CrossMark

Visualizing the knowledge domain of sustainable development research between 1987 and 2015: a bibliometric analysis

Jie Zhu[1] · **Weijian Hua**[1]

Abstract Sustainable development (SD) was posited almost three decades ago by the World Commission on Environment and Development (WCED) as an integrated approach for addressing concerns regarding a number of environmental and socio-economic issues. To represent the knowledge structure and evolution of SD in the post-WCED era, this paper resorted to CiteSpace to identify and visualize cited references and keyword networks, the distribution of categories and countries, and highly cited references relating to SD research. Two indicators embedded in CiteSpace were introduced to investigate intellectual turning points and pivotal points to outline the emerging trends, and furthermore, a new indicator (BC × CB) was developed and applied for keyword analysis. Our findings were as follows. First, the United States and UK occupy dominant positions in relation to SD studies in general and meanwhile China records the highest publication counts. Second, the concept of *nature capital* has contributed significantly to interpretations of SD and the detected promising disciplinary frontiers are materials category and social sciences. Lastly, keyword analysis shows the valuable keywords under the measure of BC × CB and furthermore citation maps and visible hot research areas are revealed as well.

Keywords Sustainable development · CiteSpace · Knowledge structures · Bibliometrics

Introduction

Sustainable development was prominently defined by WCED in its widely acclaimed report, *Our Common Future*, as "development that meets the needs of the present without compromising the ability of future generations to meet their needs" (WCED 1987, p. 43). That definition was strategically ambiguous and somewhat impractical, but it attracted

✉ Jie Zhu
  fxyzjie@whu.edu.cn

[1] Research Team on Sustainable Development, Wuhan University, Wuhan 430072, Hubei Province, China

wide attention and endorsement, especially from politicians and business leaders (Dovers and Handmer 1993; Wackermagel and Rees 1998, p. 39; Hopwood et al. 2005).

In spite of the existence of discussions on the interpretation of sustainability (Brown et al. 1987; Shearman 1990; Redclift 1992; Goodland 1995; Callicott and Mumford 1997), the concept of sustainable development had acquired a global cultural and social dimension that immensely transcended the traditional boundaries of the science (Kates et al. 2005). Sustainable development involves a range of aspects including nature, artefacts and society. It's coverage and components, have been comprehensively discussed and interpreted in different ways by scholars and representatives from developed and developing countries (Denters 2001).

Over the last three decades, there has been numerous studies within the proliferation of sub-disciplines relating to sustainable development and sustainability science. Sustainability research integrated various theories, concepts, techniques and data from a diverse array of academic disciplines (Rafols and Meyer 2010). Kajikawa et al. (2007) detected dozens of sub-domains of sustainability science by applying topological clustering, which are: Agriculture, Fisheries, Ecological Economics, Forestry, Business, Tourism, Water, Urban Planning, Rural Sociology, Renewable Energy, Health, Soil and Wildlife.

Efforts on the exploration of the landscape of sustainable development have continuously been taken, forasmuch as the recognized crucial need in decision making and resources investigating in this field. A promising approach on the analysis of the evolution structure of SD is to seek to the support from computer-based measures.

In previous works, a citation-based approach, which also is computer-based, has been applied to ecological economics (Costanza et al. 2004; Ma and Stern 2006) and water resource management (Thelwall et al. 2006). Kajikawa et al. (2007) did an excellent job to provide an academic landscape of sustainability science by using citation network analysis. They extracted and visualized 15 sub-domains of sustainability science and qualitatively proposed a fundamental framework for future research (Kajikawa 2008). Bettencourt and Kaur (2011) revealed the temporal evolution, geographic distribution and collaboration network structure and evolution of sustainability science by utilizing a popular computer-based model. Aiming to clarify the sources and influences underlying the concept of sustainable development, Quental and Lourenço (2012) identified the most influential publications, authors, journals, scientific disciplines and principles on sustainable development literature. Buter and Van Raan (2013) focused on the highly cited knowledge based (HCKB) and investigated its research orientation, co-citation network and the change in diversity of references.

Despite of fruitful quantitative researches on sustainable development (or sustainability science), however, less of them attempted to visualize the structure evolution and give the keywords analysis of the knowledge domain of SD. In this paper, we attempt to visualize the research evolution of sustainable development and furthermore highlight the research frontiers by applying two indicators, Betweenness Centrality (BC) and Citation Burst (CB). Both indicators were embedded in CiteSpace, a freely available java application (http://cluster.cis.drexel.edu/~cchen/citespace) developed by Chaomei Chen at Drexel University (USA).

Data and methods

For this study, ISI Web of Science was chosen as the data source in consideration of its wide application in congeneric articles. As the consensus on the definition, concepts and methodologies on sustainability science has not been reached, most of papers tended to

build the datasets by collecting the records that contained the expression "sustainab*" ("sustainability" or both "sustainability" and "sustainable") (Kajikawa et al. 2007, Kajikawa 2008; Bettencourt and Kaur 2011; Schoolman et al. 2012) or even more strict term (Quental and Lourenço 2012) in the titles, abstract or keywords. Besides, some papers prefer to collect data by using a collection keywords terms (Xu and Marinova 2013; Yang et al. 2013; Hassan et al. 2014). As far as we are concerned, the first approach is sample but have a better performance in revealing the landscape of SD form the macroscopic perspectives. On the quite contrary, the second approach is much better in introducing the sub-disciplines or inter-disciplines issues on the research of SD since it resorts to collect dataset by using a sequence of keywords seen as components or branches of SD field.

This paper macroscopically focused on the investigation of the SD research in the aspect of country and discipline distributions, articles and keywords analysis, and hence, the first approach would be applied to collect the dataset.

Moreover, in this paper, we prefer the sustainable development over the sustainability science. Given the discrepancy between sustainability science and sustainable development (Kajikawa et al. 2007), we think it is confused to collect the records under the search results of two query from the ISI Web of Science. Therefore, for this paper, we built the core dataset D_{ALL} by collecting all bibliographic records that were on the result list of topic research of "sustainable development" covering a timespan from 1987 to 2015. Topic Research provided by ISI Web of Science could obtain the article related to SD with the query "sustainab*" in its title, abstract or keywords, including the keywords acquired by the function of KeyWords Plus embedded in ISI Web of Science.

A total of 59,926 records in dataset D_{ALL} have been published in 32 languages, covering 49 countries, associated with 149 research areas. The top five countries in terms of publication counts were: People's Republic of China (11,718), followed by the United States (8839), UK (4905), Australia (2976), and Germany (2958). It unveils the dominance and influence of these countries on SD research more or less. Annual publication counts in Fig. 1 witnesses a remarkable increase over a period of almost 10 years and subsequently declined in 2015, with 6087 publications that year.

WoS provides Essential Science Indicators (ESI) for ranking top papers as an option for refining results to determine influential papers, publications, and emerging research trends based on publication counts and citation data obtained. We collected ESI-ranked top papers (626 items), comprising dataset D_{ESI} as a complement to investigate the emerging
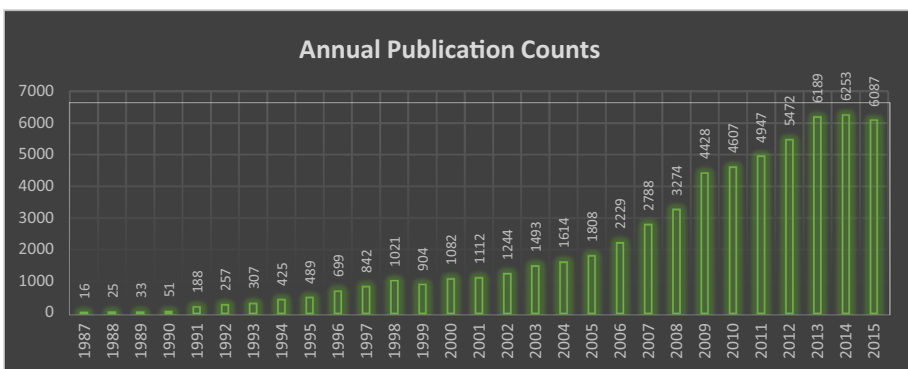

Fig. 1 Annual publication counts from 1987 to 2015 in the Web of Science using SD as a search topic
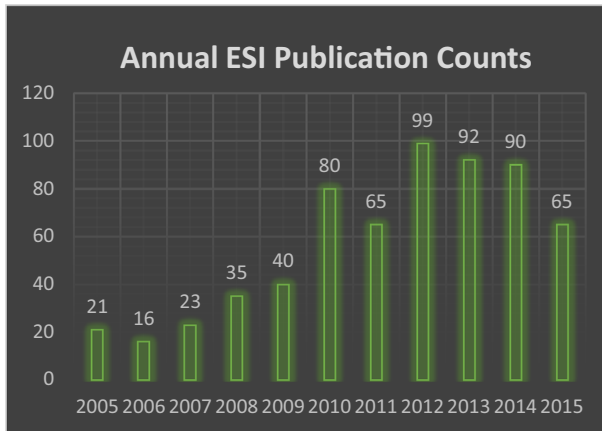
Fig. 2 Distribution of ESI papers in SD studies over the last decade

trends. Figure 2 reveals the quantitative distribution of ESI-ranked top papers in SD studies over the last decade.

