Front. Earth Sci. 2022, 16(2): 340–351
https://doi.org/10.1007/s11707-021-0875-z

RESEARCH ARTICLE

A novel bibliometric and visual analysis of global geoscience research using landscape indices

Xin AI[1,2], Mingguo MA[1,2], Xuemei WANG (✉)[2], Honghai KUANG (✉)[3]

1 Chongqing Jinfo Mountain Karst Ecosystem National Observation and Research Station, School of Geographical Sciences, Southwest University, Chongqing 400715, China
2 Southwest University Library, Southwest University, Chongqing 400715, China
3 Chongqing Engineering Research Center for Remote Sensing Big Data Application, Southwest University, Chongqing 400715, China

Abstract The landscape index is a quantitative index which reflects characteristics of structure composition and spatial pattern in landscape studies, it is, therefore, expected to describe the spatial pattern of scientific research in bibliometric analysis. In this study, a novel attempt to regard scientific research as a kind of ‘landscape’ was made, and landscape indices were improved for bibliometric analysis to measure the spatial pattern of scientific research. For illustrating the feasibility of our method, global geoscience research from 1994 to 2018 was presented as a case. Moreover, spatiotemporal migration of landscape centroids was visualized. The results indicated that global geoscience publications increased steadily and articles were highly concentrated at the country level. The top 10 countries published 69.93% of total articles and 84.68% of geoscience articles were from top 20 productive countries. The spatial migration of centroids was mainly reflected in the longitude because of significant increasing of articles in eastern countries, especially in China with the growth rate of 747.14%. At the patch scale, the change trend of improved landscape indices verified the spatiotemporal changes of global distribution of geoscience articles. At the landscape scale, the strengthening of global international collaboration is the main driving forces of spatial heterogeneity of global geoscience research. This study is expected to help readers to understand global trends of geoscience research in the past 25 years, and to promote the development of bibliometric analysis towards the directions of spatialization and visualization.

Keywords geoscience, landscape index, visualization, Geographical Information System, bibliometric analysis

Received August 28, 2020; accepted January 26, 2021

E-mails: w20141103@swu.edu.cn (Xuemei Wang),
hhkuang@swu.edu.cn (Honghai Kuang)

1 Introduction

Geoscience, as a basic natural science, mainly studies the processes and changes of the earth system (including the atmosphere, hydrosphere, lithosphere, biosphere, and solar-terrestrial space) and their interactions, revealing the material composition, structure, formation and evolution rules of the whole earth system. Geoscience research plays an important role in the correct understanding of nature, and promotes the development of the whole natural science. At present, we are facing environmental problems, such as resource bottleneck, climate change, environmental degradation challenges and continuous development (Zhang et al., 2003; Hersperger and Bürgi, 2009). Therefore, it is particularly important to quantitatively understand the development trend of global geoscience research.

In landscape studies, the landscape index is a spatial analysis method widely used to quantitatively describe landscape pattern, which is conducive to better explain landscape function and spatial variation (Chen et al., 2002). With the enrichment of landscape theories and the development of spatial statistical methods, there are considerable researches on landscape pattern using landscape indices (Manicacci et al., 1992; Vorovencii, 2015; Shen et al., 2019). Moreover, some scholars have tried to improve and even construct new landscape indices for more extensive researches. O’neill et al. (1999) suggested some additional metrics based on island biogeography, percolation theory, hierarchy theory, and economic geography. Schumaker (1996) identified a new pattern index, termed patch cohesion, to quantify habitat fragmentation. He et al. (2000) developed an aggregation index (AI), which could be compared not only between classes from the same or different landscapes, but also the same classes from the same landscape of different resolutions. Carvalho and Batty (2006) also agreed that the introduction of a fine scale geography could conducive to more comprehensive indicators of scientific output.

Bibliometric analysis is an effective tool for the quantitative analysis of scientific research trends by various bibliometric indicators (Wang et al., 2014). For example, the total number of articles (*TA*), total number of citations (*TC*), impact factor (IF), h-index were applied to quantitatively measure and analyze input, output and performance of scientific achievements of authors, institutions and countries from multiple scales (Hirsch, 2010; Liu et al., 2011a; Zhang et al., 2019). With the development of quantitative analysis in bibliometrics, some traditional bibliometric indicators have been unable to meet the research needs, so some new bibliometric indicators have been proposed. Like the g-index, which was introduced as an improvement of the h-index to measure the global citation performance of articles (Egghe, 2006). The notion of international scholarly impact of scientific research (ISISR) was established to measure countries of different levels of research activity in different fields (Hassan and Hassawy, 2013). Bibliometric indicators have no spatial attributes. For representing the spatial distribution and spatial variety of scientific research, some geographical methods were widely introduced. For example, geographical impact factor (GIF) was created to analyze the geographical influence of researchers (Zhuang et al., 2013) and the mean geographical distance (MGD) index was developed to analyze the characteristics of the distance between papers, citations and collaborators (Ahlgren et al., 2013). The citation rank based on spatial diversity (SDCR) in terms of cities and countries, focused on the measurement of the "spatial" aspect in citation networks and solved the citation bias caused by different geographical locations of citations (Wu, 2013). At present, there is still a gap in the study of spatial pattern and spatiotemporal dynamic change trend of global scientific research.

The integration of bibliometric analysis and landscape ecology is deepening. However, most existing studies are focused on the analysis of landscape publications by traditional bibliometric statistical methods (Chen et al., 2017; Zhang et al., 2018). There are relatively few comprehensive researches on quantifying the spatial pattern of scientific research on the global scale by landscape indices. Thus, above studies provided a novel method on whether scientific research could be regarded as a kind of 'landscape' and landscape indices that could quantitatively analysis spatial attributes can be served to quantitatively describe the spatial pattern of global geoscience research.

Geographical Information System (GIS) is a geographical technology developed rapidly in 1960s, and it was recognized as a comprehensive subject. The commonly used spatial analysis functions of GIS are buffer analysis, overlay analysis, path analysis, spatial interpolation and statistical classification analysis, etc. In recent years, the rapid development of GIS technology, especially the visualization and spatial analysis function, has been widely used in bibliometric studies. Frenken et al. (2009) recognized that Frame et al. (1977) firstly discussed the spatial distribution of science. From the perspective of spatial distribution, Matthiessen and Winkel (1999) firstly analyzed the scientific strength by papers in the Science Citation Index (SCI) produced by authors from the European 'greater' urban regions. Then the effect of spatial concentration of research on the publications per researcher was considered in bibliometric analysis (Bonaccorsi and Daraio, 2005). Allen (2001) conducted a review of GIS literature to determine the quantities of research in various disciplines to inform a library's collection development policy for geospatial data. GIS tools were applied in information mining and spatial presentation of scientific research documents in the Qinghai Tibet Plateau (Wang et al., 2015). GIS software has been used to demonstrate geographic distribution and visualization (Hengl et al., 2009; Bornmann and Waltman, 2011; Wu, 2015; Liu et al., 2016, 2017;Wang et al., 2019). From these studies, it can be seen that the functions of GIS, such as information query, data statistics and spatial analysis, can realize the presentation of bibliometric indicators on different spatial scales, and the spatial-temporal distribution characteristics can be deeply mined, so as to analyze the hot spots of scientific research and dynamic changes. Some commercial GIS software, such as ArcGIS and MapGIS, could calculate and analyze the bibliometric data with spatial information. Therefore, the results will be visualized on the maps by GIS technology in this study.

