A scientometric analysis of worldwide soil carbon stocks research from 2000 to 2014

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To understand the history and research status of soil carbon stocks, we collected soil carbon stocks citation data from the Science Citation Index Expanded during the period from 2000 to 2014. Next, we used HistCite to analyse the yearly output, country, institution, citation impact and citation relationships in the field. Results suggested that the research of soil carbon stocks has been steadily increasing during the studied 15-year period. The country with the highest research output was USA, and the institution with the highest research output was the Chinese Academy of Sciences. Majority of articles and the highest total location citation score (TLCS) values came from developed countries. Also, developed countries have more research advantages in this field than developing countries. The top three outputs journals were Soil Biology and Biochemistry, Global Change Biology, and Geoderma, whereas the top three TLCS journals were Global Change Biology, Soil Biology and Biochemistry, and Soil Science Society of America Journal. Articles published with higher TLCS values had a greater impact in the field of soil carbon stocks and played an important role in research trends.

Keywords: Research output, scientometrics, soil carbon stocks, visualization analysis.

GLOBAL climate change is a major environmental issue in the modern era, and evidence supporting it continues to grow[1]. Carbon dioxide (CO_2) is known to be the most important among the greenhouse gases (GHGs). Soils play a critical role in reducing atmospheric C concentrations by taking CO_2 out of the atmosphere and storing it in 'sinks', or storage compartments. Approximately 40% of global soil C stocks reside in forest ecosystems[2]. Since the year 2000, academic institutions and researchers around the world have contributed a large volume of work to the field of soil carbon stocks. In this article, we analyse research outputs and citations with the HistCite tool to understand research development trends and the current status of this field. In the sections that follow, we demonstrate the relationships between citations and summarize research trends.

Methodology

We first retrieved all research on soil carbon stocks via the *Science Citation Index Expand* (*SCIE*). We searched using phrases 'soil carbon pool', 'soil carbon storage' or 'soil carbon stocks' on 27 April 2015. Our search yielded 10,737 records made up of several document types, including journal articles, conference proceedings, reviews, editorial materials and letters. The data were exported into a text-based format via the *Web of Knowledge* website, then imported into HistCite and analysed[3]. The output and citations for each year[4], country, institution and journal were summarized; further, we analysed high-impact articles, high-impact authors and research trends.

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Results and discussion

Document type and language

There were 11 document types identified in the 10,737 records. Most documents were journal articles, which accounted for 91% of the total records, indicating that these are the main mode for scientific communication involving soil carbon pool. Proceedings papers and reviews were two other important modes to publish academic achievements in this field of research.

Papers were written in 12 languages, of which English dominated, comprising 97.8% of the total records. A reason for this might be that journals indexed by *SCIE* are primarily published in English. Furthermore, English is accepted as the international language for researchers around the world.

Yearly research output

Figure 1 shows research output each year from 2000 to 2014, according to data collected by us on 27 April 2015. During this 15-year period, the overall trend has been a steady increase of yearly output, though the number of records in the years 2001 and 2009 decreased slightly. Results also revealed that the theme of soil carbon stocks was consistently the focus of scholars and has developed at an increasingly rapid rate during the past 15 years.

Country-based distribution of research output and citations

Analysis of the country-based distribution of research can help us understand the capacity of a country and explore the capacity differences among various countries. A total of 133 countries, accounting for 68.9% of all countries, contributed to the research output of soil carbon stocks, indicating that this topic attracted a broad array of attention from all around the world. From Table 1 it can be seen that the top five countries were USA, the People's Republic (PR) of China, Germany, the UK and Canada; their published papers captured 74.6% of the total output. These countries, except the PR China, are developed countries aiming to reduce carbon emissions.

However, the PR China has also developed plans to deal with its carbon emission problems. More specifically, the PR China intends to achieve the peaking of CO_2 emissions around 2030 and to make best efforts to peak early, and also intends to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030 (ref. 5). To reduce carbon emissions, the PR China has stepped up development of its renewable and unconventional energy resources in recent years. It plans to make its annual coal-bed gas production reach 40 billion cubic metres by 2020 (ref. 6). The government has also made efforts to improve environmental awareness among the Chinese against a backdrop of energy- and resource-intensive development patterns[7]. Soil carbon stocks closely related to carbon emission reductions are naturally becoming the focus of the academic community.