In this article, we referred CiteSpace to visually depict knowledge maps and networks of SD research. CiteSpace supports visual explorations and knowledge discovery within WoS bibliographic databases. Consequently, research trends and patterns within the scientific literature can be analyzed (Chen 2006; Chen et al. 2012). Based on the algorithm of co-occurrence matrix, CiteSpace is capable of application to map and analyze co-occurrence networks (He 1999) for keywords and categories and co-citation networks (Small 1973) for cited references and journals.

The aim of this study is to visually demonstrate knowledge structures and developments within SD research from 1987 to 2015. Specifically, analytical methods entailing co-cited references, articles and countries, and co-occurring keywords and categories are applied to depict intellectual structure of SD. Moreover, turning points and pivotal nodes are highlighted by two indicators to demonstrate research frontiers. We have noticed there might be overlaps between this study and precedents, while the contribution of our research still lies here: visual illustration, time dimension and keywords analysis. Detailed explanations are under the section of empirical results respectively.

Empirical results

In this section, we would visually present a whole full view of the sustainable development research. Two indicators, Betweenness Centrality and Citation Burst would be given to identify the intellectual pivot nodes and emerging trends relating to the research of SD.

BC denotes the number of the shortest paths extending between all vertices passing through that node. A high BC node has a dominant influence on the transfer of items through networks, assuming that item transfer follows the shortest paths (Freeman 1977). Strong BC nodes tend to be part of joints bridging the tightly connected sub-graphs that represent discovered knowledge communities. From 2005 onward, CiteSpace has included the BC indicator for identifying pivot nodes within knowledge networks (Chen 2005). CB is another indictor supported and adopted by CiteSpace from 2004 onward. CB indicates

the most active areas of research, providing evidence that a particular publication is associated with a surge of citations (Kleinberg 2003). Generally, a high CB node is likely to be the intellectual turning point of a specific research field. If a cluster contains numerous nodes with strong citation bursts, then the cluster as a whole captures an active area of research, or an emerging trend (Chen 2006).

Co-cited reference analysis

A clustered network of SD research would be demonstrated in this part. To do so, we created a new project and imported dataset D_{ALL} into CiteSpace, setting a time slice between 1987 and 2015, with 2 years per slice. We designated node types as cited references, pruning as the minimum spanning tree, and selection criteria as the g-index ($k = 7$). The g-index was originally introduced by Leo Egghe (2006) in order to overcome some of the disadvantages of the popular h-index. The developer of CiteSpace modified the g-index by introducing a scaling factor k that assisted in controlling the overall size of the resultant network to accord with researchers' particular needs. The k can be any positive number and its value is proportional to the size of the resultant network.

There are 654 nodes and 835 links in the clustered network shown in Fig. 3. Each node represents one cited reference, which is depicted with a series of citation tree-rings across multiple time slices. The area of each node is proportional to the total co-citation frequency of the associated reference. A spectrum of colors indicates the temporal orders of co-citation links among cited references: the oldest are in blue, and the newest are in red. The thickness of the ring of one node is proportional to the co-citation frequencies within the corresponding time slice (Chen 2006). The clustered network is divided into 17 co-citation clusters labeled by index terms obtained from their own citers.
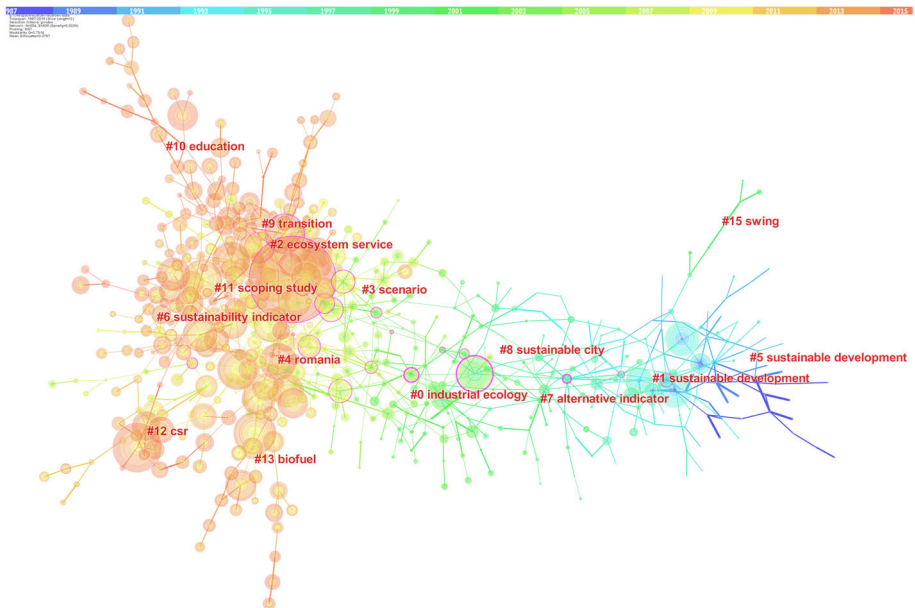

Fig. 3 A clustered network with 654 nodes and 835 links for the period 1987–2015. (Color figure online)

Table 1 Summary of the five largest clusters

#	Size	Silhouette	Label (LLR)	Label (TF–IDF)	Label (MI)
0	61	0.825	Industrial ecology	Industrial ecology	Approach
1	59	0.79	Sustainable development	Environmental management	Energy efficiency
2	51	0.843	Ecosystem service	Ecosystem service	Aquaculture development
3	42	0.852	Scenario	Resilience	Approach
4	41	0.777	Romania	Sustainability	Costa rica

This paper manifested top five clusters with their labels extracted from the titles of publications lying in their matched cluster. The noteworthy third column in Table 1, "Silhouette", indicates the homogeneity of a cluster, the value of which is proportional to the degree of compactness of the cluster members, meaning the cluster members well matched with their cluster (Rousseeuw 1987).

As shown in Table 1, the largest cluster (0) within the network had 61 members and a silhouette value of 0.825. While both selection algorithms, the log-likelihood radio (LLR) and the term frequency–inverse document frequency (TF–IDF) labelled it as *industrial ecology*, the algorithm mutual information (MI) labelled it as an *approach*. The most active citer for this cluster was "Modelling for species and habitats: new opportunities for problem solving" (Leemans 1999). The second largest cluster (1) had 59 members and a silhouette value of 0.79. It was labeled as *sustainable development* by LLR, *environmental management* by TF-IDF, and *energy efficiency* by MI. The most active citer for this cluster was "Presidential address: sustainable development, the challenge" (Manning 1990). The third largest cluster (2), with 51 members and a silhouette value of 0.843, was labeled as an *ecosystem service* by both LLR and TF-IDF, and as *aquaculture development* by MI. The most active citer for the cluster was "Earth system governance: a research framework" (Biermann et al. 2010).

Roughly speaking, this outcome is more tend to socio-economics fields, which partly unveiled the different orientation between SD and sustainability science since the latter doesn't include the association with the human exploration of nature (Kajikawa et al. 2007).

Top five highly-cited papers was shown in Table 2. The top ranked item was "A safe operating space for humanity" (Rockström et al. 2009), located in cluster 2, with a citation

Table 2 The top five highly-cited publications

Freq.	References	Source publications	#
203	"A safe operating space for humanity" (Rockström et al. 2009)	Nature	2
120	"From a literature review to a conceptual framework for sustainable supply chain management" (Seuring and Müller 2008)	Journal of Cleaner Production	12
105	"Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change" (Searchinger et al. 2008)	Science	13
102	"The economics of climate change: the Stern review" (Stern 2007)	Cambridge University Press	4
97	"Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC (Vol. 4)" (Solomon 2007)	IPCC	11

count of 203. The second article was "From a literature review to a conceptual framework for sustainable supply chain management" (Seuring and Müller 2008), located in cluster 12, with a citation count of 120. The third article was "Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change" (Searchinger et al. 2008), which was located in cluster 13 and had a citation count of 105.