Accordingly, the main objective of this study is to propose a novel method to expand the application of landscape index for the bibliometric analysis. The scientific research would be regarded as a kind of 'landscape' and seven typical landscape indices are improved to reveal the systematic change trends of spatial pattern of scientific research, as well as verify the method in the field of geoscience. Furthermore, conventional bibliometric methods were implemented by investigating annual publication outputs, especially those of articles. For an overview of the global spatial pattern and spatiotemporal migration of landscape centroids of geoscience research globally, we adopted a visual analysis by GIS technology. We hope that this study could provide scientific reference for the development of bibliometric analysis towards the directions of spatialization and visualization.

2 Data and method

2.1 Data collection

The InCites database is a scientific research evaluation tool based on the collection of Web of Science (WoS) citation data, which contains publications from countries, institutions and disciplines around the world. The InCites database has been continuously improved and now has more than 30 indicators for analysis. In the subject classification system of Incites database, the ‘Geoscience’ belonging to Essential Science Indicators (ESI) subject classification was selected. Taking advantage of updated data of the InCites database on June 2019, all publications in the field of geoscience from 1994 to 2018 are used as research target. Since this study was based on retrospective data from 1994 to 2018, regular updates of the database have no effect to the final results and conclusions of this paper. Here, publications from England, Scotland, Northern Ireland, and Wales were considered as coming from the United Kingdom (UK) (Zhang et al., 2017) and publications from the regions of Hong Kong, Macau and Taiwan were not treated as being from mainland Chinese publications but were independently counted (Wang et al., 2019).

2.2 Method

In this study, we regard scientific research as a kind of ‘landscape’. In landscape ecology, the importance of landscape index is that it can be used to describe the landscape pattern, and then establish the relationship between landscape structure and process or phenomenon, which makes the representation of landscape pattern more objective (Chen et al., 2002). Patch is the basic unit of the landscape pattern, which refers to a relatively homogeneous non-linear region that differs from the surrounding background, emphasizing spatial discontinuity and internal homogeneity (Zhang et al., 2003). In order to study the spatial pattern of global geoscience research, we extended the concept of patches to this study and still defined the patch as a spatial entity that can be directly sensed. Normally, countries, research institutions and authors with geographic information can be regarded as spatial data (Wang et al., 2014), while the number of articles can be regarded as one of the attributes of spatial data. In this study, patches are distinguished by the classification of the number of articles. Neighboring countries with the same classification were divided into a patch. In other words, each patch may consist of one or more countries, and the composition of each patch was reorganized spatially over time. In order to eliminate the influence of the change of classification on the landscape index value, this classification standard is applied to the same landscape in different periods (Li et al., 2004; Peng et al., 2006).

There are many landscape pattern indices, but most of them are not comprehensive with limitations and redundancy (Li et al., 2004a; Peng and Zhang, 2009). Therefore, in order to meet the needs of this study, we improved the formula of the following seven indices to analyze the spatial pattern of global geoscience research. In this study, the selection of landscape index mainly follows two principles: firstly, typical variables can reflect the overall pattern of global geoscience research. Secondly, the selected indicators can clearly reflect the change rules of various patterns. In the improvement of landscape indices, land use types in landscape ecology studies are replaced by the classification of number of geoscience articles and the number of articles is used instead of area in this study. The formulas were as follows (Wu et al., 2002; Wu, 2004):

$$NP = n, \tag{1}$$

where NP is the number of patches and n represents the total number of patches. NP is equal to the total number of patches, which is usually used to describe the heterogeneity and fragmentation of the entire publication pattern in this study. Moreover, NP could reflect the spatial pattern of the geoscience research. As NP increases, fragmentation is enhanced. If NP is large and relatively scattered, the number of articles varies greatly in different regions of the world.

$$PD = n/TA, \tag{2}$$

where PD is the patch density, n presents the total number of patches, and TA presents the total number of geoscience articles. This formula expresses the number of patches per unit article, which is helpful for comparison between different size of patches.

$$LPI = \max(a_1,a_2,...,a_n)/TA, \tag{3}$$

where LPI is the largest patch index, a_1, a_2, a_3,..., a_n is the number of articles per patch, and TA presents the total number of articles. LPI is essentially equal to the proportion of the largest patch to the overall publication pattern, which is helpful for determining the dominant patch type (Li et al., 2004a).

$$\mathrm{PLAND} = p_i = \frac{\sum_{j=1}^{n} a_{ij}}{TA}, \tag{4}$$

where PLAND is percentage of the publication pattern and a_{ij} represents total articles in a patch. PLAND represents the relative proportion of a patch type to the entire publication pattern, which is one of the bases for determining the dominant patch types in the publication pattern. When its value tends towards zero, it means that the type of patch is very rare in the publication pattern; when its value equals 100, it means that the whole publication pattern is composed of only one kind of patch.

$$SHDI = -\sum_{\mathrm{i}=1}^{n} (p_i \times \ln p_i), \tag{5}$$

where $SHDI$ is Shannon’s diversity index where p_i is the proportion of the publication pattern by patch type i. $SHDI$ is widely used in the detection of diversity in patch types, which can reflect spatial heterogeneity and is especially sensitive to the unbalanced distribution of patch type in the publication pattern (Liu et al., 2011; Yang, 2015a). The value of *SHDI* increases as the patch types increase or the proportional distribution among patch types becomes more equitable. If the *SHDI* is close to 0, the entire publication pattern simply consists of one dominant patch type. In this study, this index is used to reflect the heterogeneity of global geoscience research.

$$SHEI = \frac{-\sum_{i=1}^{n}(p_i \times \ln p_i)}{\ln m}, \tag{6}$$

where *SHEI* is Shannon's evenness index and *m* represents the number of patch types. *SHEI* and *SHDI* are both powerful tools for calculating the diversity of different patches at different times. When the value of *SHEI* is small, the dominance is generally high, which can reflect that the landscape is dominated by one or more dominant patch types. When it approaches 1, the dominance is low, indicating that there are no obvious dominant types and that the landscape is dominated by one or more dominant patch types. When it approaches 1, the dominance is low, indicating that there are no obvious dominant types and that each patch type is evenly distributed in the whole publication pattern.

$$\text{ARTICLE-}MN = CA/n, \tag{7}$$

where ARTICLE-*MN* is the mean number of articles in each patch where *n* represents the total articles in all patches. It is an important indicator of heterogeneity in the publication pattern.

