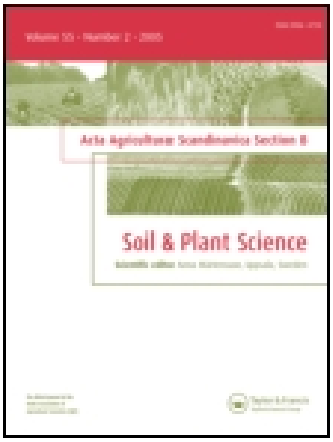

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Global trends in soil monitoring research from 1999-2013: a bibliometric analysis

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REVIEW ARTICLE

Global trends in soil monitoring research from 1999–2013: a bibliometric analysis

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A bibliometric analysis of soil monitoring during the period of 1999–2013 was performed based on Science Citation Index Expanded and Social Science Citation Index databases. The measuring parameters included scientific outputs, subject categories and major journals, international collaboration and geographic distribution of authors and countries, keywords, and hot topics. This research demonstrated a significant increase in the field since 1999. The USA was the largest contributor, generating 26.7% of the total articles with a total number of cited times per paper (CPP) of 17.4. The USDA ARS was the most productive institute with a CPP of 19.0. Hot topics were classified into two major groups according to the author keywords analysis: (1) monitoring objectives and indicators, e.g. climate change, land use and agriculture, soil moisture and heavy metals, which reveal the relationships between the soil and environmental factors; (2) monitoring techniques and monitoring scales, e.g. remote sensing and integrated '3S' techniques, and the varied scales aiming at the comprehensive detection of various soil attributes change. We found that environment policy should be formulated regarding heavy metal pollution which raised great concern about soil monitoring. Biodegradation and bioremediation were popular methods to restore the changes in microbial communities, soil water quality, soil organic matter and inorganic matter. What is more, the integration of '3S' techniques at a regional scale guaranteed the rapid data acquisition and facilitated soil mapping and its spatio-temporal pattern analysis, which should be a future research direction.

Keywords: soil monitoring; scientific outputs; research trends; bibliometrics; monitoring techniques

Introduction

Soil quality describes its capacity to perform under changing conditions, as defined by the European Commission's Joint Research Centre. With the development of economy, human disturbances and natural disasters have triggered changes in soil quality, and these changes have decreased the ability of the soil to provide ecosystem and social services (Mulder et al. 2011; Ozsoy et al. 2012). For instance, pollutants such as heavy metals in soils impair plants, water, food quality and the human body (D'Emilio et al. 2012), while soil erosion decreases agricultural productivity and threatens the food safety across the world (d'Oleire-Oltmanns et al. 2012). As a consequence, it is necessary to take effective measures to maintain the soil quality and ecological functions (Rutgers et al. 2009).

Soil monitoring is a multidisciplinary field which covers a wide range of subjects, e.g. the exploration of soil attribute, the analysis of the relationship of soil and environment factors and the monitoring techniques and scales. It facilitates data acquisition and decision-making during the assessment of the soil quality and the recovery of soil ecosystem services (Ju et al. 2010; Feng & Simpson, 2011; Loew & Schlenz 2011; Arrouays et al. 2012; Brocca et al. 2012; Greve et al. 2012). In this context, it is necessary to identify the cutting-edge trends of soil monitoring. For instance, the innovative applications of many monitoring techniques accelerated the development of the ways of soil assessment and monitoring. Traditional sampling, e.g. design-based and model-based methods, used to design soil monitoring networks at the regional and site scales in many

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countries (Saby et al. 2009; Creelman & Risk 2011; van Wesemael et al. 2011), are still convenient to determine the amount and location of soil monitoring sites. The innovative integration of remote sensing (RS), geographic information system (GIS) and global positioning system (GPS), i.e. the '3S' techniques, significantly improves the efficiency and accuracy in such field (Cecillon et al. 2009; Zerger et al. 2010).

