF[48]. Later on, Wu *et al*. analyzed WF, LF, and CF of pig production and trade in the hope of mitigating the environmental impacts of pig production in China[49]. In addition, other scholars' studies on CF and WF assessment of crops[50], construction[51], dairy products[52], and cotton textile products[53] have proliferated; therefore, cross-field application of multi-factor footprints has received more attention from academia.

In the field of multi-factor footprints, the combination of single-factor footprint with CF is the most widely studied form. In addition to the most numerous combinations of CF and WF, other forms like CF and EF-energy, CF and MF, CF and NF are also widespread combinations, with 94, 22, and 18 papers, respectively. The combination of CF and EF-energy is mainly applied in the field of industrial energy[54], such as through the study of EF-energy and CF of different metals committed to the decarbonization of metal production to achieve the goal of energy transition[55]. The combined application of CF and MF is inseparably linked to various high-tech innovations, such as additive-subtractive integrated hybrid manufacturing, which is also related to EF-energy[56]. The CF and NF combination is mainly applied in the field of agricultural production, especially in the study of the effect of different fertilizer applications on CF and NF[57,58]. Multi-factor is not limited to only two factors. The study by Galli *et al.* in 2012 was one of the first investigations to explicitly propose combining different footprint indicators, including EF-eco, CF, and WF[59]. Additionally, the combination of CF, WF, and EF-energy is also an important research subject form of multi-factor footprints, such as in the field of rapeseed oil production[60], sugarcane bioenergy[61], and steel production[62], where energy, water, and carbon are highly intertwined, affecting the sustainability of the region[63].

There are 48 and 8 cross-study papers on WF and EF-energy, NF and PF, respectively, which are emerging research combinations in multi-factor footprint studies. The study of WF and EF-energy is crucial to address water scarcity and high energy consumption in the region[64], as upgrading industrial chains and phasing out outdated production capacity can promote water and energy conservation at the same time[65]. Research on NF and PF focused on food aspects[66], such as sustainable nitrogen and phosphorus management in food production through quantitative analysis[67].

Major research methods

With the increasing diversity and complexity of footprint analysis, different research methods have emerged, such as life cycle assessment (LCA), input-output analysis (IOA), and hybrid models. Multi-factor footprint research methods mainly involve the process from quantitative analysis to comprehensive assessment, often using a variety of quantitative models and tools for analysis. Each method has its advantages and applicable research field, while in multi-factor footprint assessment, it is necessary to comprehensively consider its holistic nature and effectiveness.

Life cycle assessment

LCA is a comprehensive footprint method commonly used to assess the environmental impacts of a product or service throughout its life cycle[68], dating back to the Midwest Research Institute (MRI) study to quantify the resource requirements, emission loads, and waste streams of different beverage containers for the Coca-Cola Company, which was published by the U.S. Environmental Protection Agency (USEPA) in 1974[69]. Cradle-to-grave LCA enables the quantification of resource consumption and pollution emissions at various stages of a product's life cycle, along with a detailed accounting of CF, WF, and EF-energy[70]. A search of WoSCC articles or review articles whose topics contained footprint from 1992 to 2023 found that there were 5,771 papers involving the LCA method. In CF research, LCA reveals the main sources of emissions by tracking carbon emissions in the production process[71]. In WF analysis, LCA can effectively portray the consumption of water resources in cultivation, processing, and transportation in detail[72], especially in the agriculture and food industries. In the manufacturing and transportation industries, LCA is also used to quantify footprints that include multiple factors such as carbon, energy, and water, providing methodological support for evaluating environmental and economic performance[73]. However, LCA is highly dependent on the existence of data integrity, especially in complex supply chains, where ensuring data access and quality is challenging. As a result, the accuracy of its analytical results can be compromised[74].

Input-output analysis

IOA is another macroeconomic model commonly used for footprint calculation[75]. Introduced by economist Leontief[76] in the 1930s, this method is based on input-output tables at the national or regional level and can effectively reveal the complexity of resource flows between various industry sectors, allowing for macro quantification of CF, EF-energy, and virtual WF[77]. A search of the literature on topics containing footprint during 1992-2023 found that 1,826 articles involved IOA. In carbon footprint assessment, IOA can track the direct and indirect carbon emissions in the industrial chain, providing an effective analytical tool for the transfer of CF across departments and regions[78]. In virtual WF analysis, IOA constructs a water resource consumption coefficient matrix to reveal the water demand of each industry and its distribution in the industrial chain[79]. The advantage of IOA is that it can analyze multiple footprints simultaneously at the macro level, such as showing good applicability in EF-energy, WF, and CF[80]. However, IOA makes it difficult to capture resource consumption and environmental impacts at the micro level in the production chain when dealing with specific product footprint[81], so it is not as advantageous as LCA at the micro level.