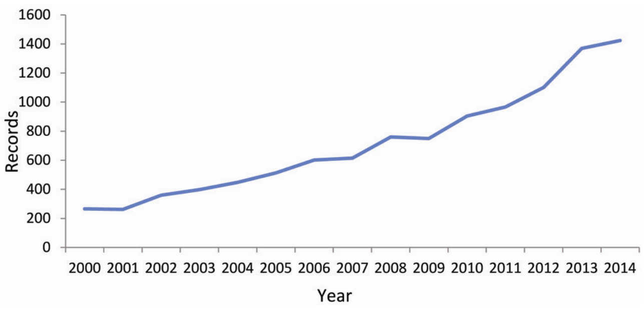

Figure 1. Yearly research output of soil carbon stocks from 2000 to 2014.

Citations can reflect the academic impact of published papers. In this study, we selected total location citation score (TLCS) as the indicator to measure the total academic influence among these countries. As Table 1 showed, USA, which had the most published papers, had the most citations. Its 31,088 citations comprised 35% of the total citations. Second was Germany, which had only 1034 published papers that contributed 6989 citations. Following USA and Germany were the UK, Canada and the PR China, with 6186, 5030 and 4744 citations respectively. Except for the PR China, the countries having high citation outputs were all developed countries.

Among the 12 countries with TLCS values more than 1500, there were 10 developed countries and 2 developing countries (the PR China and Brazil). The 10 developed countries had a total TLCS value of 65,664, more than eight times that of the two developing countries. It is thus clear that the developed countries had superior influence in the research of soil carbon storage.

TLCS represents the total academic influence of a certain country, but it cannot indicate the individual influence of a published paper. We therefore used the average number of paper citations as an indicator to analyse the influence of a paper. With regard to research output and academic impact, countries with more than 50 articles, a total of 31 countries, were chosen to calculate the average number of citations per paper.

We ranked the chosen countries according to their average paper citations in descending order. Table 1 demonstrated that the top five countries were Belgium, USA, Germany, the UK and Australia. Their average citations per paper were 11.3, 8.0, 6.8, 6.7 and 6.7 respectively. Compared with the mean of following 26 countries' citations per paper, which is 4.7, papers from the top five countries demonstrated greater academic impact, influencing research studies and positively promoting the development of soil carbon research. Consistent with the results described above, the top five countries were all developed countries. In particular, USA had the highest research output and total number of citations, producing an average of eight citations per paper. Thus USA clearly had the most academic influence in the field of soil carbon stocks.

Institution-based distribution of research output and citations

Institution-based distribution of research output can help us understand the research capacity and activities of institutions around the world. It also can help us identify leading institutions in soil carbon stocks research. As Table 2 showed, the highest institutional research output was from the Chinese Academy of Sciences, from which we found 791 records. The next four institutions, all located in USA, were the USDA Agricultural Research Service,

Table 1. Rank of records, total location citation score (TLCS) and TLCS/records by country affiliations

Country	Records	Country	TLCS	Country	TLCS/records
USA	3879	USA	31088	Belgium	11.3
PR China	1360	Germany	6989	USA	8.0
Germany	1034	UK	6186	Germany	6.8
UK	919	Canada	5030	UK	6.7
Canada	819	PR China	4744	Australia	6.7
Australia	705	Australia	4724	Denmark	6.4
Brazil	603	France	3596	Canada	6.1
France	587	Brazil	3225	France	6.1
Spain	385	Belgium	2563	Kenya	6.1
Sweden	366	Sweden	2155	Sweden	5.9
India	337	Switzerland	1792	Switzerland	5.8
Italy	335	Italy	1541	Austria	5.7
Switzerland	308			Finland	5.6

Note that the criteria for inclusion in this table were ranking records, TLCS and TLCS/records of 300, 1500 and 5.6 respectively.