As the enormous research effort rises in the soil monitoring field, it is necessary to portray its global development and research trends comprehensively. A systematic review on soil monitoring would facilitate the sharing of research achievements, identification of research directions and the development of monitoring techniques. Examples involved soil and soil environmental quality in China (Teng et al. 2014), soil biological properties and microbiological indicators in arable land (Stenberg 1999; Riches et al. 2013), soil development in restored freshwater depressional wetlands (Ballantine & Schneider 2009), soil monitoring using near-infrared reflectance spectroscopy (Cecillon et al. 2009) and large-scale soil moisture monitoring (Ochsner et al. 2013). So far, however, no bibliometric review of the global research on soil monitoring has been conducted.

Bibliometrics is a powerful tool to evaluate the research trends in variant scientific fields (Narin et al. 1976). Traditional bibliometric analyses describe the distribution patterns of the publications by countries (Schubert et al. 1989), institutes (Moed et al. 1985), journals and subject categories (Zhou et al. 2007), citation analysis and peak years of citation per publication (Chuang et al. 2007; Slyder et al. 2011). The publication amount of a country or an institute within a certain scientific field reflects its contributions towards the state of science within a defined period, but changes in the amounts of citations or publications cannot describe the trends in development or predict the future directions of a research field (Chiu & Ho 2007). Accordingly, some indicators, e.g. the distribution of author keywords, 'Keywords Plus', buzzwords in titles and abstracts, are used to evaluate the trends in development of a research field (Liu et al. 2011; Wang, He et al. 2012).

In this study, we evaluated global research trends of soil monitoring from 1999 to 2013 by using a bibliometric analysis method. Our goals included (1) summarising significant publication patterns in soil monitoring research; (2) evaluating research performance by country, institute, journal, subject category, author and keywords; (3) briefly identifying future research directions in soil monitoring.

Data and methods

The data were derived from the database of the Science Citation Index Expanded (SCI-Expanded) and Social Science Citation Index (SSCI) published by the Institute for Scientific Information (ISI), Philadelphia, USA. 'Soil AND monitor*' was used to search for every publication that contained these words in its title, abstract or keywords. Articles published in England, North Ireland, Scotland and Wales were identified as publications from the United Kingdom (UK). Articles from Hong Kong and Taiwan were separated from Mainland China. Collaborative publications by authors from different countries or institutes were estimated strictly through the complete count strategy. The journal impact factor (IF) and the total number of cited times per paper (CPP) were used as a unified criterion to evaluate all the publications. Co-word analysis, based on social network analysis, was employed by Ucinet 6.0 to discuss the relationships among hot keywords. On this basis, a bibliometric analysis was performed by Microsoft Excel 2013 to reveal patterns of soil monitoring research on a global scale in terms of the following aspects: types of publications and languages, scientific output characteristics, journals and subject categories, author productivity, geographic distribution of countries and institutes, international collaborations of authors and institutions, and temporal evolution of keyword appearance.

Results and discussions

Characteristics of scientific outputs

A total of 19,586 publications related to soil monitoring issued during the past 15 years were found. Article was the most common type, which amount to 18,940, occupying 96.7% of the total publications, followed by proceedings (1377 or 7.0%) and reviews (549 or 2.8%). Among the publications, 18,940 research articles on soil monitoring were further analysed. The numbers of publications categorised by year were listed in Figure 1. The annual publications increased from 729 in 1999 to 2074 in 2013, illustrating a significant increase in soil monitoring research in the past 15 years. Meanwhile, articles remained dominant throughout the period.