Hybrid research models and methods

In order to overcome the limitations of a single method, researchers have proposed a variety of hybrid models, such as Hybrid LCA-IOA[82], Multi-regional Input-Output Analysis (MRIO)[83], Environmentally Extended Multi-regional Input-Output Analysis (EE-MRIO)[84], *etc*., and correspondingly formed relevant databases for the integrated assessment of multi-factor footprints[85]. The Hybrid LCA-IOA first appeared in 1998 to assess environmental impacts in complex economic systems[86], which can deal with CF, WF, EF-energy, *etc*. simultaneously in the same framework by combining environmental LCA at the product level with IOA at the economic system level[87]. This way compensates for the shortcomings of LCA in macro systems and overcomes the limitations of IOA in microanalysis, becoming a mainstream tool in current multi-factor footprint studies[88]. Economist Isard extended IOA to a multi-regional framework[89], and the proposed MRIO model demonstrated strong analytical capabilities in multi-departmental footprint flow study, capable of identifying footprint transfer paths between different regions[90,91]. In 1970, Leontief integrated environmental factors, such as pollutant emissions and resource use, into input-output models[92], and EE-MRIO provided an important quantitative tool for modern environmental economics. Although these models enable the joint assessment of multi-factor footprints, their high data requirements and model complexity remain a major challenge for future research.

Other research methods, such as Structural Decomposition Analysis (SDA) and machine learning, are gradually being applied to the comprehensive analysis of multi-factor footprints. Footprint indicators will fluctuate with economic activities and structural changes. SDA can decompose these fluctuations into the contributions of multiple influencing factors. In footprint analysis, machine learning improves the accuracy, efficiency, and decision-support ability of analysis using data processing, factor identification, trend prediction, supply chain tracking, and policy evaluation. SDA reveals the driving mechanisms of changes in CF, EF-energy, and WF by decomposing the time series in footprint into multiple influencing factors, such as technological advances, consumption patterns, and changes in industrial structure[93]. Footprint prediction models based on machine learning [e.g., Random Forest, Support Vector Machine (SVM), *etc*.] can identify nonlinear relationships between footprints and their influencing factors, providing effective predictions of future footprint changes[94], and the use of deep learning can fill in the data gaps in the environmental footprint calculation[95]. A comprehensive footprint estimation model based on SVM and Neural Networks, which can simultaneously estimate the WF, CF, and EF-energy of a company or region, is trained using historical datasets and can adapt to footprint prediction needs under different environmental conditions[96]. Future research should further enhance the integration of data and models to form a more complete database to realize the dynamic assessment of multi-factor footprints on a larger scale.

RESULTS

Country and author influences

Countries

To explore the publication and collaborative relationships among different countries on multi-factor footprints, this study imported 1,079 articles from WoSCC into VOSviewer for visualization and analysis, and all the authors were counted. We found that 88 countries contributed to the publication of multi-factor footprint studies from 1982 to 2023. Of these, 50 countries published five or more articles, as shown in Figure 4. Table 4 shows detailed information on the top 10 countries in terms of the number of publications.

In terms of the number of publications, the round nodes of China and USA are the largest. China leads with 392 publications, accounting for 36.33% of the total, while the USA follows with the second-largest number, contributing 13.72%. This indicates that both countries have made significant contributions to the body of multi-factor footprint research. Moreover, it can be found that the average citations per publication of

Table 4. The information on the top 10 most productive countries

#	Country	TP	TC	ACP	TLS
1	China	392	15,493	39.52	218
2	USA	148	7,799	52.70	166
3	Spain	90	3,234	35.93	80
4	Italy	79	3,057	38.70	60
5	UK	61	3,823	62.67	87
6	Netherlands	57	4,091	71.77	76
7	Turkey	56	5,522	98.61	35
8	Pakistan	53	4,081	77.00	87
9	Australia	43	3,490	81.16	62
10	Brazil	42	1,010	24.05	30

TP: Total publications of one country during 1992-2023; TC: total citations received by one country; ACP: average number of citations per publication; TLS: total link strength of the co-authorship links with other countries.

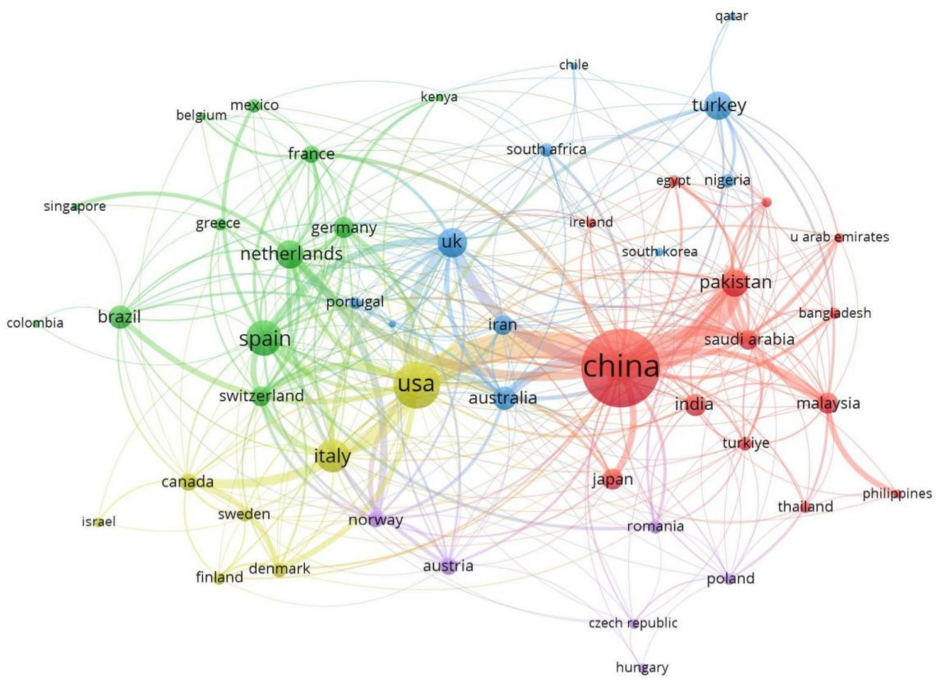

Figure 4. The collaboration networks of the most productive countries.