Table 2. Top ten number of records, TLCS and TLCS/records by institution affiliations

Institution	Records	Institution	TLCS	Institution	TLCS/records
Chinese Acad Sci	791	Colorado State Univ	4134	Woods Hole Res Ctr	22.7
USDA ARS	256	Ohio State Univ	4048	Duke Univ	22.1
Ohio State Univ	253	Chinese Acad Sci	3070	Colorado State Univ	17.3
Colorado State Univ	239	Duke Univ	2493	Univ Calif Irvine	16.6
US Forest Serv	212	Max Planck Inst Biogeochem	2385	Ohio State Univ	16.0
Agr & Agri Food Canada	188	USDA ARS	2212	Univ Calif Santa Barbara	14.9
INRA	187	INRA	1744	Max Planck Inst Biogeochem	14.6
Univ Florida	186	Agr & Agri Food Canada	1713	Marine Biol Lab	14.1
Max Planck Inst Biogeochem	163	Univ Bayreuth	1667	Univ Minnesota	13.4
Oregon State Univ	163	Oregon State Univ	1644	Univ Alaska	12.9

Ohio State University, Colorado State University, and USDA Forest Service. Results showed that the PR China and USA allocated a large number of resources to soil carbon stocks research, especially to government and government-supported scientific organizations. The reason may be that the field of soil carbon stocks is one of fundamental scientific researches and primarily non-profit, therefore requiring funds and support from the government.

The institution-based distribution of citations was different to that of the output which was shown in Table 1. Using TLCS as an example, the top five institutions in terms of citations were Colorado State University, Ohio State University, the Chinese Academy of Sciences, Duke University and the Max Planck Institute for Biogeochemistry, with 4134, 4048, 3070, 2493 and 2385 citations respectively. In particular, Duke University (USA) had only 113 published papers and is not in the top 10 outputs institutions, but the university has shown great academic influence in this field.

We used average paper citations to explore high citations-per-paper institutions. Results were still different from the above research output and citations analysis. With regard to research output and academic impact, institutions with more than 50 records were chosen to calculate average paper citations. The top five institutions in terms of citations per paper were the Woods Hole Research Centre, Duke University, Colorado State University, The University of California at Irvine and Ohio State University. The papers published by these institutions had more influence than other institutions in the area of soil carbon stocks. Two institutions, Ohio State University and Colorado State University, obviously, featured in the top five for published papers and average paper citations and thus can be considered the leading institutions in the field of soil carbon stocks.

Distribution of core journals and citations

There were 857 journals that published 10,737 articles in the area of soil carbon pool. All journals were sorted in descending order by their respective number of published articles. Next, the number of articles was summed from the first journal until the total number of published articles reached 8590, accounting for 80% of the 10,737 articles. Using this approach, a total of 133 journals were identified as core journals for soil carbon stocks research.

Table 3. Top 20 core journals for soil carbon stocks research

Journal	Records	Share (%)	TLCS	Share (%)
Soil Biology and Biochemistry	614	5.7	5271	8.1
Global Change Biology	455	4.2	7062	10.8
Geoderma	398	3.7	3713	5.7
Soil Science Society of America Journal	397	3.7	4110	6.3
Forest Ecology and Management	356	3.3	3213	4.9
Plant and Soil	344	3.2	2201	3.4
Agriculture Ecosystems and Environment	270	2.5	1910	2.9
Biogeochemistry	230	2.1	2518	3.9
Soil and Tillage Research	213	2.0	2631	4.0
European Journal of Soil Science	183	1.7	745	1.1
Biogeosciences	171	1.6	1702	2.6
Ecosystems	163	1.5	1386	2.1
PLoS ONE	134	1.2	0	0.0
Global Biogeochemical Cycles	133	1.2	204	0.3
Journal of Geophysical Research – Biogeosciences	131	1.2	14	0.0
Biology and Fertility of Soils	125	1.2	556	0.9
Ecological Modelling	115	1.1	535	0.8
Canadian Journal of Social Science	104	1.0	634	1.0
Catena	101	0.9	252	0.4
Ecological Applications	99	0.9	2143	3.3