We summarised the characteristics of the major scientific productivity during the period of 1999–2013 in Table 1. The statistics revealed a solid growth in soil monitoring studies with regard to the number of publications, the average number of citations and references, and the amount of research collaborations. The number of outputs increased from 707 in 1999 to 2020 in 2013. The page counts of the articles fluctuated slightly within a small range, averaging

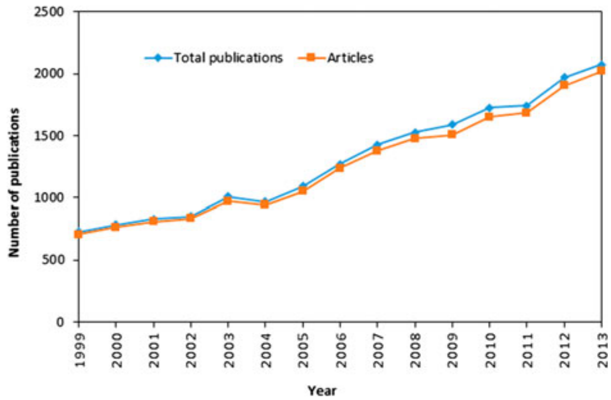

Figure 1. Characteristics by year of soil monitoring network-related articles.

10.8 pages per paper. The average number of references per publication increased steadily from 31.1 in 1999 to 43.8 in 2013, revealing an expanding knowledge basis on soil monitoring together with increasing citations per article on average (16.6). Another indicator, namely the collaboration index, denoting the average number of authors on a single publication, increased from 3.4 in 1999 to 4.7 in 2013, indicating that soil monitoring became an increasingly cooperative research field during the past 15 years.

Subject categories and major journals

According to the classification of SCI/SSCI subject categories in 2013, soil monitoring research covered 169 categories. Top 10 subject categories included environmental sciences (5721; 30.2%), soil science (2527; 13.3%), water resources (2459; 13.0%), multidisciplinary geosciences (2315; 12.2%), ecology (1572; 8.3%), agronomy (1351; 7.1%), plant science (1183; 6.2%), environmental engineering (1142; 6.0%), analytical chemistry (898; 4.7%) and meteorology & atmospheric sciences (870; 4.6%).The annual publication outputs in subject categories with a total number above 1000 were shown in Figure 2. It is observed that environmental sciences had the highest growth rate, which implies a close relationship between soil monitoring and its environmental applications and effects. These top subject categories also demonstrated the high correlations of ecological and water resource issues with soil monitoring research.

Articles on soil monitoring were published in 2004 ISI-indexed journals, and the top 20 most frequently published journals were summarised in Table 2. *Science of the Total Environment* had the largest number of scientific outputs with the 9th of CPP and the 8th of IF ranks, respectively. *Remote Sensing of Environment* attracted a wide discussion on the monitoring technique with a small amount of outputs. *Applied and Environmental Microbiology* had the highest citation rate with a CPP up to 47.2, while *Environmental Science & Technology* topped the IF ranking. Obviously, the titles and themes of these renowned journals also illustrate that environmental sciences, soil quality, and water and atmospheric resources are important subjects in soil monitoring research.

Author performance and collaborations

In total, 52,796 authors from 152 countries published 18,940 articles during 1999–2013, and a large proportion of the papers on soil monitoring were published by a small group of productive authors.

Table 1. Characteristics by year of scientific outputs from 1999 to 2013.

PY	TP	AU	AU/TP	NR	NR/TP	PG	PG/TP	TC	TC/TP
1999	707	2397	3.4	21,961	31.1	7707	10.9	20,103	28.4
2000	766	2628	3.4	23,830	31.1	8060	10.5	21,782	28.4
2001	812	2909	3.6	25,296	31.2	8925	11.0	19,172	23.6
2002	833	3098	3.7	28,099	33.7	9410	11.3	20,142	24.2
2003	973	3661	3.8	31,335	32.2	10,676	11.0	23,730	24.4
2004	944	3632	3.8	30,800	32.6	10,241	10.8	21,929	23.2
2005	1049	4211	4.0	34,971	33.3	11,620	11.1	20,339	19.4
2006	1235	5149	4.2	43,111	34.9	13,846	11.2	22,490	18.2
2007	1377	5719	4.2	49,194	35.7	14,508	10.5	22,547	16.4
2008	1476	6177	4.2	51,985	35.2	15,130	10.3	18,517	12.5
2009	1507	6698	4.4	57,014	37.8	15,560	10.3	17,004	11.3
2010	1652	7535	4.6	66,724	40.4	17,405	10.5	15,228	9.2
2011	1686	7628	4.5	69,247	41.1	18,004	10.7	9436	5.6
2012	1903	8770	4.6	78,606	41.3	20,702	10.9	6247	3.3
2013	2020	9512	4.7	88,516	43.8	22,427	11.1	2704	1.3
Total	18,940	79,724	–	700,689	–	204,221	–	261,370	–
Average	–	5315	4.1	46,713	35.7	13,615	10.8	17,425	16.6