Turkey, Australia, and Pakistan are more than 77 times, of which Turkey reaches 98.61 times, indicating that the research results published by those countries in multi-factor footprint research have a greater influence, while China is only 39.52 times. On the one hand, because of the largest number of China's publications, the average number of citations is less. On the other hand, it shows that China's research needs to improve its influence and recognition in the multi-factor footprints field. In terms of total link strength, China has the closest communication with other countries, with an intensity of 218, and has cooperative relationships with over 10 countries, including the USA, Pakistan, the UK, Japan, *etc*. Among them, the node connectivity between China and USA, as well as between China and Pakistan, is stronger, indicating a higher level of cooperation and academic communication, which contributes to excellent research results.

Authors

To identify the main research authors and their research directions in the field of multi-factor footprints, this study utilized VOSviewer to statistically analyze author information and cross-checked it with data from the Web of Science. In total, 3,740 authors were included in the analysis. The information on the top 10 authors based on the number of publications is shown in Table 5.

In terms of publications, Italian author Galli ranks first with 15 publications and 73.13 citations per publication. He defined footprint series indicators based on EF-eco, CF, and WF, developed EE-MRIO, and integrated footprint indicators with economic trade statistics[97]. By applying MRIO with EF-eco expansion, he examined the resource dependence and carbon emissions of food systems in the European Union (EU) 27 countries from 2004 to 2014 to offer support to sustainable EU food system transition[98]. In terms of the average citations per publication, Usman, Wackernagel, and Hoekstra each have more than 120 citations per article, with respective averages of 163.33, 141.79, and 121.42 times. Usman focused on studying the relationship between multi-factor footprints and other economic and social indicators, investigating dynamic links between EF-eco, agriculture, forest area, non-renewable and renewable energy, and financial development in Brazil, Russia, India, China, and South Africa (BRICS) from 1990 to 2018[99]. Since 1998, Wackernagel has focused on EF-eco[100] and subsequently expanded his research to integrate it with CF analysis, conducting extensive and in-depth studies. Hoekstra highlighted the importance of assessing LF, WF, EF-energy, *etc*., and emphasized the need for future work to incorporate the footprints, improve calculation techniques, estimate the maximum sustainable footprint level, *etc*.[26], which received 679 citations, indicating that deepening the combination of multi-factor footprint research is widely recognized by academia. In collaboration with other scholars, Hoekstra combined the multi-factor footprint study with practical, integrated accounting and analysis of CF, WF, and LF under different agricultural systems in Tunisia[101].

Keywords co-occurrence analysis

The keywords of the literature can be analyzed to accurately master the research hotspots in the field of multi-factor footprints and understand the latest research progress. There were 4,150 keywords in 1,079 literature selected in this study. To make the mapping drawn by VOSviewer clearer and more accurate, this study first merged similar keywords (such as "life cycle assessment", "life-cycle assessment" and "lca", "trade" and "international trade"), then deleted irrelevant keywords (such as "china", "impact", and "model"), and set the occurrences threshold of a keyword to 30 times. Finally, 41 keywords met the condition. The keywords co-occurrence network and density visualization mapping are shown in Figure 5.

Statistical results show that from the frequency of keyword appearances, there are three major constituent footprints in multi-factor footprint research: CF (353 times), EF-eco (347 times), and WF (312 times). All three appear more than 310 times, with the large node and bright area, which are high-frequency topics of research in this field. Consumption (230 times), sustainability (189 times), and LCA (222 times) relate to the calculation, methodology, and significance of multi-factor footprint research, revealing the focus of the research. In terms of keyword connectivity intensity, energy (479), economic growth (622), and environmental Kuznitz curve (441) are densely connected, of which the three major footprints of carbon (1,194), ecology (1,266), and water (1,152) not only occupy the center of the co-occurrence network diagram but also have high connectivity intensity of more than 1,100. With the three footprints as the center, energy, economy, environment, food, and other components are closely connected, such as by quantifying CF, WF, and EF-eco covering 1,935 food items of 17,110 family members of Chinese households, summarizing the patterns of food consumption and waste generation and the factors influencing them[102].

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Table 5. The information on the top 10 most productive authors

#	Author	TP	TC	ACP
1	Galli, Alessandro	15	1,097	73.13
2	Wackernagel, Mathis	14	1,985	141.79
3	Feijoo, Gumersindo	13	423	32.54
4	Moreira, Maria Teresa	13	324	24.92
5	Hoekstra, Arjen	12	1,457	121.42
6	Wood, Richard	11	859	78.09
7	Gonzalez-Garcia, Sara	10	250	25.00
8	Usman, Muhammad	9	1,470	163.33
9	Lin, David	9	730	81.11
10	Kucukvar, Murat	9	568	63.11

TP: Total publications of one author during 1992-2023; TC: total citations received by one author; ACP: average number of citations per publication.