Table 4. Top ten journals with the highest average paper citations

Journal	TLCS/records	Records	TLCS
Nature	73.9	30	2353
Advances in Agronomy, **85**	66.0	1	74
Science	58.4	16	971
Advances in Agronomy, **88**	49.0	1	55
Annual Review of Ecology Evolution and Systematics	38.0	1	39
Advances in Agronomy, **97**	27.0	1	29
Bioscience	23.8	10	263
Ecological Applications	20.2	99	2143
Ecology Letters	19.5	24	469
Environment International	16.5	9	173

Table 3 shows the top 20 core journals, which had 4736 articles, thus comprising 44.1% of all 10,737 articles. The journal with the most output was *Soil Biology and Biochemistry*, accounting for 5.7% of the total number of records, followed by *Global Change Biology*, and *Geoderma*, which accounted for 4.2% and 3.7% of all records respectively.

Journals publishing more articles were not necessarily guaranteed to have higher TLCS values. For example, in Table 3, though *Soil Biology and Biochemistry* had the most published articles, i.e. 614, its citations count of 5271 was less than that of *Global Change Biology*, with 455 articles producing 7062 citations, and it was the latter which was the highest TLCS journal. *Soil Biology and Biochemistry* was second, followed by the *Soil Science Society of America Journal*, which had 4110 citations. These journals, with high TLCS scores, had more influence on the development of research on soil carbon stocks. It was also found that high TLCS scores did not guarantee high average paper citations, which was shown in Table 4. The highest average citations per paper was in *Nature*, producing 73.9 citations per paper, followed by *Advances in Agronomy*, **85** and *Science*; their average paper citations were 66.0 and 58.4 respectively.

Leading journals *Nature* and *Science*, with less related articles, still had high citation outputs. Given the impact factor (IF > 30) of these two journals, it is apparent that articles related to soil carbon stocks contributed much to their citation outputs and IF; however, articles involving soil carbon pool were not easily accepted for publication by these journals. Most related articles were published in discipline-specific journals focused on soil, biology, ecology, plant and environment.

High-impact articles and authors

High-impact articles were selected using TLCS. From Table 5 it can be seen that the top ten high-impact articles were written by 28 authors, of which R. Lal wrote two by himself[8,9]. The highest impact articles on soil carbon stocks were published in eight different journals. *Nature*, and *Forest Ecology and Management* each published two high-impact articles. Considering that *Forest Ecology and*

Table 5. Top ten high-impact articles

Author	Title	Journal	Year	TLCS
Jobbagy, E. G., Jackson, R. B.	The vertical distribution of soil organic carbon and its relation to climate and vegetation	*Ecological Applications*	2000	595
Guo, L. B., Gifford, R. M.	Soil carbon stocks and land use change: a meta analysis	*Global Change Biology*	2002	567
Davidson, E. A., Janssens, I. A.	Temperature sensitivity of soil carbon decomposition and feedbacks to climate change	*Nature*	2006	494
Six, J. *et al.*	Stabilization mechanisms of soil organic matter: implications for C-saturation of soils	*Plant and Soil*	2002	463
Lal, R.	Soil carbon sequestration impacts on global climate change and food security	*Science*	2004	422
Lal, R.	Soil carbon sequestration to mitigate climate change	*Geoderma*	2004	286
Johnson, D. W., Curtis, P. S.	Effects of forest management on soil C and N storage: meta analysis	*Forest Ecology and Management*	2001	249
Paul, K. I. *et al.*	Change in soil carbon following afforestation	*Forest Ecology and Management*	2002	248
Kalbitz, K. *et al.*	Controls on the dynamics of dissolved organic matter in soils: a review	*Soil Science*	2000	212
Fontaine, S. *et al.*	Stability of organic carbon in deep soil layers controlled by fresh carbon supply	*Nature*	2007	208

Table 6. Top ten authors with high TLCS values

Author	Records	TLCS
Lal, R.	187	3201
Paustian, K.	72	2037
Six, J.	74	1857
Smith, P.	94	1523
Paul, E. A.	32	1215
Conant, R. T.	28	1191
Jackson, R. B.	28	1073
Davidson, E. A.	27	1011
Kogel-Knabner, I.	69	993
Jobbagy, E. G.	17	874

Management published 356 articles while *Nature* published only 30 articles, we conclude that being a high-IF journal is one important factor with respect to the impact of an article. Note that these articles were published between 2000 and 2007, indicating that scholarly research focused on this theme needed a relatively long time to achieve broader publicity and acceptance.