The landscape centroid at the landscape scale is defined as the arithmetic average of all points in the element shape in two-dimensional space, such as the geometric center of Asia in Urumqi and that of China in Lanzhou. Thus, we calculated the geometric centers of each country in the world, and then linked the volume of interannual articles of each country to these centers. To analyze the migration of geometric centers on the global scale, the concept of the centroid, which is commonly used in physics and statistics, is introduced to calculate the centroids of the global geoscience articles (Yang and Wang, 2015). The inter-annual variation of the centroid positions can reflect the migration process of centroids of global geoscience research over time. The formulas for the centroid coordinates are as follows (Wang and Tiyip, 2009; Yang and Wang, 2015):

$$X_t = \sum_{i=1}^{n}(C_{ti} \times X_i) / \sum_{i=1}^{n} C_{ti}, \tag{8}$$

$$Y_t = \sum_{i=1}^{n}(C_{ti} \times Y_i) / \sum_{i=1}^{n} C_{ti}, \tag{9}$$

where X_t and Y_t respectively represent the centroid coordinates of the global articles in *t* year, C_{ti} represents the number of publications in *i* countries in *t* years, and X_i and Y_i represent the geometric center of the country *i*.

3 Results

3.1 Characteristics of research outputs

Figure 1 shows that there has been a steadily increasing trend in global publications annually from 1994 to 2018. The number of publications increased from 18917 (1994) to 58946 (2018), with the growth rate of 211.60% in the past 25 years. The main literature type was article, which included articles published as proceedings papers and book chapters, making up 85.51% of the total publications. Articles were followed by editorial materials (40531 documents, 4.47%), meeting abstracts (31439 documents, 3.39%), reviews (22411 documents, 2.45%) and others. The proportion of articles showed a significant growth trend (83.16% in 1994, 92.82% in 2018), while the proportion of editorial materials was decreasing (5.00% in 1994, 2.79% in 2018). The proportion of meeting abstracts increased to the maximum (10.31%) in 2009 and then decreased, so did the change trend of reviews (3.94% of the total in 2009).

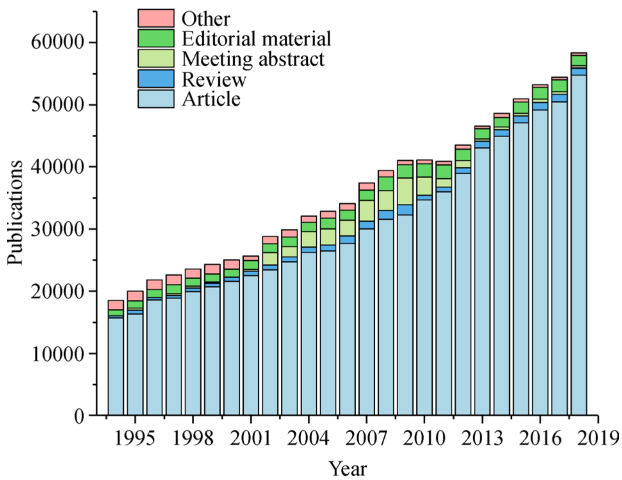

Fig. 1 Characteristics by year of geoscience publications.

3.2 Characteristics of productivity

The top 20 most productive countries were ranked based on the total number of articles and total citations (Table 1). Seen from the spatial distribution of these countries (Supplementary Fig. 1), 12 were in Europe, 4 were in Asia, 2 were in North America, 1 was in South America, and 1 was in Oceania. We found that articles were highly concentrated at the country level. The world's top 10 countries accounted for almost 69.93% of total geoscience articles and top 20 countries published 84.68% of total

Table 1 Top 20 productive countries in geoscience research

Country	*TA*	*R*/%	*TC*	Single country		International collaboration		
				SA	%	*CA*	%	*MC*(*n*)
USA	240234	1(25.63)	8438483	134124	0.56	106110	0.44	China (18682)
China	104285	2(11.13)	1709506	63844	0.61	40441	0.39	USA (18682)
UK	76597	3(8.17)	2529759	27809	0.36	48788	0.64	USA (17093)
Germany	70167	4(7.49)	2091571	22760	0.32	47407	0.68	USA (14435)
France	62696	6(6.69)	1895582	20409	0.33	42287	0.67	USA (12687)
Canada	50773	7(5.42)	1401954	22300	0.44	28473	0.56	USA (12975)
Russia	47835	8(5.10)	468937	33454	0.70	14381	0.30	USA (3737)
Japan	42213	9(4.50)	996393	22439	0.53	19774	0.47	USA (7661)
Australia	39681	10(4.23)	1228738	15088	0.38	24593	0.62	USA (7768)
Italy	39439	11(4.21)	974046	18251	0.46	21188	0.54	USA (5694)
India	26641	12(2.84)	362335	19639	0.74	7002	0.26	USA (2331)
Spain	24875	13(2.65)	581668	9307	0.37	15568	0.63	USA (3721)
Switzerland	21240	14(2.27)	749589	4986	0.23	16254	0.77	USA (5089)
Netherlands	19385	15(2.07)	675857	5642	0.29	13743	0.71	USA (3973)
Norway	15160	16(1.62)	413244	4277	0.28	10883	0.72	USA (3391)
Sweden	14087	17(1.50)	403501	3899	0.28	10188	0.72	USA (3086)
Brazil	12583	18(1.34)	244730	5825	0.46	6758	0.54	USA (2343)
South Korea	10037	20(1.07)	188733	4542	0.45	5495	0.55	USA (2880)
Poland	9808	21(1.05)	118691	5733	0.58	4075	0.42	USA (852)
Austria	9399	22(1.00)	249192	2083	0.22	7316	0.78	Germany (2611)

Notes: a) *TA*: total articles; b) *TC*: total cited articles; c) *SA*: single-country articles; d) *CA*: articles with international collaborations; e) *MC*(*n*): major collaborator (i.e., the number of collaborated articles between two countries).

articles. The productivity ranking of countries was led by the USA with respect to both most articles (240234, 25.63% of the total) and the highest cited articles (8438483). China published the second most articles (104285, 11.13%), followed by the UK (76597, 8.17%), Germany (70167, 7.49%) and France (62696, 6.69%). However, among top five most productive countries, the *CA* of China was lowest. With respect to international cooperation, the articles with the most international collaboration were from the USA. The UK and Germany took second and third place, respectively, with relatively high *TC*. It is noteworthy that China had achieved rapid progress in global geoscience research with the growth rate of 747.14% in the past 25 years. In contrast, although Switzerland and Austria did not perform well in *TA*, the *CA* of international collaboration were relatively high, which suggested that their research level was significantly improved by international collaboration. Notably, all major collaborator of 18 countries was the USA, which played a dominant role in international collaboration.