Keyword clustering and time zone evolution analysis

To master the direction of multi-factor footprint research, CiteSpace was used to analyze the clustering of keywords in the literature to obtain Figure 6. Specifically, the link strength is cosine, and the scale factor k = 25 regarding g-index. In the figure, the Modularity Q = 0.5091 (> 0.3) and the Weighted Mean Silhouette S = 0.7784 (> 0.7). When Q > 0.3 indicates that the clustering is valid and S > 0.7 indicates that the clustering is plausible[103], the result of this clustering is valid and plausible.

In the field of multi-factor footprint research, nine keyword clustering labels were formed, and most of the nine different colored clustering blocks overlapped, and the overlapping area indicates a close connection between the clusters. Among them, clusters #0, #2, and #4 are related to the main research objects in multi-factor footprints, #1 and #3 involve environment issues such as eco-industrial security, #5 and #6 are connected to the theoretical models, and research methods of multi-factor footprints, and #7 and #8 are about sustainable development. The specific information on each cluster is shown in Table 6.

To further clarify the development trend of multi-factor footprints, the time zone evolution of keywords was mapped based on keyword clustering to better analyze the development time as well as the coherence of the research content, as shown in Figure 7.

These clusters represent different research directions, hotspots, and development trends within the multi-factor footprint research field. Cluster #0 focuses on assessing the integrated impact of human activities on the environment, especially in terms of CF, WF, and renewable energy use on economic growth, for example, exploring the rule of the evolution of the three-dimensional footprint of water, carbon and ecology and the economic growth of cities in the middle reaches of the Yangtze River[43]. This cluster content has been used throughout the multi-factor footprint research, from the emergence of EF-eco in 1998 to the combination of CF and EF-energy, and from theory to real application, future research may address social issues such as urbanization[104] and financial development[105] based on continuing to explore multi-factor footprint relationships in depth.

Cluster #1 focuses on how to ensure ecological security by managing natural capital and maintaining ecosystem-carrying capacity. The first to propose the concept of ecological security was Holling[106], and research hotspots include the assessment of ecological deficits and the use of three-dimensional EF-eco in recent years[107] to quantify and predict the health of ecosystems and their potential socio-economic impacts.

Table 6. The information on keywords topical clusters

Cluster-ID	Size	Silhouette	Mean year	Top terms
0	89	0.854	2018	**Ecological footprint**; renewable energy; water footprint; carbon footprint; economic growth
1	84	0.748	2010	**Ecological security**; natural capital; carrying capacity; three-dimensional ecological footprint; ecological deficit
2	65	0.716	2016	**Ecological footprint**; energy footprint; nitrogen footprint; crop production; maize
3	58	0.718	2016	**Industrial ecology**; supply chain; life cycle assessment; multi-regional input-output analysis; input-output analysis
4	53	0.766	2014	**Carbon footprint**; water scarcity; reverse osmosis; production; production systems
5	43	0.827	2015	**Life cycle assessment**; water footprint; ecological footprint; renewable energy; carbon footprint
6	41	0.753	2010	**Input-output analysis**; land footprint; international trade; process integration; decomposition analysis
7	33	0.813	2019	**Sustainable diet**; food consumption; sustainable diets; nutrient management; environmental footprints
8	31	0.84	2012	**Sustainable development**; land use; waste management; bitcoin energy consumption; bitcoin carbon footprint

Size indicates the number of keywords contained in each cluster; Silhouette measures the quality of the clusters; Mean year indicates the average year of occurrence of the keywords in the cluster; Top Terms lists the most representative keywords in each cluster, where the bolded part is the label of each cluster.

Since 2010, methods of energy-value analysis have emerged, and research has gradually shifted to more complex and comprehensive footprint models, such as the evaluation of ecological security in the arid zones of Central Asia based on the Emergy Ecological Footprint (EEF) model[108] and quantitative analysis of the dynamic changes in ecological security of China's provinces based on EEF hybrid indicators[109]. In the future, it may be possible to explore how to ensure long-term ecological security through natural resource management on a regional, national, or even global scale.

Cluster #2 focuses on quantifying the environmental impacts of EF-energy and NF, especially in agricultural production, such as a comprehensive assessment of the environmental impacts and economic benefits of rice production systems using CF, NF, and WF[110]. Future studies may pay more attention to the role of clean energy in a low-carbon economy[111] and the application of advanced agricultural technologies on agricultural sustainability[112], such as the transition from rain-fed maize to irrigated maize cultivation with a 53.7% increase in yields and production value, and along with increasing degrees of EF-energy, CF, and WF, the implementation of optimization strategies to balance maize cultivation yield and environmental impacts[113].

Cluster #3 is related to the supply chain and dates back to the research of Frosch, which advocated the recycling of resources and the minimization of waste[114]. LCA and IOA methods are important methods in the research, covering various aspects, including construction[115] and climate change[116], such as the assessment of CF and WF of the pork supply chain in Catalonia from the feed to the final product[117]. Additionally, the related research regarding manufacturing is also inextricably linked to this cluster concerning CF and others[118]. Future research may continue to achieve better supply chain management by analyzing CF, EF-energy, MF, and WF of industrial production.