The high-impact authors were chosen using TLCS. As Table 6 displayed, the author with the highest TLCS value was R. Lal, who had 187 articles and a TLCS value of 3201. The second and third places were taken by K. Paustian and J. Six, with TLCS value of 2037 and 1857 respectively. Not surprisingly, these three scientists are considered to be leading scholars in the field of soil carbon stocks research.

Citation visualization analysis

We used HistCite to generate a visualized citation chronological chart for papers on soil carbon stocks research. As shown in Figure 2, the top 30 papers with TLCS citations were selected in generating the citation chronological chart, of which top ten TLCS papers were shown in Table 7. In the figure, there are 30 nodes and 55 links. Further, the minimum TLCS value is 128, and the maximum is 595. The relative sizes of the nodes in the figure show the cited number of papers, while the arrows point to the cited papers.

From the figure it can be seen that several highly cited papers were published in the year 2000. Paper no. 98, the most-cited article, had a great impact on the research development of soil carbon stocks. In the article by E. G. Jobbagy and R. B. Jackson, the authors reported that, globally, the relative distribution of soil organic carbon (SOC) with depth had a slightly stronger association with vegetation than with climate, but the opposite was true for the absolute amount of SOC. The authors also suggested that shoot/root allocations combined with vertical root distributions affected the distribution of SOC with depth[10]. Paper no. 96, citing paper no. 98, used radiocarbon to determine turnover times of soil organic matter and partition soil respiration[11]; paper no. 98 focused on the association of SOC with outside climate and vegetation with different depths, whereas paper no. 96 emphasized the inside dynamic mechanics of the

Table 7. Top ten TLCS values for papers on soil carbon stocks from visualized citation analysis

Number	Author/title/journal	TLCS
38	Schlesinger, W. H. *et al.*, Soil respiration and the global carbon cycle. *Biogeochemistry*, 2000, **48**(1), 7–20.	143
40	Paustian, K. *et al.*, Management options for reducing CO_2 emissions from agricultural soils. *Biogeochemistry*, 2000, **48**(1), 147–163.	138
70	Balesdent, J. *et al.*, Relationship of soil organic matter dynamics to physical protection and tillage. *Soil and Tillage Research*, 2000, **53**(3–4), 215–230.	153
96	Trumbore, S., Age of soil organic matter and soil respiration: radiocarbon constraints on belowground C dynamics. *Ecological Applications*, 2000, **10**(2), 399–411.	194
98	Jobbagy, E. G. *et al.*, The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, 2000, **10**(2), 423–436.	595
111	Kalbitz, K. *et al.*, Controls on the dynamics of dissolved organic matter in soils: A review. *Soil Science*, 2000, **165**(4), 277–304.	212
116	Giardina, C. P. *et al.*, Evidence that decomposition rates of organic carbon in mineral soil do not vary with temperature. *Nature*, 2000, **404**(6780), 858–861.	192
202	Gaudinski, J. B., *et al.* Soil carbon cycling in a temperate forest: radiocarbon-based estimates of residence times, sequestration rates and partitioning of fluxes. *Biogeochemistry*, 2000, **51**(1), 33–69.	165
218	Kuzyakov, Y. *et al.*, Review of mechanisms and quantification of priming effects. *Soil Biology and Biochemistry*, 2000, **32**(11–12), 1485–1498.	180
322	Johnson, D. W. *et al.*, Effects of forest management on soil C and N storage: meta analysis. *Forest Ecology and Management*, 2001, **140**(2–3), 227–238.	249