The analysis of high-cited references on SD research has been implemented more or less (Costanza et al. 2004; Ma and Stern 2006; Quental and Lourenço 2012; Markard et al. 2012; Buter and Van Raan 2013; Knowles et al. 2013; Linnenluecke and Griffiths 2013). This convey not only identified the highly-cited publications under the approach of citation counts, but also introduced two indicators to reveal pivotal and representative papers in the research structure of sustainable development.

It is noteworthy that some nodes (in Fig. 3) with purple rings circling the outer rim tended to be intellectual pivot nodes, meaning they bridged sub-domains of SD research. These papers usually had strong BC strength, representing the dominance in the specific research field. In Table 3, we listed top five ranked high BC papers. "Natural capital and sustainable development" (Costanza and Daly 1992), published in *Conservation Biology* and located in cluster 7, was the node with the highest BC value (0.39). "The value of the world's ecosystem services and natural capital" (Costanza et al. 1997), published in *Nature* in 1997 and located in cluster 7, ranked second with a BC value of 0.36. "A road map for natural capitalism" (Lovins et al. 1999), published in *Harvard Business Review* and located in cluster 0, ranked third with a BC value of 0.22.

Figure 4 depicted a cited reference network between 1987 and 2015 by using the function of the citation burst detection. CiteSpace highlights strong CB as a red inner ring within a node, indicating that citation of this document increased rapidly over a given time period. The size of the red rings represents the strength of its burst property.

Table 4 demonstrated a ranked list of high-CB publications based on the networks in Fig. 4, as well as the impact duration of the ranked publications, indicated by blue and red line segments in the column marked "Duration." The duration of the impact, as a time interval, is depicted as a blue line. The time period during which a paper was found to have a burst (CB) is shown as a red line segment, indicating the beginning and ending year of the duration of the burst.

As shown in Table 4, *Our Common Future*, also referred to as the *Brundtland Report* (WECD 1987), had the strongest CB (53.7413) during the period from 1988 to 1995. This result highlighted the significant impact of the *Brundtland Report*. "The value of the world's ecosystem services and natural capital" (Costanza et al. 1997) ranked second for

Table 3 The top five ranking high BC references

| BC	References	Source publications	#
0.39	"Natural Capital and Sustainable Development" (Costanza and Daly 1992)	Conservation Biology	7
0.36	"The value of the world's ecosystem services and natural capital" (Costanza et al. 1997)	Nature	7
0.22	"A road map for natural capitalism" (Lovins et al. 1999)	Harvard Business Review	0
0.20	"Sustainability Science" (Kates et al. 2001)	Science	3
0.19	"Toward some operational principles of sustainable development" (Daly 1990)	Ecological Economics	1
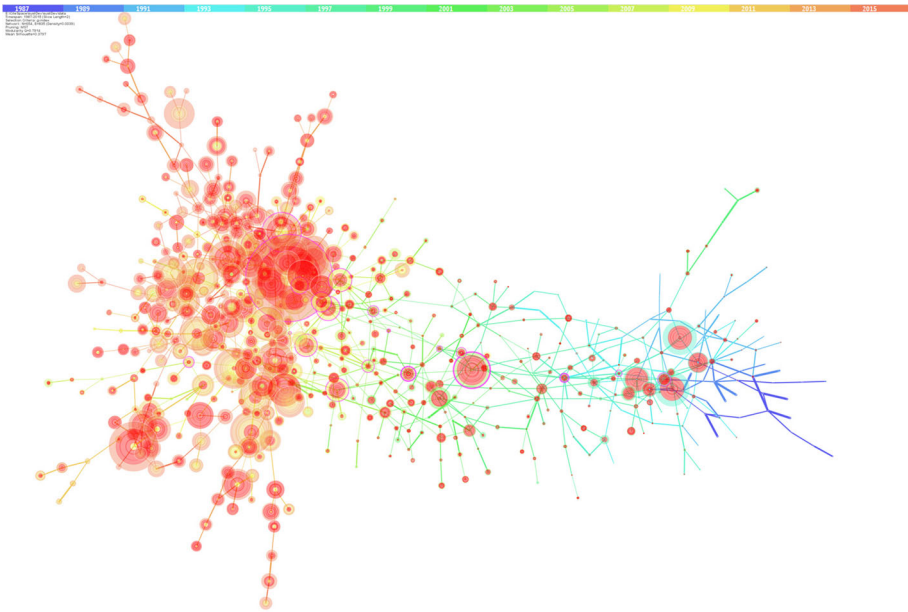
Fig. 4 The cited reference network with citation burst detection from 1987 to 2015. (Color figure online)

Table 4 The top five ranked publications by citation burst. (Color table online)

References	Citation Bursts		
	Strength	Year	Duration (1987–2015)
WCED (1987)	53.7413	1987	1988—1995
Costanza et al. (1997)	47.0051	1997	1998—2005
Pearce et al. (1989)	40.4881	1989	1991—1997
Rockström et al. (2009)	40.849	2009	2013—2015
Redclift (1987)	35.164	1987	1987—1994

CB strength (47.0051) from 1998 to 2005, while Pearce et al. (1989) ranked third (40.4881) from 1991 to 1997.

Instead of the humdrum on observing the variation of citation amount in the selected known famous articles, this convey preferred to detect the strength of both mentioned indicators to evaluate the individual value and impact of one paper. Since three tables represented different orientation, it is noteworthy that some papers are on both tables simultaneously. For instance, Rockström et al.'s (2009) work was listed on both Tables 2 and 4 and Costanza et al.'s (1997) paper was on both Tables 3 and 4. That phenomenon signified the strong impact and dominance of these papers in the SD research and more attentions should be drawn on them.

Based on outcomes above, the highest cited paper in our research was not same with the result from Quental and Lourenco (2012) in the light of the fact that we didn't exclude any

Table 5 The top 20 highly ranked cited journals with impact factors and countries of publication

Journal	Impact factors	Frequency	BC	Publishing Country
Science	33.611	6270	0.21	USA
Nature	41.456	4495	0.15	UK
Ecological Economics	2.72	4424	0.37	Netherlands
Energy Policy	2.575	3456	0.08	UK
Proceedings of the National Academy of Sciences of the United States of America	9.674	3120	0.15	USA
Cleaner Production	3.844	3081	0.03	UK
Environmental Management	2.723	2897	0.02	UK
World Development	1.965	2402	0.05	UK
Renewable & Sustainable Energy Reviews	5.901	2182	0.03	UK
Environmental Science & Technology	5.33	2110	0.05	USA
Energy	4.844	2018	0.02	UK
Global Environmental Change	5.089	1891	0.11	UK
Agriculture Ecosystems & Environment	3.402	1760	0.04	Netherlands
Ambio	2.289	1643	0.1	Norway
Biological Conservation	3.762	1594	0.13	UK
Landscape and Urban Planning	3.037	1571	0.01	Netherlands
Biosciences	2.064	1464	0.12	India
Renewable Energy	3.476	1441	0.01	UK
Academy of Management Review	7.475	1392	~	USA
Land Use Policy	2.631	1372	~	UK

record from out dataset. Given the truth of highest cited paper, combined with the ending year of its impact duration in Table 4, we conjectured that the burst of Rockström et al.'s (2009) would be lengthened in the recent future. Basically, we suggest those identified articles should earn the concentrations from researchers or institutes, especially who are devoted to investigating the literature review, evolution structure and research frontiers of sustainable development, after all sometimes it's not possible to forecast the whole citation network even though we have known some famous papers. In consideration of the shortcoming of statistics for citation counts and the subjective bias from individual academic, we highlighted the advantage of new approach and some results far away from our anticipations, which are the contributions this study attempted to support.

To be a complement, Table 5 showed the top 20 highly cited journals, with their impact factors and places (countries) of publication. *Science* had the highest citation frequency (6270). Its impact factors (33.61) and BC ratio (0.21) were also high. *Nature* ranked second, with the highest impact factors (41.456), along with a citation count of 4495, and a BC ratio of 0.15. It should be noted that the *Journal of Ecological Economics*, with a citation frequency of 4424, had the highest BC ratio (0.37), reflecting this journal's predominance in the history of SD research. Generally, most of the journals in the list are published in UK, with a few published in the United States and Netherlands.