CF is one of the most central indicators in multi-factor footprint research, and Cluster #4 focuses on how to reduce carbon emissions. Water scarcity and Greenhouse gas (GHG) emissions are two key environmental issues affecting crop production, and reducing CF and WF can help mitigate their environmental harm[50]. Since 2014, it has been shown that optimal management of production systems plays an important role in

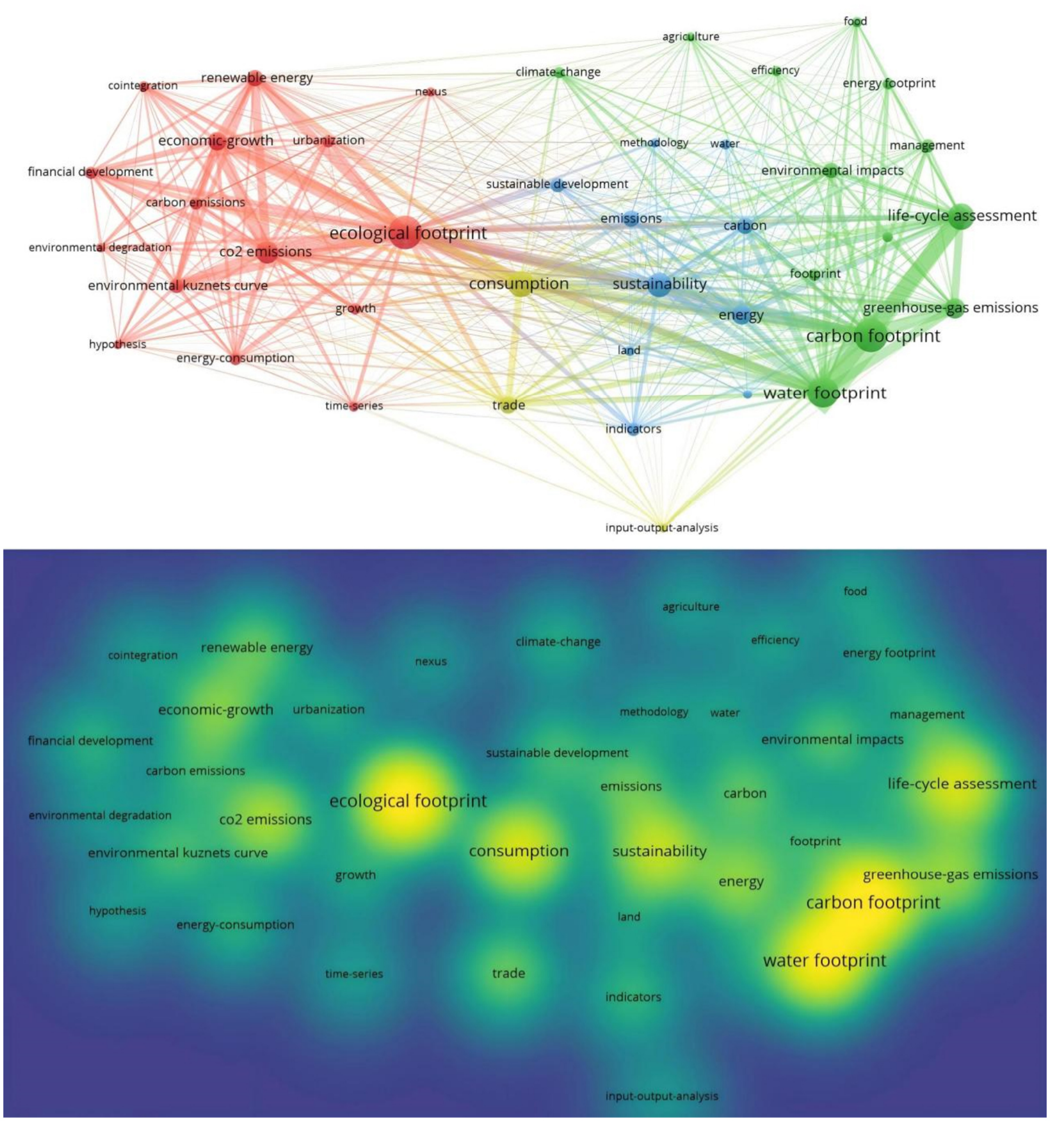

Figure 5. The keywords co-occurrence network map (up) and density map (below).

CF reduction; for example, appropriate annual rotation system adjustments may help reduce GHG emissions and nitrogen losses[119]. Future research will continue to explore how to reduce CF and maximize productivity through technological innovation and production process optimization.

Cluster #5 LCA is one of the important research methods in multi-factor footprint research, which provides a comprehensive perspective for understanding the environmental impacts of products and services throughout their life cycle. Research objects include CF, WF, EF-eco, and renewable energy, emphasizing system concepts, such as the development of a water-land-carbon footprint model for hog production systems from the LCA perspective[49]. Future developments may focus on how to better apply the LCA method to the specific study of multi-factor footprints.