PY, published year; TP, number of publications; AU, number of authors; NR, cited reference count; PG, page count; TC, number of citations; AU/TP, average number of authors; NR/TP, cited references; PG/TP, pages; TC/TP, citations per article.

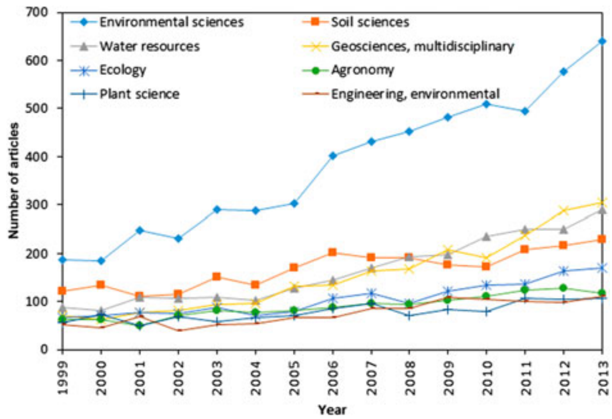

Figure 2. The annual growth trends of the top eight subject categories.

The top five productive authors included L. Dendooven, H. Vereecken, J. Poesen, M. Schuhmacher and J. L. Domingo (Table 3). L. Dendooven contributed the most articles on soil monitoring, P. K. Hopke obtained the highest CPP for total outputs, while J. Poesen topped the CPP rankings as the first and corresponding authors, respectively. Certainly, the author statistics may had limitations as an author changed his/her name, or two or more authors shared the same name. Thus, an international identity number of an author should be provided after his or her first publication in an ISI-listed journal (Liu et al. 2012).

We evaluated the author collaborations from the international and institutional aspects. Table 4 summarised the 20 most productive countries/areas, 11 of which were from Europe, 4 from Asia, 2 from North America, 2 from Oceania and 1 from South America. The USA headed the country ranking in terms of productivity, contributing the most independent (3665) and internationally collaborative (1388) articles during the period of 1999–2013. China ranks second with 1565 of total publications, followed by the UK (1484), Canada (1262) and Germany (1254). The top five countries totally published 6793 single-country articles, comprising 35.9% of the total 18,896 articles. We also found out that the number of academic publications on soil monitoring was highly correlated with the economic development of a country. All of the G7 (Canada, France, Germany, Italy, Japan, the UK and the USA) were in the top 20 countries, contributing 7521 (52.0%) of the total independent publications. Four major developing countries (BRIC: Brazil, Russia, India and China) produced 1997 single-country articles and 1004 internationally collaborative articles.

A total of 11,457 institutes participated in soil monitoring research. Table 5 summarised the top 20 productive institutes. Among them, 11 were from the USA, 2 from France and 1 per country from China, Spain, Canada, Italy, Sweden, Netherlands and Russia. The USDA ARS was ranked 1st in the institutional productivity with 705 scientific outputs, followed by the Chinese Academy of Sciences with 581 articles and the Institut National de la Recherche Agronomique (INRA) with 272. The Centre National de la Recherche Scientifique (CNRS) topped in the

Table 2. The 20 most productive journals in soil monitoring research.