Country-wise analysis

As a global issue, sustainable development has been tabled and featured as a priority within the national policies among many countries. Table 6 depicts the impacts of different countries on SD research. It shows the top 20 ranked high BC countries, along with citation counts and the start year of being cited. The BC value indicates the extent of a country's predominance and impact at the historical and macroscopic levels.

The United States clearly ranked first with a BC value of 0.20 and 6770 publications. This finding reveals the country's prominent position, globally, in relation to SD studies, commencing from 1987. UK was ranked second, with a BC value of 0.15 and 3758 references, followed by Netherlands with 1651 publications and a BC value of 0.14.

It is noteworthy that China had the highest publication count (10,463) but a BC value of just 0.03, which equaled with Sweden, Scotland, and Poland. It is difficult to explain why China was ranked lowest for its BC value, given the truth that SD research in China began in 1992.

In the sight of time dimension, with the assistance of CB detection, Table 7 was formulated to demonstrate the contribution to SD research from 20 top ranked countries.

As reflected in its highest CB strength (116.024), the United States showed a powerful and continuing impact on SD studies from 1987 up to 2001. UK followed with 101.701 during the period from 1997 to 2003. Given that their BC was the highest, as indicated in Table 6, the United States and UK evidently exhibited undisputed predominance and leadership in SD research. Zimbabwe was a record setter from 1990 to 2006 with a CB strength of 9.047.

Specifically, countries in Eastern Europe were behind but still closely followed the step of those in Western Europe and North America. This phenomenon triggered our interest in the temporal and spatial difference in the research orientation of sustainable development, especially given the less bibliometrics analysis on such issue. Perhaps we would explored this phenomenon further afterwards, but unfortunately, that's not what this paper focused on.

Despite the record of the highest publication counts (10,463), China did not feature in Table 7, which, to some degree, revealed that the publication count of a country was not proportional to its impact.

WoS provides ESI Top Papers as an option for refining search results to enable researchers to identify emerging research trends. We mapped D_{ESI}, (Fig. 5) using the

Table 6 Top 20 highly ranked BC countries with citation counts and start years

#	Country	BC	Counts	Start Year	#	Country	BC	Counts	Start year
1	USA	0.20	6770	1987	11	Canada	0.05	1955	1988
2	UK	0.15	3758	1998	12	Romania	0.04	1160	1996
3	Netherlands	0.14	1651	1990	13	New Zealand	0.04	374	1990
4	Australia	0.11	2304	1991	14	Denmark	0.04	440	1993
5	France	0.10	1405	1994	15	Belgium	0.04	515	1992
6	Spain	0.08	1292	1993	16	Austria	0.04	533	1992
7	Germany	0.08	2309	1990	17	Sweden	0.03	1000	1992
8	Italy	0.07	1586	1992	18	Scotland	0.03	541	1992
9	Switzerland	0.06	870	1992	19	Poland	0.03	625	1997
10	Portugal	0.06	522	1993	20	China	0.03	10463	1992

Table 7 Top 20 high CB countries with burst duration and publication counts. (Color table online)

Countries	Citation Bursts				Counts
	Strength	Begin	End	Duration (1987–2015)	
USA	116.024	1987	2001		6,770
UK	101.761	1997	2003		3,758
Canada	47.958	1988	2003		1,955
Malaysia	33.762	2012	2015		717
Romania	26.217	2009	2010		1,160
Lithuania	18.328	2006	2008		390
Latvia	16.333	2011	2013		197
Netherlands	14.650	1990	2003		1,651
Germany	14.623	2001	2002		2,309
Scotland	13.019	1996	2002		541
Japan	11.273	1999	2003		946
Serbia	9.502	2010	2012		216
Zimbabwe	9.047	1990	2006		55
Czech	8.801	2013	2015		314
Ukraine Republic	7.095	2006	2009		90
Kenya	7.068	1994	2002		187
Russia	6.830	1995	2003		246
Wales	6.340	1998	2004		242
Costa Rica	6.336	1990	1999		56
Hong Kong	6.333	1995	2000		10

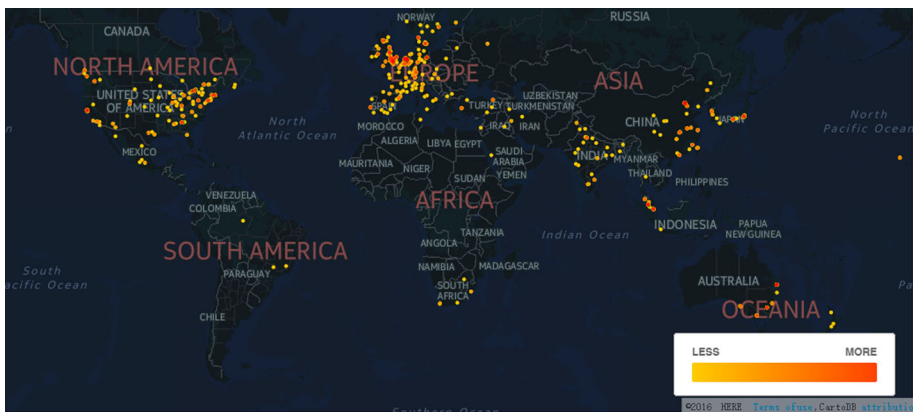**Fig. 5** A map based on D_{ESI}, showing the distribution of countries where SD research has been published

CartDB platform (https://cartodb.com/) to present a vivid depiction of the geographical distribution of publications. Figure 5 showed that most ESI top papers were published in Europe, North America, and the Far East, with some published in India and the Middle East and a few published in South Africa and Oceania. Figure 6 presented the detailed distribution of ESI papers in 10 countries from 2005 to 2015. It revealed that the top three positions for publication count were occupied by the United States (191), UK (98), and

Country	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
USA	5	8	4	10	15	21	17	30	33	31	17	191
England	5	3	3	7	4	14	8	12	17	12	13	98
China	1	0	2	2	2	7	9	14	15	18	14	84
Germany	2	2	4	4	0	13	4	7	13	11	8	68
Australia	0	1	3	2	1	7	3	13	9	11	5	55
Netherlands	1	0	0	4	2	9	3	10	9	7	4	55
Canada	3	3	3	2	4	6	5	8	6	7	6	53
France	1	0	2	3	5	7	5	5	9	2	4	43
India	0	0	0	0	3	5	3	7	5	6	5	34
Spain	1	0	0	3	2	5	6	4	3	6	3	33

Fig. 6 Distribution of ESI papers in the top ten ranked countries during the last decade

China (84), which indicated that these countries are likely to lead the SD research frontiers in the future.

In wake of the 2008 Beijing Olympic Games, the environmental awareness has been widely arisen in China, especially in the context of tremendous revolt against ecological damage caused by economic growth. Since the continued concentration and pressure on the environmental issue, the term "sustainable development" was re-picked up by scholars, civil society and decision makers, which partly interpreted China's performance in Fig. 6.

Category analysis

Disciplines related to sustainable development or sustainability science has been widely analyzed by many researchers (Kajikawa et al. 2007; Kajikawa 2008; Yarime et al. 2010; Schoolman et al. 2012; Bettencourt and Kaur 2011; Quental and Lourenço 2012; Hassan et al. 2014). Different from precedents, in this part, based on ISI subject categories, we would utilized both two mentioned indicators to investigate the outstanding disciplines.

Our dataset D_{ALL} entailed over 100 categories and each article was assigned to one or more subjects, according to the source journal. Table 8 listed the top 20 high BC subjects and revealed the extent of the role of each subject in SD research as well. As we can see, Engineering ranked first with a BC strength of 0.13 and a publication count of 11,467 starting from 1987, followed by Psychology with just 286 publications and the same BC strength (0.13), starting from 1989.

Environmental Science, which has the highest publication count (26,222) and a BC strength of 0.05, is not included in Table 8. Pediatrics, Radiology, Physiology, and Respiratory System, all of which had high-BC strength but low publication counts, evidently have been influential in SD research. However, the briefness of the duration of impact is inevitably associated with lower publication counts.