3.3 Characteristics of publication pattern

Firstly, we classified the number of articles in global geoscience research into eight types (Table 2).

The Spatial and temporal changes of patches have been visualized every four years from 1994 to 2018 in the software ArcGIS 10.2 (ESRI). Seen from the overall spatial distribution characteristics of patches (Supplementary Fig. 1), the distribution of type I, II, and III was gradually contracted, whereas the distribution of type V, VI and VII was obviously expanded. Globally, type I, II and III were the most widely distributed, so they were identified as the main-stream article types in 1994 and 1998. Type V and type VII were mainly concentrated in North America, Western Europe and North Asia. The spatial distribution of type IV was the smallest, and it did

Table 2 Classification and definition of the patch types

Patch type	Number of articles in global geoscience research
I	No published articles
II	Less than 100
III	101–500
IV	501–1000
V	1001–2500
VI	2501–5000
VII	5001–10000
VIII	More than 10000

not expand significantly until 2010. It's remarkable that the darkest region appeared on the map in 2010 and 2014, because the number of articles of the USA exceeded 10000. Globally, the distribution of type VIII expanded as a result of that China and the USA have published more than 10000 articles in 2018. Since 2002, patches with more articles were also gradually located in North America, Western Europe, East Asia, and Oceania. There was no significant progress in Central Asia and Africa during the study period.

Next, we counted the numbers of countries covered by (Fig. 2) and articles of each patch (Fig. 3). In 1994, type I and type II included 92% of the global countries, the proportion of which decreased annually and dropped to 76.8% in 2018. In particular, the number of countries included in type I dropped from 120 (1994) to 68 (2018). Although type I and type II contained the most countries, but the total articles accounted for the lowest of global articles, and the number of articles declined from 8.5% (1994) to 2.6% (2018). Type VI emerged in 2006 with the same continued increasing trend as types II, III, IV, and V.

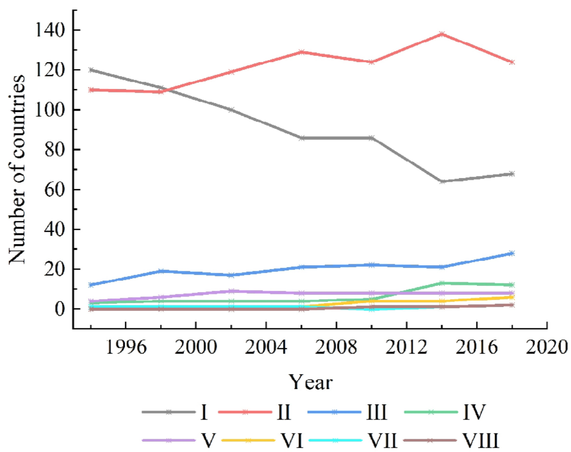

Fig. 2 The number of countries of each patch.

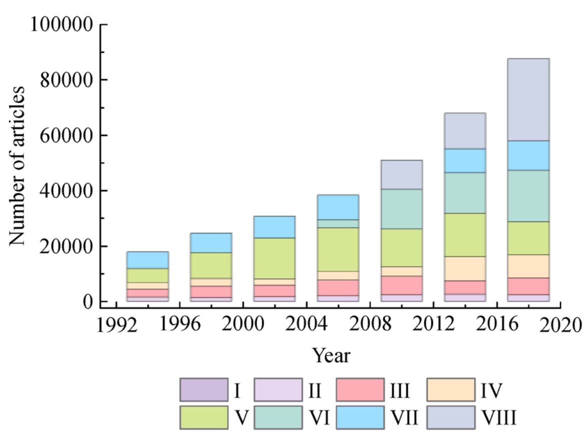

Fig. 3 The number of articles of each patch.

Although the number of countries included in type VII did not change significantly, the number of articles increased by 78.3% during the study period. The country productivity ranking was led by the USA, and the number of articles increased from 1994 to 2014. In 2010 and 2014, Type VIII only consisted of the USA. However, it was determined by both China and the USA in 2018.

3.4 Patch scale analysis

Based on the above formulas, we calculated seven improved landscape indices in 1994, 1998, 2002, 2006, 2010, 2014 and 2018 to quantitatively describe the spatial pattern of geoscience research. At the patch scale, Table 3 clearly revealed that the *NP* and *PD* of type I were the largest compared with other plaque types. *NP* decreased 27 and *PD* decreased 5.06 from 1994 to 2018, the obvious downward trend of which indicated that the spatial fragmentation degree of type I was the highest, but it

Table 3 Patch-scale publication pattern index

Type	Year	*NP*	*PD*	*LPI*/%	PLAND/%
I	1994	82	5.72	—	—
	1998	80	3.73	—	—
	2002	77	2.92	—	—
	2006	75	1.98	—	—
	2010	74	1.49	—	—
	2014	55	0.78	—	—
	2018	55	0.66	—	—
II	1994	23	1.68	3.01	8.51
	1998	21	1.38	1.27	5.24
	2002	35	1.23	1.19	5.14
	2006	35	1.09	1.21	4.93
	2010	36	0.78	1.04	4.52
	2014	54	0.74	0.88	3.69
	2018	56	0.60	0.69	2.60
III	1994	7	0.45	3.71	16.45
	1998	10	0.45	3.24	17.17
	2002	11	0.36	3.26	13.84
	2006	13	0.34	3.04	15.01
	2010	13	0.25	3.48	13.19
	2014	14	0.21	1.56	7.33
	2018	15	0.17	1.29	7.13
IV	1994	6	0.17	5.34	12.46
	1998	5	0.12	4.51	11.21
	2002	4	0.13	2.16	7.68
	2006	4	0.10	2.48	8.20
	2010	4	0.08	2.68	6.78
	2014	9	0.15	3.32	12.69
	2018	10	0.11	2.53	9.37

(*Continued*)