Cluster #6 IOA is another important research method in multi-factor footprint study, which is used to quantify the impacts of various types of economic activities (e.g., trade) on resource consumption and

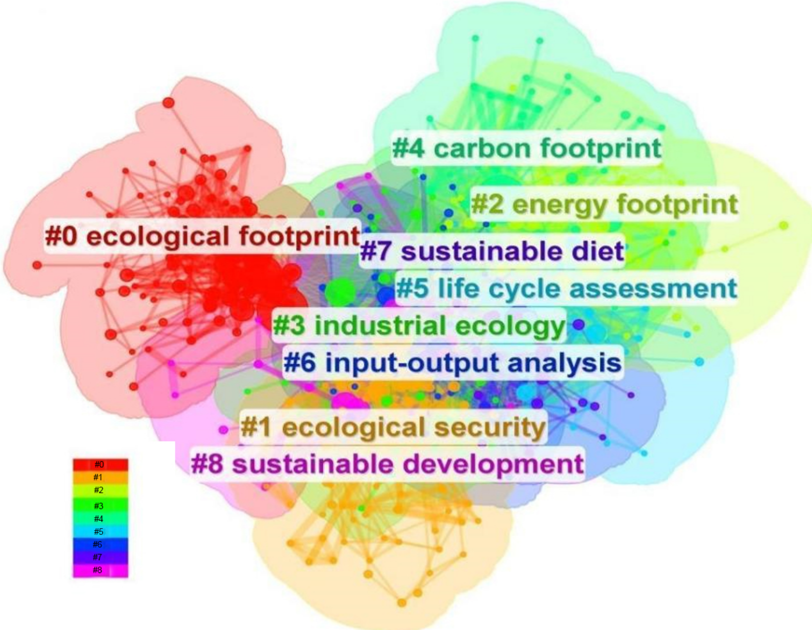

Figure 6. The topical clusters of keywords.

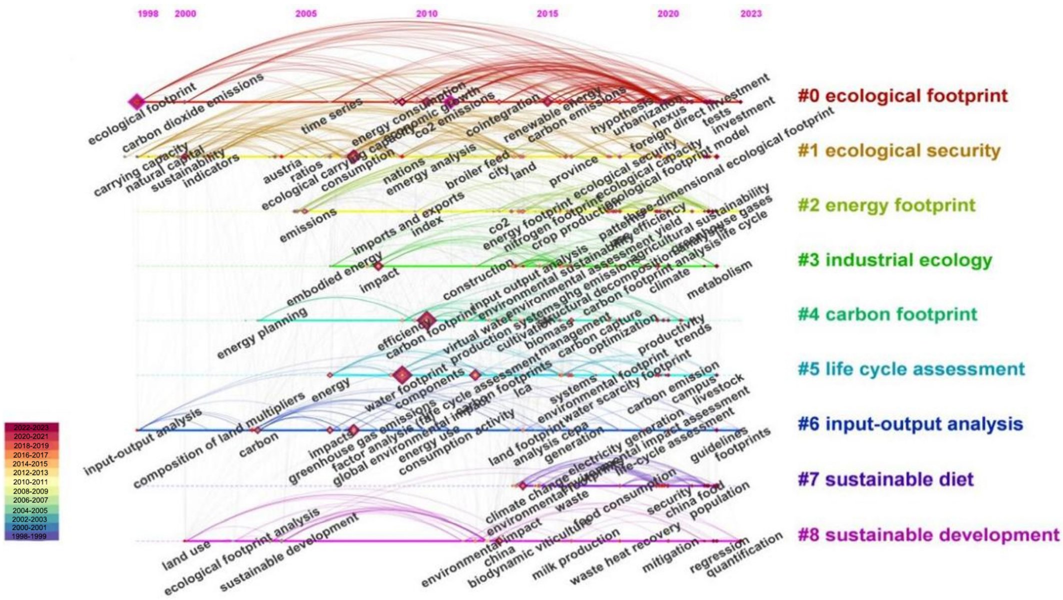

Figure 7. The time zone evolution of keywords.

environmental footprints. Liu *et al.* used an environmentally extended input-output table to assess consumption-based footprints covering water, GHG, and pollutants in the case of Japan[120]. Since its emergence in 1998, the IOA method has been continuously refined from provinces to countries, from single-factor footprint to multi-factor footprints, and from single-region IOA to EE-MRIO, and has been revitalized in combination with data such as households[121].

The concept of sustainable diets was first introduced by the Food and Agriculture Organization of the United Nations (FAO) in 2010[122], and Cluster #7 focuses on the multi-factor footprints of food production and consumption, such as past and future WF, LF and CF assessments of the dairy industry in China[52], food-related NF and PF assessments in Indonesia[67], and integrated WF, EF-energy and CF analyses of China's apple production from an environmental-economic perspective[123]. Future studies may further explore the changes in the multi-factor footprints of food consumption under the background of a warming climate for sustainable diets adapted to the increasing population.

Because sustainability is a goal of global environmental governance nowadays, Cluster #8 not only covers the quantitative analysis of multi-factor footprints such as CF, EF-eco, and LF but also focuses on their application in specific scenarios to achieve sustainability. For example, it includes CF and WF assessment of energy-saving options for electric cabin air conditioning in industrial sites[124], sustainable viticulture by determining the multi-factor footprints of grapes[125], and the impact of climate uncertainty on the CF and EF-energy of Bitcoin through cryptocurrency-related environmental attention[126], among others. Future research may focus on exploring how environmental problems can be mitigated under different circumstances through green technology innovations[127] and policy interventions[128] based on quantitative accounting of multi-factor footprints to advance the global goal of sustainable development.