Not surprisingly, most of categories above have an affiliation with socio-economic pillar, forasmuch as the term "sustainable development" is leaned to "development" (WCED 1987) and economy is still accorded primacy in policy and decision making (Korten 2015; Monbiot 2013).

Most of the disciplines shown in Table 8 were introduced within the half decade that followed the publication of the *Brundtland Report*, especially those evidencing a high publication frequency, which consequently, failed to specify the influence and effect of time dimension.

Table 8 The top 20 highly ranked BC subjects with publication counts and start years

#	Subject	BC	Freq.	Year	#	Subject	BC	Freq.	Year
1	Engineering	0.13	11,467	1987	11	Physics	0.07	437	1991
2	Psychology	0.13	286	1989	12	Statistics & Probability	0.07	151	1995
3	Environmental Studies	0.1	6616	1987	13	Physiology	0.07	27	1992
4	Pediatrics	0.1	71	1996	14	Respiratory System	0.07	22	1993
5	Radiology	0.1	23	1994	15	Social Sciences	0.06	1284	1989
6	Social Issues	0.09	192	1987	16	Public	0.06	951	1991
7	Zoology	0.09	154	1992	17	Biochemistry & Molecular Biology	0.06	280	1996
8	Chemistry	0.08	1673	1989	18	Life Sciences & Biomedicine—Other Topics	0.06	233	1992
9	Computer Science	0.07	3026	1992	19	Pharmacology & Pharmacy	0.06	198	1994
10	Materials Science	0.07	2435	1991	20	Immunology	0.06	91	1993

To elaborate on the temporal impact, Table 9 manifests the precise disciplinary impact duration in detail with the help of citation burst detection and a total of 20 disciplines are listed in descending order of CB strength.

As shown above, Materials Science was ranked first from 2013 to 2015, with a remarkable CB strength of 253.798. Given the duration and high CB strength of this discipline, we forecast that the time span of the burst will likely extend into the future. Operation Research & Management Science ranked second, with a CB strength of 200.637 from 2007 to 2010, followed by Management with a CB strength of 146.164 from 2007 to 2011. The latter displayed similar characteristics in terms of its designation and the time span of its impact to those of the discipline ranked second.

It is noteworthy that the burst durations of seven disciplines occurred within the last decade. These disciplines were Materials Science, Operation Research & Management Science, Management, Social Sciences, Business, and Computer Science. To be further, Table 10 listed 10 CB subjects whose impact durations end recently.

In this part, we utilized a different approach to investigate the emerging trends and clearly represent the impact duration of contribution from different disciplines in the time dimension, which complement the current status of study in sustainable development.

We want to emphasize the outcome above vividly reveals the disciplinary frontiers in SD studies especially the remarkable Materials Science and Social Sciences with an unbelievably high CB strength of 253.798 and 252.605 (120.207 + 132.398) respectively. The result is evidentially helpful to decision makers in resource allocation in consideration of immense disciplinary bias from politicians in the context of China. Where worthy to note are Social Sciences and Social Sciences—Other Topics, the listed items in Tables 9 and 10. We didn't inspect the discrepancy of both and it might illustrate why the ISI category classification is not well to conduct bibliometrics analysis in interdisciplinary areas (Pudovkin and Garfield 2004; Leydesdorff and Opthof 2010; Hassan et al. 2014). However, interdisciplinary analysis was not the attention we preferred to pay in this paper.

Table 9 Top 20 highly ranked CB disciplines with burst duration and publication counts. (Color table online)

Subject	Citation Bursts				Counts
	Strength	Begin	End	Duration (1987-2015)	
Materials Science	253.798	2012	2015		2,435
Operations Research & Management Science	200.637	2007	2010		1,724
Management	146.164	2007	2011		4,102
Social Sciences	132.398	2013	2015		1,284
Water Resources	128.996	1995	2005		3,046
Social Sciences - Other Topics	120.207	2013	2015		2,360
Urban Studies	87.798	2002	2006		1,613
Business	83.546	2007	2010		3,021
Computer Science	83.505	2008	2009		3,026
Ecology	70.265	1998	2001		2,926
Agriculture	67.063	1996	2001		3,777
Forestry	60.442	1990	2004		994
Education & Educational Research	55.589	2010	2013		1,877
Hospitality	48.132	2010	2012		949
Planning & Development	46.975	1987	1997		3,072
Telecommunication	45.392	2007	2008		352
Soil Science	44.213	1998	2003		558
International Relations	43.553	1987	1999		523
Economics	40.065	2007	2008		3,914
Sociology	39.927	1988	2004		671

Table 10 Disciplines with burst durations ending in 2015, based on the dataset D_{ALL}. (Color table online)

Subject	Citation Bursts			
	Strength	Begin	End	Range (1987-2015)
Materials Science	253.798	2012	2015	
Surgery	3.668	2013	2015	
Immunology	4.096	2013	2015	
Biochemical Research Methods	9.142	2013	2015	
Research & Experimental Medicine	4.891	2013	2015	
Arts & Humanities - Other Topics	17.609	2013	2015	
Social Sciences - Other Topics	120.207	2013	2015	
Social Sciences	132.398	2013	2015	
Polymer Science	4.743	2013	2015	
Humanities	15.980	2013	2015	

Additionally, other subjects should be focused as well. For instance, Management, Chemistry, and Computer Science are featured in both Tables 8 and 9, and their bursts occurred during the last decade.

Keyword analysis

Keywords can provide information about the core content of articles. Therefore, keyword analysis can be used to identify evolving research frontiers relating to a knowledge domain (He 1999). Given the gap of keyword analysis in SD study, this part should be the most important contribution of this convey.

Based on D_{ALL}, a keyword co-occurrence network was generated under the minimum spanning tree algorithm. The merged network as shown in Fig. 7, consisted of 584 nodes and 1888 links, each node representing one keyword, and its size was proportional to the co-occurrence frequencies. The keywords network was divided into nine co-citation clusters, labeled with index terms (noun phrases) extracted from the titles of the publications which belonged to this cluster. What we sought to in this part is to identify the real valuable keywords and unveil citation links of keywords in promising papers derived from dataset D_{ESI}.

The detection intensity of both BC and CB provided by CiteSpace are accurate up to four decimal places, which means a large number of keywords should be listed in this part if we presented them all (267 keywords with BC values and 161 keywords with CB strengths). While listing them in two separate tables would be easy, this is not an economical option. Unlike disciplinary analysis, there lies high possibility that most of keywords with high CB strength would fail to be listed in the high BC table if we just showed the top ranked keywords, and vice versa. Moreover, in our definition, the qualified valuable keywords should perform better in both high BC list and high CB list. Even though we
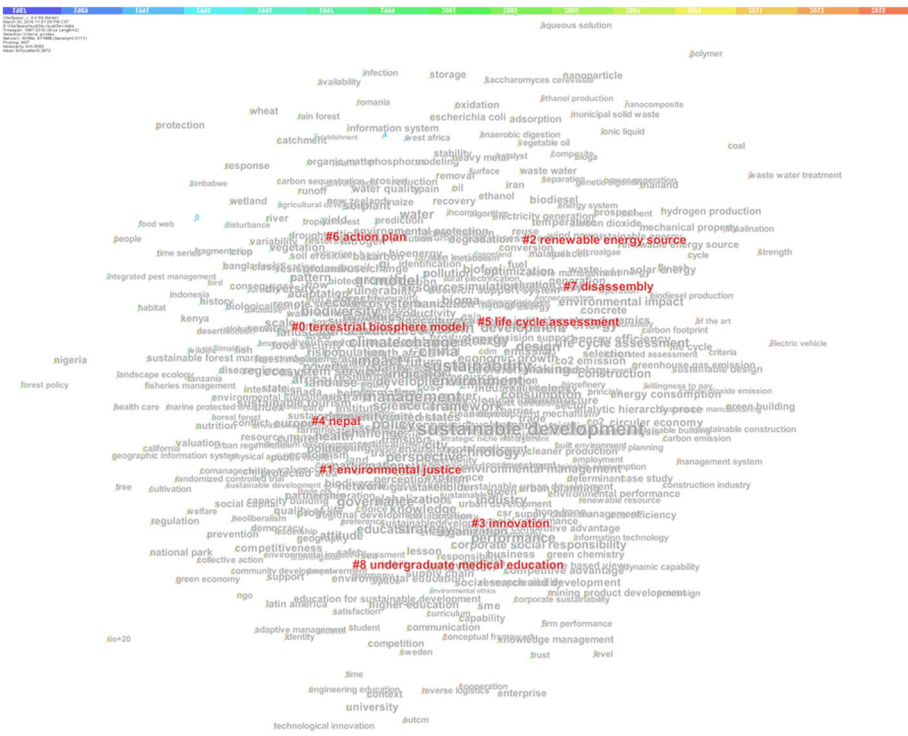

Fig. 7 Keyword co-occurrence network with 584 notes and 1888 lines

cannot deny it is an important keywords, it's still hard to exist in the context of above definition if a keyword just have a high BC strength but extremely low CB strength especially in consideration of that a keyword should be features by both two indicators.