Type	Year	*NP*	*PD*	*LPI*/%	PLAND/%
V	1994	5	0.22	8.91	29.41
	1998	5	0.20	12.82	37.64
	2002	6	0.19	16.33	47.72
	2006	5	0.13	16.63	41.11
	2010	8	0.14	7.45	26.77
	2014	7	0.10	5.63	23.06
	2018	7	0.08	2.67	13.67
VI	1994	0	—	—	—
	1998	0	—	—	—
	2002	0	—	—	—
	2006	1	0.03	7.47	7.47
	2010	3	0.06	12.49	27.87
	2014	3	0.04	11.51	21.54
	2018	2	0.06	7.99	21.27
VII	1994	1	0.06	33.17	33.17
	1998	1	0.04	28.74	28.74
	2002	1	0.03	25.62	25.62
	2006	1	0.03	23.27	23.27
	2010	0	—	—	—
	2014	1	0.01	12.72	12.72
	2018	2	0.02	6.03	12.02
VIII	1994	0	—	—	—
	1998	0	—	—	—
	2002	0	—	—	—
	2006	0	—	—	—
	2010	1	0.02	20.87	20.87
	2014	1	0.01	18.96	18.96
	2018	2	0.02	17.19	33.93

decreased with time. In terms of spatial distribution, the range of type I continually contracted and gradually aggregated. The *NP* of type II increased by 143.48% and *NP* of type III increased by 114.29% from 1994 to 2018. However, the PLAND and *LPI* of type II and type III were relatively small, which illustrated that they were more scattered spatially in the past 25 years. The *NP* of type V only increased 2, and the PLAND of type V and type VII was much larger than that of the other types, the sum of which accounted for more than 62% of the total geoscience articles. Thus, type V and type VII were the dominant types in 1994, 1998, 2002 and 2006. Since 2010, type V, type VI and type VIII were the dominant patch types in the spatial pattern in the field of geoscience. From 1994 to 2006, the *LPI* of type VII was the largest, indicating that the dominance of type VII was higher and played a relatively important role in the spatial pattern; however, the *NP* of type VIII was only 1 in 2010 and 2014, and increased to 2 in 2018. *PD* basically remained the same, and the *LPI* was relatively large, which indicated that type VIII did not appear until 2010, and it also existed as a dominant patch from 2010 to 2018.

3.5 Landscape scale analysis

ARTICLE-*MN* increased annually with a growth rate of 478.84% from 1994 to 2018, and peaked at 572.56 in 2018 (Table 4). It shows that the average number of geoscience articles in each patch has increased significantly throughout the entire period. *SHDI* is a sensitive index for comparing and analyzing the diversity and spatial heterogeneity of publication patches in different periods. *SHEI* can also be used to reflect the dominance of publication patches. Compared with the *SHDI* and *SHEI* from 1994 to 2018, *SHDI* generally decreased and then peaked at 1.83 in 2014. The change trend of *SHEI* was similar to that of *SHDI*, and it was mostly toward 1 in 2014. In contrast, the values of *SHDI* and *SHEI* in 2002 were significantly lower than those in other years. It indicated that the patches were the most balanced in the whole global spatial pattern in 2014 and most unbalanced in 2002.

Table 4 Landscape-scale publication pattern index

Year	ARTICLE-*MN*	*SHDI*	*SHEI*
1994	120.42	1.49	0.92
1998	168.71	1.43	0.89
2002	205.23	1.33	0.82
2006	270.15	1.54	0.86
2010	354.17	1.63	0.91
2014	489.15	1.82	0.94
2018	576.62	1.73	0.92

3.6 Characteristics of spatiotemporal migration of landscape centroids

Figure 4 shows the temporal and spatial migration of the landscape centroids of the global geoscience articles in the past 25 years. It can be seen that the global landscape centroid was at 21°48′W, 42°48′N in 1994 and then gradually migrated to the Southeast, which was located at 15°54′E, 38°24′N in 2018. The change trend of annual centroids was mainly reflected in the longitude position, which migrated from 21°48′W to 15°54′E. The range of latitudes varied from 38°24′N to 42°48′N. Countries in the northern hemisphere published more articles, so that the latitudes of the centroids were always in the northern hemisphere and gradually migrated from high latitudes to low latitudes. The longitudes of the landscape centroids were in the western hemisphere from 1994 to 2006 and then migrated to the eastern hemisphere since 2007. This was due to the fact that countries in the western hemisphere

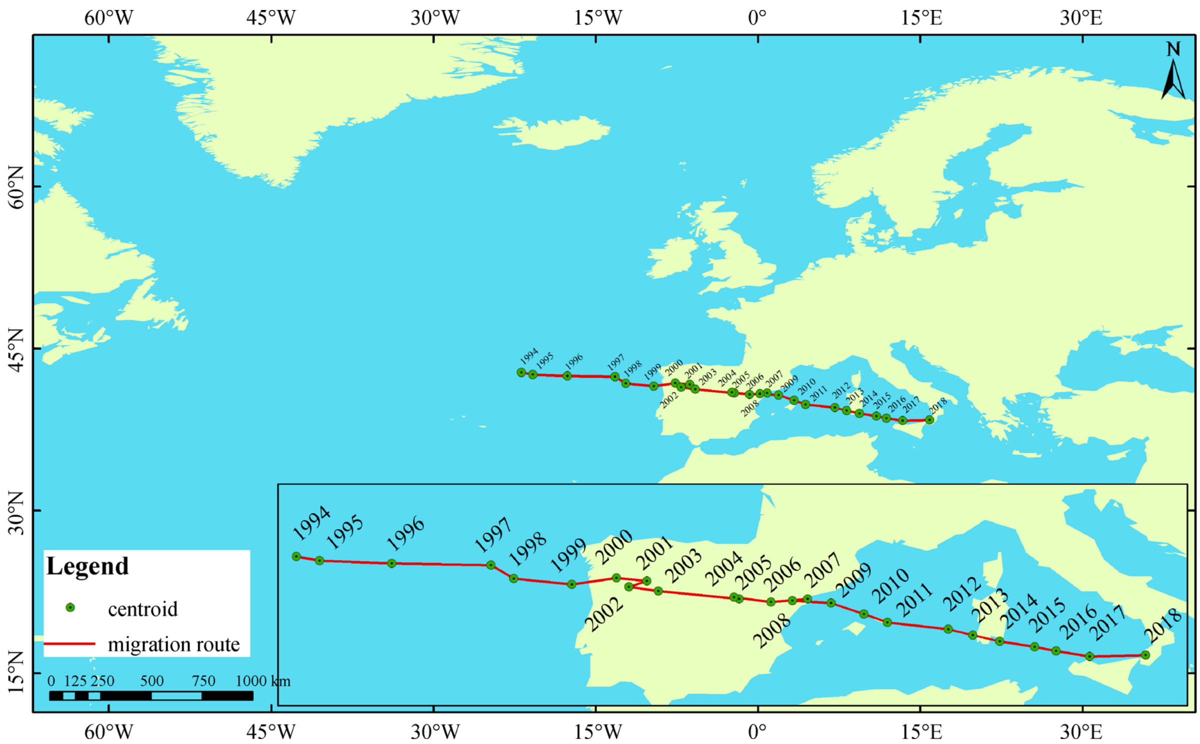

Fig. 4 Spatiotemporal changes of the landscape centroids of the geoscience articles during 1994 to 2018.