To summarize, EF-eco became popular content in multi-factor footprint research once it was formally proposed in 1998. A few years later, it triggered further consideration of ecological security, and the IOA method came into being and ran through the whole research process. The proposal of the eight Millennium Development Goals (MDGs) in 2000 raised attention to the research of sustainability, and it has been further emphasized, especially after 2015[129]. After 2000, various factor footprints such as CF and EF-energy successively became popular research objects. Around 2005, LCA became another important research method, and at the same time, the content of industrial ecology was further deepened. Furthermore, dietary sustainability became a popular research topic.

Keywords burst analysis

Keyword clustering analysis presents research directions and topic changes in multi-factor footprints, while keyword burst analysis focuses on identifying keyword change trends in the time dimension. To further identify the research hotspots in the field and mine the research frontiers, this study utilized the Burst Detection algorithm of CiteSpace to explore the intensity and duration of keywords. Specifically, the number of states is 2, Y[0,1] is 1, and the minimum duration is 2. Furthermore, meaningless keywords, such as "indicators" and "nations", were eliminated. Figure 8 shows the top 15 keywords with the strongest citation bursts in the multi-factor footprint field.

In terms of burst intensity, EF-eco (15.13), WF (9.79), and CF (7.68) all have high citation burst strength, indicating that these three footprints are the core objects in multi-factor footprint research. In addition, international trade (9.16), energy (6.03), land use (6.11), and sustainability (5.51) with relatively high burst intensity inspire us to pay attention to trade and economy, energy consumption, land use, and sustainability in future multi-factor footprint research. Furthermore, the citation burst strength of IOA and LCA are 7.07 and 4.46, respectively, indicating that these two methods are the mainstream approaches in the study of multi-factor footprints. Financial development has burst until 2023, which shows that in the wave of globalization, the relationship between economic development and environmental sustainability is at the forefront of multi-factor footprint research[130,131].

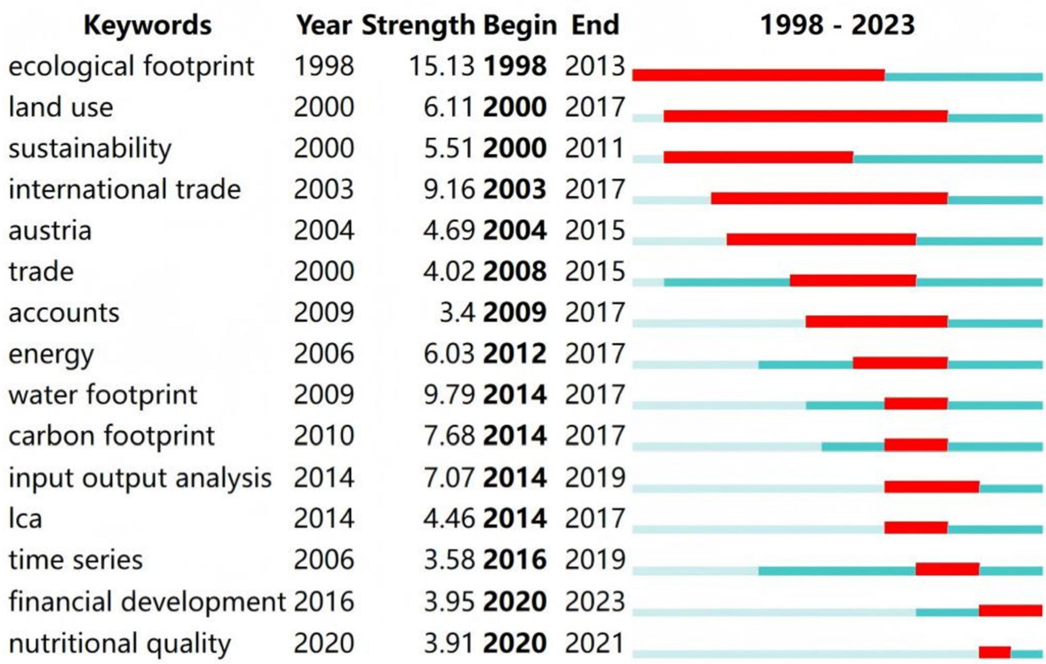

Figure 8. The top 15 keywords with the strongest citation bursts.

DISCUSSION

With the intensification of global environmental problems, research related to multi-factor footprints has received increasing attention from the global academic community, so it is necessary to provide an overview of current research progress. To summarize the existing research results and better analyze the direction of future research, this study adopts a bibliometric approach to review 1,079 multi-factor footprints literature published from 1982 to 2023 using VOSviewer and CiteSpace and obtains the following five conclusions:

1. Multi-factor footprint research is growing rapidly and has great potential for future development. Since the end of the 20th century, multi-factor footprint research emerged and has entered a phase of rapid growth in recent years, especially after 2020. This trend shows that multi-factor footprint research has been widely emphasized, and the integration with the global sustainable development goals has driven a research boom in this field.