Journal	TP (R;%)[a]	TC (R;%)[b]	CPP (R)	IF (R)[c]
Science of The Total Environment	303 (1;1.6)	5810 (4;2.2)	19.2 (9)	3.163 (8)
Journal of Environmental Quality	288 (2;1.5)	5361 (7;2.1)	18.6 (10)	2.345 (15)
Journal of Hydrology	280 (3;1.5)	5533 (5;2.1)	19.8 (8)	2.693 (11)
Soil Biology & Biochemistry	265 (4;1.4)	6555 (3;2.5)	24.7 (3)	4.410 (2)
Environmental Science & Technology	262 (5;1.4)	7167 (1;2.7)	27.4 (2)	5.481 (1)
Environmental Monitoring and Assessment	259 (6;1.4)	1895 (18;0.7)	7.3 (20)	1.679 (19)
Chemosphere	251 (7;1.3)	5434 (6;2.1)	21.6 (7)	3.499 (5)
Soil Science Society of America Journal	226 (8;1.2)	4190 (9;1.6)	18.5 (11)	2.000 (17)
Plant and Soil	203 (9;1.1)	3403 (12;1.3)	16.8 (14)	3.235 (6)
Water Air and Soil Pollution	200 (10;1.1)	1890 (19;0.7)	9.5 (19)	1.685 (18)
Forest Ecology and Management	198 (11;1.0)	3516 (11;1.3)	17.8 (12)	2.667 (12)
Environmental Pollution	185 (12;1.0)	4306 (8;1.6)	23.3 (4)	3.902 (4)
Hydrological Processes	172 (13;0.9)	2948 (14;1.1)	17.1 (13)	2.696 (10)
Agricultural Water Management	171 (14;0.9)	2154 (17;0.8)	12.6 (17)	2.333 (16)
Geoderma	165 (15;0.9)	2688 (15;1.0)	16.3 (15)	2.509 (13)
International Journal of Remote Sensing	158 (16;0.8)	2566 (16;1.0)	16.2 (16)	1.359 (20)
Vadose Zone Journal	156 (17;0.8)	1534 (20;0.6)	9.8 (18)	2.412 (14)
Agriculture Ecosystems & Environment	156 (17;0.8)	3545 (10;1.4)	22.7 (6)	3.203 (7)
Applied and Environmental Microbiology	149 (19;0.8)	7039 (2;2.7)	47.2 (1)	3.952 (3)
Atmospheric Environment	144 (20;0.8)	3348 (13;1.3)	23.3 (4)	3.062 (9)

[a]TP (%), number of publications (percentage of journals in the studied field),
[b]TC (%), total citation count (percentage of citations of the total journals),
[c]IF 2013 ISI, impact factor.

Table 3. The top 20 productive authors from 1999 to 2013.