To be specific, the CB detection algorithm focused more on each time slot (each year), revealing the burst strength of a keyword. However, it did not consider the important role and dominance of a keyword throughout a whole network. The BC algorithm could compensate for CB's deficiency, as it focuses on the entire network when selecting a keyword that is important and highly weighted across the entire Web. In other word, the CB detection algorithm has a better performance in revealing the burst strength of a keyword in the time dimension. If a keyword has a high CB strength, then it probably is the promising node which to some extent stands for the emerging trends in a specific field. The BC algorithm focused on the whole structure network to investigate dominant and highly weighted keywords which are usually the backbone nodes in the web.

Some keywords with low BC values may have the capacity to reveal the frontiers of one specific research field because of their high CB strength. However, they are likely to be located on the edge of networks, or as minor branches of a specific field. From the perspective of the entire Web, those keywords contribute less to network's backbone, and hence, have shortness in drawing attentions from the public, decision maker and even researchers. To display the advantages of both the BC and CB algorithms simultaneously, we decided to multiply BC by CB to obtain a new indicator (BC × CB) to represent the dominant and contemporary impact of a keyword.

After computing the value of BC × CB of all keywords derived from Fig. 7, Table 11 shows the results of the top 25 keywords in second column and their impact duration of citation burst. In this paper we define them "valuable keywords".

The keyword *resource* ranked highest, with a strength of 26.4125 and the CB impact duration from 1991 to 2000, followed by *development* (21.888), *agriculture* (19.734), *conservation* (16.8084) and *population* (16.3152). *Sustainable development* recorded the highest citation frequencies (8576) and secondly highest CB impact of 91.17 but failed to be listed in Table 11 with a mere BC × CB value of 0.9117.

We suggested those valuable keywords should be strongly focused by academics, citizens and politicians as we believe it provides a perspective to construct concept network on SD, and further, to achieve the consensus on the recognition of sustainable development, because we sincerely insist that all definitions or concepts related to SD should be connected in order to prompt the practice on the issue of SD. Additionally, in light of the keyword's better performance in the spread of concepts compared to other linguistic forms, Valuable keywords are useful in the aspect of communication and education on sustainable development.

Nevertheless, we need to emphasize there still lies some problems here. Since values of BC and CB provided by CiteSpace were only accurate up to four decimal places, which means it has a probable chance that some keyword with high BC strength but very low CB value (maybe 0.00001) or in a reverse situation, would be excluded by this application. Moreover, we don't know whether this new indicator was applied or analyzed already, therefore we couldn't provide any empirical research here.

How the keyword cites, or is cited by, other articles is anther interest we sought to explore in this research. Here, a web application (http://www.mapequation.org/apps/MapGenerator.html), called map generator, was utilized to display a weighted map showing the strength of its constituent modules. The algorithm of this application was developed by Rosvall and Bergstrom (2008). Every module in the map represents a cluster of nodes, and the weighted and directed links between modules represent the citation flow

Table 11 The top ranked 25 "valuable keywords" with the impact duration of CB. (Color table online)

Keyword	Indicators				Freq.
	BC × CB	BC	CB	CB Duration (1987-2015)	
Resource	26.4125	1.25	21.13	1991 — 2000	517
Development	21.888	0.95	23.04	1992 — 2000	595
Agriculture	19.734	0.6	32.89	1987 — 2006	643
Conservation	16.8084	0.42	40.02	1991 — 2005	1,106
Population	16.3152	0.66	24.72	1993 — 2006	355
Sustainable	14.0844	0.97	14.52	1993 — 2005	328
Environment	13.286	0.14	94.9	1991 — 2006	1,422
Ecology	10.5938	0.46	23.03	1991 — 2005	415
Biodiversity	8.94	0.24	37.25	1991 — 2004	828
Management	6.4344	0.84	7.66	1991 — 2005	2,760
Biological control	4.3836	0.52	8.43	2005 — 2008	92
Ecosystem	3.8379	0.11	34.89	1997 — 2006	433
Pollution	3.395	0.5	6.79	1991 — 1998	278
Economics	3.3594	0.11	30.54	1992 — 2007	267
Community	3.2165	0.35	9.19	2002 — 2004	550
Ecological economics	3.0906	0.17	18.18	1995 — 2007	66
Deforestation	2.984	0.16	18.65	1991 — 2005	240
Policy	2.8288	0.52	5.44	1997 — 1999	1,483
Growth	2.713	0.1	27.13	1991 — 2004	944
Fishery	2.4724	0.28	8.83	2001 — 2005	206
Sustainable agriculture	2.3322	0.06	38.87	1993 — 2003	326
Environmental policy	2.0916	0.18	11.62	1994 — 2006	234
Aquaculture	1.9872	0.32	6.21	1993 — 2002	175
Water resource	1.751	0.05	35.02	1999 — 2007	288
Hydropower	1.7172	0.36	4.77	2001 — 2002	72

and relationship between them. The color and width of the arrows indicate the flow volume. The physical size of each module reflects the fraction of time spent at a node by a random walker following citations within the module and arrows between modules points in the direction of a citation, for example, A → B, indicates that "A cites B" (Rosvall and Bergstrom 2008).

Figure 8 was created using the map generator to demonstrate the citation relationship between modules consisted by hot keywords in dataset D_{ESI}. The weight map revealed a structure that all modules were connected to each other by chains of citations. The thick arrow in the midst of CO_2 *emission* and *country* indicated substantial traffic in citation between both of them. Other pairs entailing arrows with a notable width included: *community* and *adaptive capacity*, *waste* and *waste water*, *soil quality* and *spatial variability*, *impact assessment* and *management*, *model* and *system*, *model* and *emission*, CO_2 *emission* and *emission*, and *supply chain management* and *environmental management*.

It is worthy to note that these connections were not always direct, because modules on opposite sides were only linked through intermediate modules (Rosvall and Bergstrom 2008). For instance, although *model* rarely cited *country* or vice versa, *model* and *country* were connected via strong links to and between the intermediaries: *model* → *emission* → *environmental impact* → CO_2 *emission* → *country*.
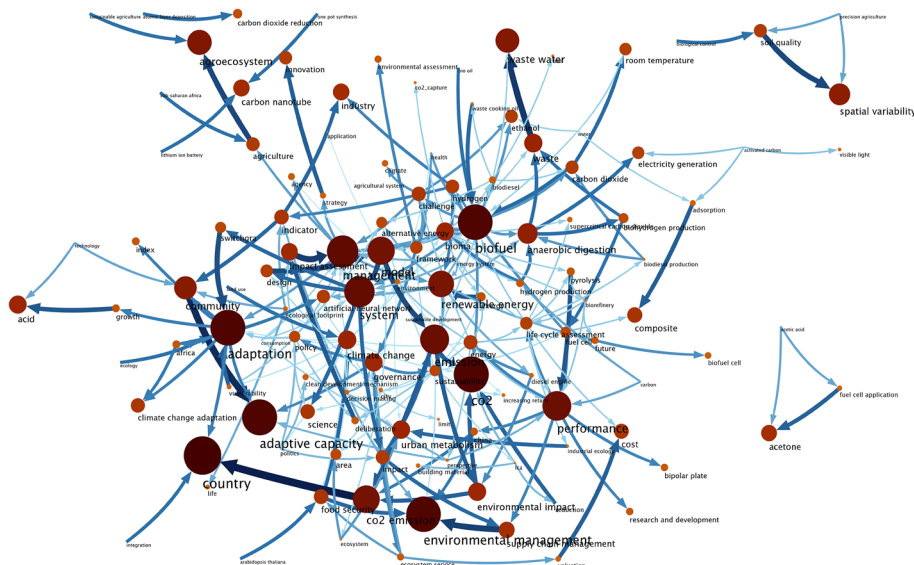
Fig. 8 Weighted map of keywords based on citation patterns

This map provides a view of keyword to screen how the concepts related to sustainable development were connected, and moreover, it gives us a perspective to contemplate the correlation among those keywords: whether the appearance of some keyword was caused by other keyword, in particular the one cited by it?