published more than half articles before 2007, such as two North American countries, the USA and Canada, contributed more than 27.31% of the global geoscience articles annually, with the highest proportion of 40.92% in 1994, while there were relatively fewer papers in eastern countries. However, since 2007, the number of articles of eastern countries, especially China, which showed a rapid increasing trend with a growth rate of 747.14% during the past 25 years, while the proportion of articles of the west has declined to 39.63%.

4 Discussion

4.1 Principal findings

Based on the above analysis, we found that the top 10 countries published 69.93% of all geoscience articles and 84.68% of total articles were from top 20 productive countries. The top 10 countries were the USA, China, UK, Germany, France, Canada, Russia, Japan, Australia and Italy. More studies showed that the spatial concentration has remained high in world science (Frenken et al., 2009). Azer (2017) also found that there was a strong correlation between number of citations and number of countries involved. By contrast, we concluded that scientific articles were highly concentrated at the country level on special fields. Consistent with findings of Zhou and Leydesdorff (2006), it is noteworthy that China has become a major player in the production of scientific researches, showing the substantial increase in contribution to world science.

At present, there are only a few studies that quantitatively measure the dynamic spatial migration of scientific research on the global scale through specific geographical methods. Batty (2003) has assessed the concentration of scientific citations at the national level and the spatial concentration of highly cited authors was discussed. In this study, we also had a surprise discovery of dynamic changes of spatial pattern of global geoscience research by analyzing the characteristics of patches from 1994 to 2018 and the spatial distribution of patches verified the results of the productivity characteristics. Further, the change trend of the value of landscape indices happened to verify the spatiotemporal change of global geoscience articles from 1994 to 2018, as shown in Supplementary Fig. 1.

As can be seen from Figs. 5 and 6, the value of *SHDI* and *SHEI* presented a typical inverted N-shape change trend with time. Therefore, the development of global geoscience research can be divided into three periods: 1) from 1994 to 2002, the spatial heterogeneity decreased; 2) from 2003 to 2014, the spatial distribution of global geoscience research tended to be significantly balanced; 3) from 2015 to 2018, the spatial distribution became more unbalanced. For further exploring the forces of spatial heterogeneity of geoscience research, we counted the number of ICAs (international collaborative articles). The number of ICAs can be quantified by a quadratic

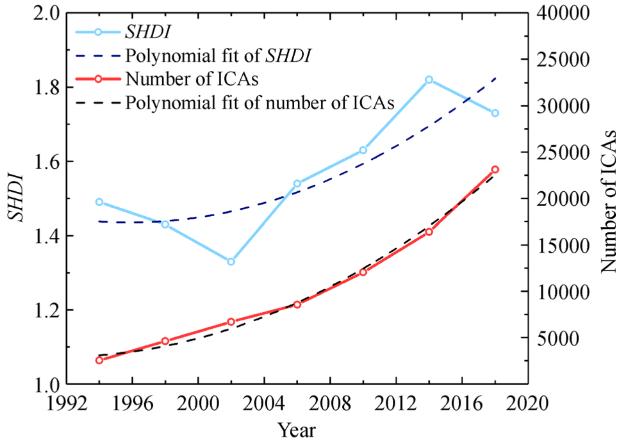

Fig. 5 Relationship between *SHDI* and number of ICAs.

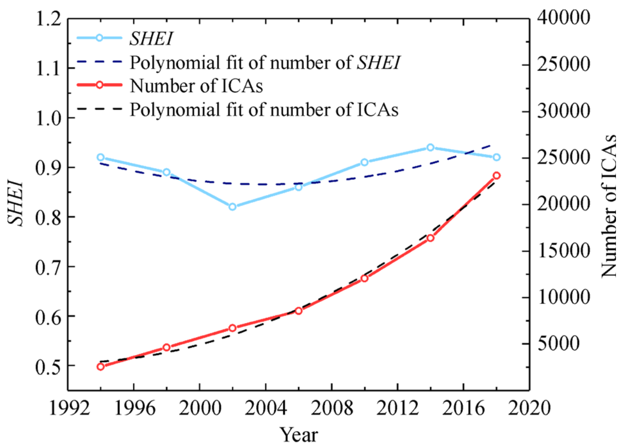

Fig. 6 Relationship between *SHEI* and number of ICAs.

polynomial model $y = 448.04x^2 - 346.04x + 2988.9$ (R^2= 0.9934), where x and y present time and the number of geoscience articles. As is consistent with other scientific research (Liu et al., 2016), the international cooperation plays an increasingly important role in global scientific research. Meanwhile, it was also found that the value of *SHDI* and *SHEI* increased with the number of ICAs. Table 5 summarizes the correlations between ICAs and the value of *SHDI* and *SHEI*. There was significantly linear correlation between ICAs and *SHDI*, with the correlation coefficients r^2 of 0.6582 ($p < 0.05$). However, the correlation between ICAs and *SHEI* had a polynomial fit with r^2 of 0.2406 ($p < 0.05$). The observation revealed that the strengthening of global international collaboration is one of the main driving forces of spatial heterogeneity of global geoscience research.

4.2 Meaningful implication

The greatest contribution of this paper is achieving the integration of landscape index and bibliometric analysis, and checking the feasibility in global geoscience research. Expanding the application range of the landscape index is one of the development trends in landscape science. According to the spatial significance of landscape index, seven improved indices including *NP*, *PD*, PLAND, *LPI*, ARTICLE-*MN*, *SHDI*, and *SHEI* were proposed to represent the spatial pattern of geoscience articles. The visualization function of GIS technology is to visualize the location, distribution, shape and other attributes of spatial data through computer graphics technology, representing the correlation among spatial entities. In this study, instead of using tables and charts to analyze the quantity and quality of scientific research, we used the visualization function of GIS to display non-spatial data such as the number of articles on the map. We associated the annual articles of each country with the vector layer containing geographical coordinates to form a new layer, and finally got the trend line representing the dynamic spatiotemporal change of the landscape centroids. It could be a novel attempt to expand the application of landscape methods to bibliometric analysis.