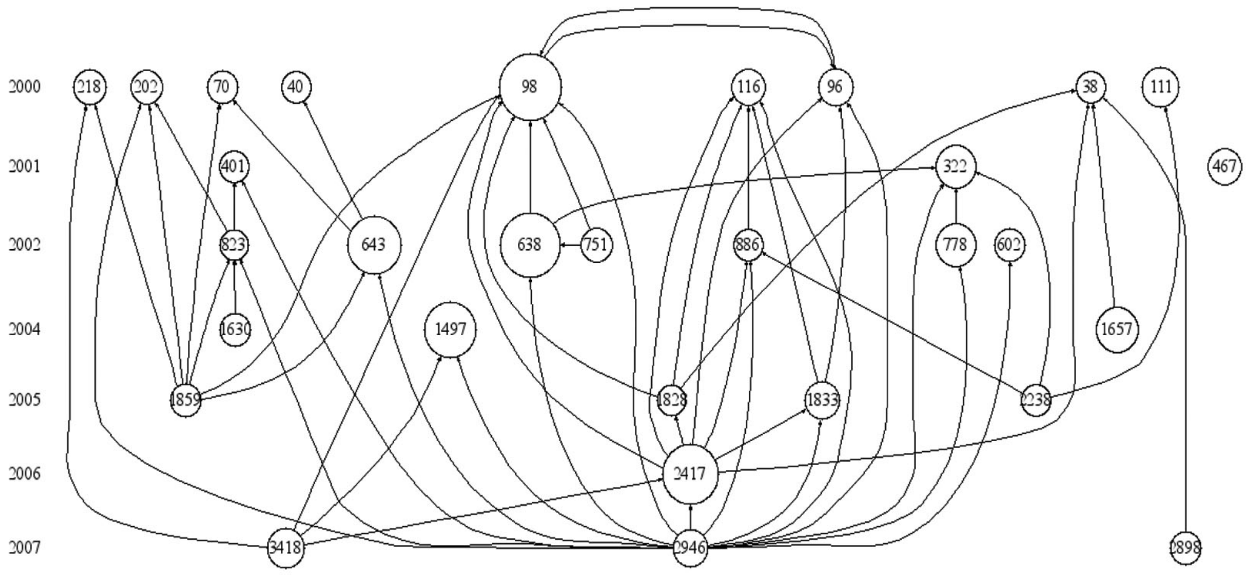

Figure 2. Chronological citation chart for research output of soil carbon stocks.

carbon cycle. Further, paper no. 96, again citing paper no. 98, gave a relatively deep insight into the actual SOC change with time.

Paper no. 2417, citing paper nos 98 and 96, tried to resolve the disagreement on the effects of climate change on global soil carbon stocks[12]. Besides environmental factors that had an impact on soil carbon stocks, human activity, especially positive land use and management, had a significant influence on soil carbon. Paper no. 2946, titled ‘How strongly can forest management influence soil carbon sequestration?’ turned to forest management to address the issue of GHG emissions; the authors cited paper nos 98, 96 and 2417 to support their study[13].

Conclusion

Overall, the research trend of soil carbon stock has steadily increased from 2000 until 2014, with its research output significantly increasing from 2011 until 2013. These trends imply that soil carbon stock as an important research area for addressing climate change received greater attention. As the global climate change problem still exists, we believe that soil carbon stock research will continue to grow in the future.

Except for the PR China, Brazil and India, research output was concentrated in the developed countries, such as USA, Germany, the UK, Canada and Australia; however, a total of 133 countries throughout the world contributed to soil carbon stocks research, showing that climate change is a global problem with soil carbon stocks research continuing to gain worldwide popularity. Most research papers were published in discipline-specific journals on soil, biology, ecology, plants and environment, though papers accepted by leading comprehensive journals had more citations. Articles with high TLCS values published in 2000 affected scholars for the 15 following years and had a strong association with research in the field.

Research had two main trends between 2000 and 2014. First, it focused on the impact of outside factors on soil carbon stocks, such as climate and vegetation, as well as human activities such as agriculture, forest management and so on. Second, concerning the dynamics and cycle of the soil carbon pool, research focused on both outside and inside factors. Research regarding soil carbon stocks clearly advanced human understanding of the relationships between climate change and soil carbon pool, though at times researchers did not reach a consensus on certain themes.

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