Mostly, keywords analysis is an available way to reveal the research frontiers (He 1999). Based on the dataset D_{ESI} as well as the support from the VOSviewer, a heat map (Fig. 9) was given to show the "hot" emerging areas of SD research. Each point on the map is associated with a color located within the spectrum ranging between red and blue,
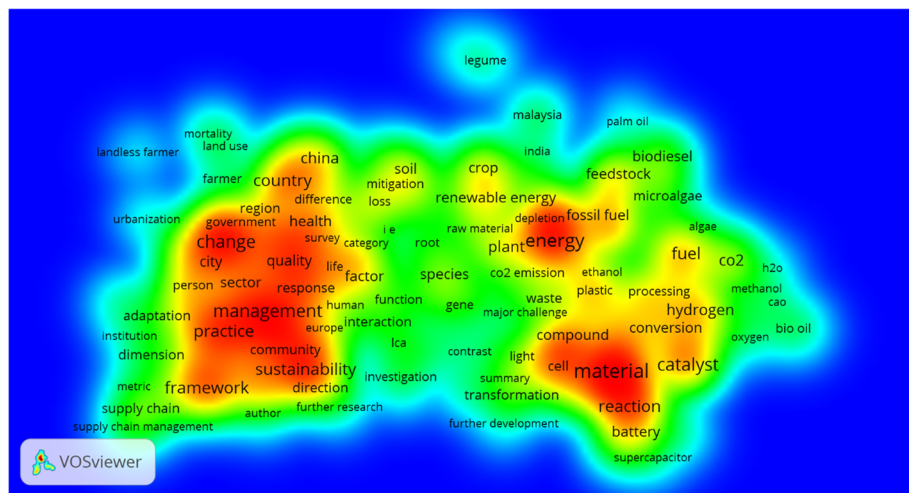
Fig. 9 Heat map of keywords based on D_{ESI} and supported by VOSviewer. (Color figure online)

which depends on the density of items at that point. By default, the greater the number of items in proximity to a point, and the greater their weights, the closer the color of the point will be to red. Conversely, the smaller the number of items around a point, and the lower their weights, the closer the color of the point will be to blue. As we can see, there are three hot areas in the map representing the following topics: management, change, practice, energy, and material.

It should be noted that two hot areas, energy and material, were connected. This connection indicates that SD researchers are paying more attention to renewable and sustainable material and energy which are evident research frontiers. Moreover, because of urbanization and modernization, management and practice, in the context of sustainable development or sustainability science, are becoming attractive terms for decision makers within governments.

Conclusion and implication

As a worldview, sustainable development spans nearly 30 years and its concept has gradually extended on almost every aspect of our lives. Even though the basis of official definition has been criticized as being vague and lacking operability (Woods 2002; Revkin 2002), it still provides us a platform for raising constructive questions and reaching an ideological consensus.

In this paper, we utilized two datasets, D_{ALL} (59,926 items) and D_{ESI} (626 items), both obtained from ISI Web of Science of Thomson Reuters. We introduced two indicators to identify and feature the highlighted references, countries, categories and keywords to explore a visible landscape of sustainable development and meanwhile the evolution structure and research frontiers were represented as well.

According to the outcome from co-cited reference analysis, publications under sustainable development roughly manifested a phenomenon of socio-economic orientation. Rockström et al.'s (2009) study evidenced the most citations, with a record of 203 counts and a CB strength of 40.849 within Fig. 3. WCED's (1987) report, *Our Common Future*, has evidently been highly influential in the history of SD studies, recording the highest CB impact (53.7413). Based on the new approach, we have a chance to re-evaluate the highlighted papers instead of counting the citations, which is the contribution we supported in this part. Notably, as shown in Table 3, "nature capital" has significantly contributed to the theory and concept of sustainable development. This result give Chinese politician an alert when to interpret the concept of sustainable development in the context of China.

In Addition, most journals engaged with research on sustainable development are published in the United States, UK, and Netherlands. Based on our examination of the dataset D_{ALL}, *Nature* had a citation frequency of 4495 and a BC strength of 0.15, with the highest impact factor (41.456), and *Science* had the highest citation frequency of 6270 and a high impact factor (33.611).

In the section of country analysis, the United States dominates sustainable development research, evidenced by the highest BC value (0.20), the highest CB value (116.024) and the highest number of ESI publications (191). UK followed with a BC strength of 0.15, a CB value of 101.761, and 98 ESI papers. Although China accounted for the highest number of publications (10,463) and an impressive number of ESI publications (84), it recorded a low BC value (0.03) and did not feature in Table 7 (citation bursts). Moreover, we found performances from Eastern Europe are closed coming after countries in Western Europe and North America. This phenomenon trigger our interest in the temporal and spatial

difference, which we believed, should be strongly focused, especially in consideration of the different measures resorted by different countries to achieve sustainable development goals and the urgent need in the achievement of international consensus on policy decisions on the agenda, or even the pact, related to sustainable development. Additionally, it would support a helpful hand to look for the available corporation countries in the aspect of policy making on the field of sustainable development.

In spite of numerous efforts having been taken in disciplinary analysis, however, some new results still be found in this part. Generally, most of categories have an affiliation with socio-economic pillar. Engineering recorded the highest BC value (0.13) with 11,467 papers, followed by Psychology (286 publications) with the same BC strength and Environmental Studies (6616) attached a BC strength of 0.1. Materials Science and Operations Research & Management Science recorded surprisingly high CB values of 253.798 from 2012 to 2015 and 200.637 from 2007 to 2010, respectively. Moreover, as shown in Table 10, Materials Science with a CB value of 253.798 and Social Sciences with a CB value of 132.398 emerged as two promising disciplines (or fields) that revealed precisely where the frontiers of sustainable development lie. The results above provided directions to policy makers in allocating the fiscal finance on education and scientific research. Especially, Social Sciences should be valued more according to outcome mentioned in Table 10, forasmuch as there doesn't exist a common definition of sustainable development right now.

Keyword analysis is the big contribution we could provide in this paper. We underlined the valuable keywords, the citation network of keywords and hotspots in Table 11, Figs. 8 and 9 respectively. To summarize, *resource*, *agriculture* and *ecosystem* stand out in Table 11, *management*, *change*, *energy*, and *material* are vividly evidenced in the heat map (Fig. 9), and a prominent link: *model* → *emission* → *environmental impact* → CO_2 *emission* → *country* is highlighted in Fig. 8.

Remarkably, we want to emphasize the valuable keywords acquired based on the application of a new indicator (BC × CB). Those valuable keywords are both backbone nodes and promising nodes in the entire keyword network, which should be strongly focused by academics, civil folks and politicians. Moreover, it provides a practical approach to construct concept networks on SD and contribute to the integration of SD researches. To be a complement, the weighed map (Fig. 8) gives us a keyword perspective to screen how SD concepts are connected and prompt our wonder: whether the appearance of some keyword was caused by other keyword, in particular the one cited by it? Again, unfortunately, we did not make it to explore further since that is not what this article wants to concentrate.

Sustainable development provides us a unique opportunity to observe and reconsider the relationship between human and nature. In this paper, we used bibliometrics methods to conduct a quantitative visual study of SD research and we hope it would be useful to who concerned about the issues of sustainable development. Some questions are discussed above and some are not. Those questions are the directions we wish to explore further.

References

Bettencourt, L. M., & Kaur, J. (2011). Evolution and structure of sustainability science. *Proceedings of the National Academy of Sciences, 108*(49), 19540–19545.

Biermann, F., Betsill, M. M., Gupta, J., Kanie, N., Lebel, L., Liverman, D., et al. (2010). Earth system governance: A research framework. *International Environmental Agreements: Politics, Law and Economics, 10*(4), 277–298.

Brown, B. J., Hanson, M. E., Liverman, D. M., & Merideth, R. W., Jr. (1987). Global sustainability: Toward definition. *Environmental Management, 11*(6), 713–719.

Buter, R. K., & Van Raan, A. F. J. (2013). Identification and analysis of the highly cited knowledge base of sustainability science. *Sustainability Science, 8*(2), 253–267.