4.3 Limitations and future research

Some limitations of this study should be noticed. This paper exists some limitations. Seven commonly used landscape indices were selected to analyze the dynamic changes in the publication pattern of the global geoscience research. However, there are various landscape indices that can be further used in bibliometric analysis of the spatial pattern, such as the contagion index, which can describe the trend of the degree of aggregation or extension of patch types. In the results of landscape scale analysis, what caused the *SHDI* and *SHEI* in 2014 to be significantly larger than other years is worth further exploring. We also found that the migration phenomenon of patches in space. In previous researches, whether the geographical aggregation of research brings advantages to scientific research has been widely discussed (Bonaccorsi and Daraio, 2005; Carvalho and Batty, 2006; Frenken et al., 2009). However, these studies lacked sufficient evidence and verification. It is a pity that we also did not thoroughly explore the advantages of spatial aggregation. Moreover, it is an arduous task to completely evaluate the achievements of

Table 5 The correlation between *ICA*s and *SHDI* and *SHEI*

Landscape index	Type	Equations	R^2
SHDI	Linear fit	$y = 1.926\times10^{-5}x + 1.3637$	0.6582
SHEI	Polynomial fit	$y = 2.11\times10^{-10}x^2 - 10^{-6}x + 0.8916$	0.2406

scientific research. Some studies used not only total number, but also mean + SD, Median and IQR for bibliometric analysis (Azer and Azer, 2019). In this study, we only used the total number of articles to improve and calculate the landscape indices for the analysis of geoscience research.

Given the continuous evolution of interdisciplines, it is necessary to overcome the barriers of terms among different disciplines and transform the methods of data processing in various fields of collaboration. On the one hand, the improved landscape indices have been proved to be able to quantitatively describe the spatial pattern of scientific research. Next, we will try to improve calculation formulas of landscape indices by mean + SD, Median and IQR instead of total number. However, each landscape index has limitations and redundancy (Li and Wu, 2004). In the following studies, we could try to compare the responses of different pattern indices to different pattern series (type number, research area scope, etc.) at the landscape level and different scale of landscape, and discuss whether the improved indices can reflect the spatial change characteristics of different patterns, and further clarify the practicability and limitations of these indices used in spatial pattern quantification for scientific research. Furthermore, it is worth exploring the driving force of spatial pattern of scientific research, such as the level of economic development, population, natural environment, gender differences in authorship and even the inter-rater coefficient of agreement between evaluators measured by Cohen κ (Azer and Azer, 2018; Pina et al., 2019).

On the other hand, it is key to store, extract and quantitatively analyze geographic information from numerous scientific researches by GIS technology. In addition, GIS technology can also dynamically display the geographical location of authors and institutions over time, such as WebGIS, which can be applied to further demonstrate the spatial migration of authors, institutions and cooperation around the world. Another example is that AuthorMapper can display Springer's literature database on the basis of Google Earth (Wang et al., 2014). What's more interesting is to upload cited publications among countries with spatial geographic information to Geocommons software, visualize the results of global knowledge flows on the map, and create interactive visual analysis works. Some prediction models in GIS technology, such as the data analysis method of RBF neural network with the characteristics of knowledge reasoning, can be applied to the trend prediction of not only geoscience but also other geographical scientific research.

5 Conclusions

From the above analysis, it can be seen that the novel developed method was effectively applied to the spatial visualization, achieving in-depth analysis of spatial pattern in geoscience research on the global scale.

From 1994 to 2018, global publications increased steadily and articles were highly concentrated at the country level. The productivity ranking of countries was led by the USA with respect to the total number of articles, total citations and international collaboration. In terms of spatial distribution, North America, Western Europe, East Asia, and Oceania have made the greatest contribution to global geoscience research since 2002. There was no significant progress in Central Asia and Africa. At the patch scale, the change trend of improved landscape indices happened to verify the spatiotemporal change trends of global distribution in the field of geoscience. At the landscape scale, the strengthening of global international collaboration is one of the main driving forces of spatial heterogeneity. As to results of the spatial analysis of landscape centroid of geoscience articles, the change trend of annual centroids was mainly reflected in the longitude position as a result of significant increasing of articles of eastern countries, especially China.

This study afforded a new perspective of interdisciplinary of landscape methods and bibliometric analysis, hoping to provide research reference for the future study.

Acknowledgements This work was jointly supported by the project of National Social Science Fund of China (17ZDA188) and the National Natural Science Foundation of China (Grant Nos. 41830648, 41771453).

Electronic Supplementary Material is available in the online version of this article at http://dx.doi.org/10.1007/s11707-021-0875-z and is accessible for authorized users.

References

Ahlgren P, Persson O, Tijssen R (2013). Geographical distance in bibliometric relations within epistemic communities. Scientometrics, 95(2): 771–784

Allen R S (2001). Interdisciplinary Research: a literature-based examination of disciplinary intersections using a common tool, geographic information system (GIS). Sci Tech Libr, 21(3–4): 191–209

Azer S A (2017). Top-cited articles in problem-based learning: a bibliometric analysis and quality of evidence assenssment. J Dent Educ, 81(4): 458–478

Azer S A, Azer S (2019). Top-cited articles in medical professionalism: a bibliometric analysis versus altmetric scores. BMJ Open, 9(7): e029433

Azer S A, Azer S (2018). What can we learn from top-cited articles in inflammatory bowel disease? A bibliometric analysis and assessment of the level of evidence. BMJ Open, 8(7): e021233

Batty M (2003). The geography of scientific citation. Environ Plan, 35 (5): 761–765

Bonaccorsi A, Daraio C (2005). Exploring size and agglomeration effects on public research productivity. Scientometrics, 63(1): 87–120

Bornmann L, Waltman L (2011). The detection of "hot regions" in the 515 geography of science—a visualization approach by using density maps. J Informetrics, 5(4): 547–553

Carvalho R, Batty M (2006). The geography of scientific productivity: scaling in U.S. computer science. J Stat Mech, 2006(10): P10012

Chen C, Jia Z, Wu S, Tong X, Zhou W, Chen R, Zhang C (2017). A bibliometric review of Chinese studies on the application of landscape connectivity. Acta Ecol Sin, 37: 3243–3255

Chen W, Xiao D, Li X (2002). Classification, application, and creation of landscape indices. Acta Ecol Sin, 13(1): 121–125 (in Chinese)

Egghe L (2006). Theory and practice of the g-index. Scientometrics, 69 (1): 131–152

Frame J D, Francis N, Mark P C (1977). The distribution of world science. Soc Stud Sci, 7(4): 400–400