2. Multi-factor crossed studies have deepened the understanding and resolution of environmental problems. Traditional single-factor footprint studies have gradually given way to more complex multi-factor footprint studies. Among them, the combination of individual single-factor footprint and CF is the most widely studied combination. For example, the combination of CF and WF is widely used in agricultural production and urban development, especially for assessing the environmental impacts of global supply chains and trade, as well as CF and EF-energy, CF and LF, CF and MF, and CF and NF. By combining the analysis of multiple footprints, researchers can assess the environmental impacts of specific products or services in a more comprehensive way, providing a more informative basis for policymakers. For example, in agricultural production, by simultaneously assessing CF, WF, and EF-energy, scholars can propose measures to optimize production processes and reduce environmental loads, thereby ensuring economic efficiency while achieving environmental sustainability. In the future, innovative attempts can be made to analyze the combination of multiple factor footprints, such as NF and PF, to expand the research boundary and deepen the understanding of the problem.

3. Diverse research methods drive breakthroughs in the field of multi-factor footprints. The main research methods include LCA, IOA, and hybrid models. Each of these methods has its advantages. LCA can comprehensively assess the environmental impacts of a product's life cycle from cradle to grave and is suitable for analyzing resource consumption at the micro level. IOA reveals the complexity of inter-industry resource flows through input-output tables, which is especially suitable for analyzing CF and virtual WF at the macro level. Hybrid models, such as Hybrid LCA-IOA, MRIO, and EE-MRIO, combine the advantages of LCA and IOA and can analyze macro and micro footprint flows simultaneously, which is especially outstanding in cross-regional and global footprint transfer studies. In addition, methods such as SDA and machine learning are expanding the breadth and depth of footprint research and can reveal the drivers of footprint change, as well as forecast and account for them. The combination of these methods provides a powerful tool for multi-factor footprint research, promotes the accurate assessment of resource consumption and environmental impacts, and provides data support for the formulation of global environmental policies. The improvement of the coupling of models and data in the application process is the future direction of development. Future multi-factor footprint research should focus on integrating and optimizing research methods, leveraging new technologies to improve hybrid models, and strengthening multi-source data integration to better assist enterprises and policy-making.

4. International cooperation accelerates progress in global multi-factor footprint research. In terms of the number of publications and international cooperation relations, China and the USA not only lead in the number of publications but also maintain close academic cooperation between the two countries. However, the recognition and influence of their literature need to be further improved. The research results of Turkey, Pakistan, and Australia in this field have considerable influence on the academic community. More cooperation between countries and authors can bring a broader perspective and recognition to multi-factor footprint research and help promote the globalization process of multi-factor footprint study, especially in cross-border issues such as global supply chains, climate change, and sustainable development.

5. Research hotspots have been extended to interdisciplinary and multiple fields. The hotspots of multi-factor footprint research have gradually expanded to a wider range of fields, such as industrial energy, food production, material manufacturing, international trade, *etc*., reflecting the interdisciplinary nature of the research. Nine major clusters demonstrate the close connection between different fields, from EF-eco and renewable energy to industrial ecology and sustainable development, and the research involves multiple dimensions, such as environment, economy, and energy. The earliest research mainly focused on EF-eco, after which the attention of CF and WF increased significantly and gradually became the core hotspots in this field. In addition, emerging areas such as EF-energy and MF have also received attention gradually in recent years, showing the diversification of research objects. As the global warming problem intensifies, future research should increasingly focus on greenhouse gases. Multi-factor footprint research is gradually developing from a single dimension to a multi-dimensional and dynamic direction, and the research is expanding from a theoretical model to practical application, especially presenting deeper research in agriculture, industry, and other fields. Additionally, multi-factor footprint research is gradually shifting from pure footprint accounting to the combination of economic development and environmental impacts, and future research frontiers may be about how to achieve environmentally sustainable development alongside economic growth, which requires scholars to put forward more comprehensive policy recommendations and practical solutions through innovative combined research, such as big data analysis and interdisciplinary cooperation. Scholars can collaborate with relevant industries and policymakers to apply research findings in real-world scenarios. For instance, in urban planning, multi-factor footprint analysis can be utilized to guide the design of sustainable cities, optimize energy and water supply systems, and reduce carbon emissions. In the industrial sector, industry footprint reduction guidelines can be used to

promote the transformation of industries toward environmental sustainability.

In general, this study provides a holistic view of multi-factor footprint research, including research trends, common combinations of research objects, applications of research methods, active research groups, and cutting-edge research hotspots. The results of this study can help scholars understand the theoretical framework and research progress of multi-factor footprints, which can guide the identification of future research directions. However, there are still some limitations in this study. In the process of searching and manual selection, it is not possible to precisely ensure that all relevant literature on multi-factor footprints was included, and some excellent non-English literature was not included in the analysis. Furthermore, there were some shortcomings in the application of the methods. Future research can build on this study to conduct a more comprehensive and improved analysis.

DECLARATIONS

Authors' contributions

Made substantial contributions to the conception and design of the writing and revision: Miao, Z.
Performed data analysis and writing: Huo, D.
Performed proof-reading and formal analysis: Li, Y.

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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