Callicott, J. B., & Mumford, K. (1997). Ecological sustainability as a conservation concept. *Conservation Biology, 11*(1), 32–40.

Chen, C. (2005). The centrality of pivotal points in the evolution of scientific networks. In *Proceedings of the 10th international conference on intelligent user interfaces*. Association for Computing Machinery (ACM) (pp. 98–105).

Chen, C. (2006). CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *Journal of the American Society for Information Science and Technology, 57*(3), 359–377.

Chen, C., Hu, S., Liu, S., & Tseng, H. (2012). Emerging trends in regenerative medicine: A scientometric analysis in CiteSpace. *Expert Opinion on Biological Therapy, 12*(5), 593–608.

Costanza, R., d'Arge, R., de Groot, R., Farberk, S., Grasso, M., Hannon, B., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature, 387*, 253.

Costanza, R., & Daly, H. E. (1992). Natural capital and sustainable development. *Conservation Biology, 6*(1), 37–46.

Costanza, R., Stern, D., Fisher, B., He, L., & Ma, C. (2004). Influential publications in ecological economics: A citation analysis. *Ecological Economics, 50*(3), 261–292.

Daly, H. E. (1990). Toward some operational principles of sustainable development. *Ecological Economics, 2*(1), 1–6.

Denters, E. (2001). A. Boyle; D. Freestone, eds., International law and sustainable development: Past achievements and future challenges, Oxford University Press, Oxford 1999, xxx + 377 pp. ISBN 0-19-829807-2. *Netherlands International Law Review, 48*(01), 101–103.

Dovers, S. R., & Handmer, J. W. (1993). Contradictions in sustainability. *Environmental Conservation, 20*(03), 217–222.

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

Freeman, L. (1977). A set of measures of centrality based on betweenness. *Sociometry, 40*(1), 35–41.

Goodland, R. (1995). The concept of environmental sustainability. *Annual Review of Ecology and Systematics, 26*, 1–24.

Hassan, S. U., Haddawy, P., & Zhu, J. (2014). A bibliometric study of the world's research activity in sustainable development and its sub-areas using scientific literature. *Scientometrics, 99*(2), 549–579.

He, Q. (1999). Knowledge discovery through co-word analysis. *Library Trends, 48*(1), 133.

Hopwood, B., Mellor, M., & O'Brien, G. (2005). Sustainable development: Mapping different approaches. *Sustainable Development, 13*(1), 38–52.

Kajikawa, Y. (2008). Research core and framework of sustainability science. *Sustainability Science, 3*(2), 215–239.

Kajikawa, Y., Ohno, J., Takeda, Y., Matsushima, K., & Komiyama, H. (2007). Creating an academic landscape of sustainability science: An analysis of the citation network. *Sustainability Science, 2*(2), 221–231.

Kates, R., Clark, W. C., Hall, J. M., Jaeger, C., Lowe, I., McCarthy, J. J., et al. (2001). Sustainability science. *Science, 292*(5517), 641–642.

Kates, R. W., Parris, T. M., & Leiserowitz, A. A. (2005). What is sustainable development? Goals, indicators, values, and practice. *Environment (Washington DC), 47*(3), 8–21.

Kleinberg, J. (2003). Bursty and hierarchical structure in streams. *Data Mining and Knowledge Discovery, 7*(4), 373–397.

Knowles, B., Blair, L., Hazas, M., & Walker, S. (2013, September). Exploring sustainability research in computing: where we are and where we go next. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing* (pp. 305–314). ACM.

Korten, D. C. (2015). *When corporations rule the world*. San Francisco: Berrett-Koehler Publishers.

Leemans, R. (1999). Modelling for species and habitats: New opportunities for problem solving. *Science of the Total Environment, 240*(1), 51–73.

Leydesdorff, L., & Opthof, T. (2010). Normalization at the field level: Fractional counting of citations. arXiv preprint arXiv:1006.2896.

Linnenluecke, M. K., & Griffiths, A. (2013). Firms and sustainability: Mapping the intellectual origins and structure of the corporate sustainability field. *Global Environmental Change, 23*(1), 382–391.

Lovins, A. B., Lovins, L. H., & Hawken, P. (1999). A road map for natural capitalism. *Harvard Business Review, 77*(3), 145–158.

Ma, C., & Stern, D. I. (2006). Environmental and ecological economics: A citation analysis. *Ecological Economics, 58*(3), 491–506.

Manning, E. W. (1990). Presidential address: Sustainable development, the challenge. *The Canadian Geographer, 34*(4), 290–302.

Markard, J., Raven, R., & Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. *Research Policy, 41*(6), 955–967.

Monbiot, G. (2013). *Captive state: The corporate takeover of Britain*. Hants: Pan Macmillan.

Pearce, D. W., Markandya, A., & Barbier, E. (1989). *Blueprint for a green economy*. London: Earthscan Publications Ltd.

Pudovkin, A. I., & Garfield, E. (2004). Rank-normalized impact factor: A way to compare journal performance across subject categories. *Proceedings of the American Society for Information Science and Technology, 41*(1), 507–515.

Quental, N., & Lourenço, J. M. (2012). References, authors, journals and scientific disciplines underlying the sustainable development literature: A citation analysis. *Scientometrics, 90*(2), 361–381.

Rafols, I., & Meyer, M. (2010). Diversity and network coherence as indicators of interdisciplinarity: case studies in bionanoscience. *Scientometrics, 82*(2), 263–287.

Redclift, M. (1987). The production of nature and the reproduction of the species. *Antipode, 19*(2), 222–230.

Redclift, M. (1992). The meaning of sustainable development. *Geoforum, 23*(3), 395–403.

Revkin, A. C. (2002, August 20). Forget nature. Even Eden is engineered. *The New York Times*. Retrieved from http://www.nytimes.com/2002/08/20/science/earth/20MANA.html. Accessed 26 May 2016.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., et al. (2009). A safe operating space for humanity. *Nature, 461*(7263), 472–475.

Rosvall, M., & Bergstrom, C. T. (2008). Maps of random walks on complex networks reveal community structure. *Proceedings of the National Academy of Sciences, 105*(4), 1118–1123.

Rousseeuw, P. J. (1987). Silhouettes: A graphical aid to the interpretation and validation of cluster analysis. *Journal of Computational and Applied Mathematics, 20*, 53–65.

Schoolman, E. D., Guest, J. S., Bush, K. F., & Bell, A. R. (2012). How interdisciplinary is sustainability research? Analyzing the structure of an emerging scientific field. *Sustainability Science, 7*(1), 67–80.

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., et al. (2008). Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science, 319*(5867), 1238–1240.

Seuring, S., & Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production, 16*(15), 1699–1710.

Shearman, R. (1990). The meaning and ethics of sustainability. *Environmental Management, 14*(1), 1–8.

Small, H. (1973). Co-citation in the scientific literature: A new measure of the relationship between two documents. *Journal of the American Society for Information Science, 24*(4), 265–269.

Solomon, S. (Ed.). (2007). *Climate change 2007—the physical science basis: Working group I contribution to the fourth assessment report of the IPCC* (Vol. 4). New York: Cambridge University Press.

Stern, N. (2007). *The economics of climate change: The Stern review*. Cambridge: Cambridge University Press.

Thelwall, M., Vann, K., & Fairclough, R. (2006). Web issue analysis: An integrated water resource management case study. *Journal of the American Society for Information Science and Technology, 57*(10), 1303–1314.

Wackernagel, M., & Rees, W. (1998). *Our ecological footprint: Reducing human impact on the earth (No. 9)*. Gabriola Island: New Society Publishers.

Woods, D. (2002). *Sustainable development: A contested paradigm. Birmingham*. Cologny, UK: Economics Forum of the Foundation for Water Research.

World Commission on Environment and Development (WCED). (1987). *Our common future*. Oxford: Oxford University Press.

Xu, L., & Marinova, D. (2013). Resilience thinking: A bibliometric analysis of socio-ecological research. *Scientometrics, 96*(3), 911–927.

Yang, L., Chen, Z., Liu, T., Gong, Z., Yu, Y., & Wang, J. (2013). Global trends of solid waste research from 1997 to 2011 by using bibliometric analysis. *Scientometrics, 96*(1), 133–146.

Yarime, M., Takeda, Y., & Kajikawa, Y. (2010). Towards institutional analysis of sustainability science: A quantitative examination of the patterns of research collaboration. *Sustainability Science, 5*(1), 115–125.