Frenken K, Hardeman S, Hoekman J (2009). Spatial scientometrics: towards a cumulative research program. J Informetrics, 3(3): 222–232

Hassan S U P, Haddawy (2013). Measuring international knowledge flows and scholarly impact of scientific research. Scientometrics, 94 (1): 163–179

He H S, Dezonia B E, Mladenoff D J (2000). An aggregation index (AI) to quantify spatial patterns of landscapes. Landsc Ecol, 15(7): 591–601

Hengl T, Minasny B, Gould M (2009). A geostatistical analysis of geostatistics. Scientometrics, 80(2): 491–514

Hersperger A M, Bürgi M (2009). Going beyond landscape change description: quantifying the importance of driving forces of landscape change in a Central Europe case study. Land Use Policy, 26(3): 640–648

Hirsch J E (2010). An index to quantify an individual's scientific research output that takes into account the effect of multiple coauthorship. Scientometrics, 85(3): 741–754

Li H B, Wu J G (2004). Use and misuse of landscape indices. Landsc Ecol, 19(4): 389–399

Li J X, Wang Y J, Shen X H, Song Y C (2004a). Landscape pattern analysis along on urban-rural gradient in the Shanghai metropolitan region. Acta Ecol Sin, 24(9): 1973–1980

Li L, Liu Y, Zhu H, Ying S, Luo Q, Luo H, Kuai X, Xia H, Shen H (2017). A bibliometric and visual analysis of global geo-ontology research. Comput Geosci, 99: 1–8

Li X Z, Bu R C, Chang Y (2004). The response of landscape metrics against pattern scenarios Acta Ecol Sin, 24(1): 123–134

Liu Y, Lu Y H, Fu B J (2011). Implication and limitation of landscape metrics in delineating relationship between landscape pattern and soil erosion. Acta Ecol Sin, 31(1): 267–275

Liu F, Lin A, Wang H, Peng Y, Hong S (2016). Global research trends of geographical information system from 1961 to 2010: a bibliometric analysis. Scientometrics, 106(2): 751–768

Liu X, Zhang L, Hong S (2011a). Global biodiversity research during 1900–2009: a bibliometric analysis. Biodivers Conserv, 20(4): 807–826

Manicacci D, Olivieri I, Perrot V, Atlan A, Gouyon P H, Prosperi J M, Couvet D (1992). Landscape ecology: population genetics at the metapopulation level. Landsc Ecol, 6(3): 147–159

Matthiessen M C, Winkel S A (1999). Scientific centres in Europe: an analysis of research strength and patterns of specialisation based on bibliometric indicators. Urban Stud, 36(3): 453–477

O'neill R V, Riitters K H, Wickham J D, Jones K B (1999). Landscape pattern metrics and regional assessment. Ecosyst Health, 5(4): 225–233

Pina D G, Barać L, Buljan I, Grimaldo F, Marušić A (2019). Effects of seniority, gender and geography on the bibliometric output and collaboration networks of European Research Council (ERC) grant recipients. PLoS One, 14(2): e0212286

Peng H E, Zhang H R (2009). Study on factor analysis and selection of common landscape metrics. For Res, 22(4): 470–474

Peng J, Wang Y L, Zhang Y, Ye M T, Wu J S (2006). Research on the influence of land use classification on landscape metrics. Acta Geogr Sin, 61(2): 157–168

Schumaker N (1996). Using landscape indices to predict habitat connectivity. Ecology, 77(4): 1210–1225

Shen S, Yue P, Fan C (2019). Quantitative assessment of land use dynamic variation using remote sensing data and landscape pattern in the Yangtze River Delta. Sustain Comput Infor, 23: 111–119

Vorovencii I (2015). Quantifying landscape pattern and assessing the land cover changes in Piatra Craiului National Park and Bucegi Natural Park, Romania, using satellite imagery and landscape metrics. Environ Monit Assess, 187(11): 692

Wang H W, Tiyip T (2009). Remote sensing dynamic monitor and driving force of soil salinization in arid area: a case of delta oasis of Weigan and Kuqa River. Arid Land Geogr, 32(3): 445–453

Wang X, Li X, Zhang Z, Ma M (2014). Spatial display of bibliometric indicators using information system. Lib Inform Service, 58(3): 72–77

Wang X, Zhang Z, Li X (2015). Tendency analysis of the international studies of qinghai-tibet plateau using MKD and GIS. J China Soc Sci Tech Inform, 34(9): 930–937

Wang Y, Hong S, Wang Y, Gong X, He C, Lu Z, Zhan F B (2019). What is the difference in global research on central Asia before and after the collapse of the USSR: a bibliometric analysis. Scientometrics, 119 (2): 909–930

Wu A (2015). Trends of the geographical distribution of the core journals in china. Journal of Academic Libraries, 33(03): 96–100

Wu J (2004). Effects of changing scale on landscape pattern analysis: scaling relations. Landsc Ecol, 19(2): 125–138

Wu J (2013). Geographical knowledge diffusion and spatial diversity citation rank. Scientometrics, 94(1): 181–201

Wu J, Shen W, Sun W, Tueller P T (2002). Empirical patterns of the effects of changing scale on landscape metrics. Landsc Ecol, 17(8): 761–782

Yang M, Wang X (2015). A biliometrics analysis of world libraries' papers based on GIS. Remote Sensing Technology and Application, 30(4): 819–824

Yang W R (2015a). Spatiotemporal change and driving force of urban landscape pattern in Beijing. Acta Ecol Sin, 35(13): 4357–4366

Zhang D, Fu H Z, Ho Y S (2017). Characteristics and trends on global environmental monitoring research: a bibliometric analysis based on Science Citation Index Expanded. Environ Sci Pollut Res Int, 24(33): 26079–26091

Zhang Q J, Fu B J, Chen L D (2003). Several problems about landscape pattern change research. Sci Geogr Sin, 23(3): 264–270

Zhang X, Estoque R C, Xie H, Murayama Y, Ranagalage M (2019). Bibliometric analysis of highly cited articles on ecosystem services. PLoS One, 14(2): e0210707

Zhang X, Zhang F, Wang D (2018). Analysis of bibliometrics and visualization on landscape in china and abroad during 2010–2016. J SW China Normal U (Natrual Science Edition), 43(7): 149–156

Zhou P L, Leydesdorff L (2006). The Emergence of China as a Leading Nation in Science. Res Policy, 35(1): 84–103

Zhuang Y, Liu X, Nguyen T, He Q, Hong S (2013). Global remote sensing research trends during 1991–2010 a bibliometric analysis. Scientometrics, 96(1): 203–219