		Total outputs		First author		Corresponding author	
Author name	Institute	TP	TC/TP(R)	FAP	TC/FAP(R)	CP	TC/CP(R)
L. Dendooven	CINVESTAV	53	10.4 (18)	4	4.8 (15)	31	9.4 (16)
H. Vereecken	Forschungszentrum Julich	37	14.9 (15)	1	8.0 (12)	1	8 (17)
J. Poesen	Katholieke Univ Leuven	30	34.1 (5)	1	325.0 (1)	3	123.0 (1)
M. Schuhmacher	Univ Rovira & Virgili	27	17.7 (12)	3	31.7 (6)	1	22.0 (12)
J. L. Domingo	Univ Rovira & Virgili	27	17.7 (12)	2	16.0 (10)	24	18.7 (13)
W. Wagner	Vienna Univ Technol	26	34.6 (4)	4	127.0 (2)	1	115.0 (2)
D. Arrouays	INRA	23	14.2 (16)	2	6.0 (14)	2	6.0 (19)
M. Nadal	Univ Rovira & Virgili	22	15.3 (14)	4	25.3 (8)	2	4.0 (20)
R. Lal	Ohio State Univ	22	28.9 (7)	0	0 (17)	2	35.5 (6)
W. De Vries	Univ Wageningen & Res Ctr	22	33.3 (6)	10	41.0 (4)	2	24.5 (9)
J. P. Wigneron	INRA	21	35.2 (3)	4	32.5 (5)	4	30.3 (8)
K. W. Kim	Kwangju Inst Sci & Technol	20	9.7 (19)	4	2.8 (16)	5	14.4 (14)
P. K. Hopke	Clarkson Univ	20	38.5 (1)	0	0 (17)	14	39.7 (4)
D. A. Angers	Agr & Agri Food Canada	20	24.6 (8)	1	9 (11)	2	7.0 (18)
T. S. Steenhuis	Cornell Univ	19	23.3 (10)	0	0 (17)	3	36.0 (5)
C. D. Evans	Ctr Ecol & Hydrol	19	35.7 (2)	10	46.8 (3)	6	67.0 (3)
F. Worrall	Sci Labs	18	21.4 (11)	13	27.1 (7)	3	34.3 (7)
J. Utzinger	Swiss Trop & Publ Hlth Inst	18	24.4 (9)	0	0 (17)	3	24.0 (10)
Y. A. Pachepsky	USDA ARS	18	9.7 (19)	1	7 (13)	6	11.3 (15)
C. Neal	Inst Hydrol	18	12.4 (17)	9	16.1 (9)	1	24.0 (10)

TP, number of publications; TC, total citation count; FA, number of articles published as the first author; CP, number of articles published as the corresponding author; TC/TP, citations per article; TC/FA, citations per article in terms of the first authors; TC/CP, citations per article in terms of the corresponding authors.

Table 4. The 20 most productive countries/territories in soil monitoring research.

		Single-country				Internationally collaborated			
Country	TP	SP	TC	TC/SP (R)	SP (%)	CP	TC	TC/CP (R)	CP (%)
USA	5053	3665	61,409	16.8 (6)	72.5	1388	26,629	19.2 (6)	27.5
China	1565	993	7324	7.4 (18)	63.5	572	7937	13.9 (17)	36.5
UK	1484	730	14,279	19.6 (3)	49.2	754	15,424	20.5 (4)	50.8
Canada	1262	800	11,507	14.4 (10)	63.4	462	8061	17.4 (12)	36.6
Germany	1254	605	9938	16.4 (7)	48.2	649	12,142	18.7 (9)	51.8
France	1214	586	8964	15.3 (9)	48.3	628	10,622	16.9 (14)	51.7
Italy	1117	719	8198	11.4 (14)	64.4	398	7246	18.2 (11)	35.6
Spain	1017	651	10,306	15.8 (8)	64.0	366	6052	16.5 (15)	36.0
Australia	915	555	6997	12.6 (13)	60.7	360	5356	14.9 (16)	39.3
Japan	674	416	4119	9.9 (15)	61.7	258	3256	12.6 (18)	38.3
Brazil	625	430	2535	5.9 (19)	68.8	195	3310	17.0 (13)	31.2
India	577	435	4179	9.6 (16)	75.4	142	1546	10.9 (19)	24.6
Netherlands	569	203	4166	20.5 (1)	35.7	366	8744	23.9 (2)	64.3
Switzerland	433	153	2828	18.5 (4)	35.3	280	6474	23.1 (3)	64.7
Belgium	419	164	2202	13.4 (12)	39.1	255	4809	18.9 (7)	60.9
Sweden	356	185	3210	17.4 (5)	52.0	171	3370	19.7 (5)	48.0
South Korea	347	231	1873	8.1 (17)	66.6	116	1269	10.9 (19)	33.4
New Zealand	285	149	2123	14.2 (11)	52.3	136	2560	18.8 (8)	47.7
Denmark	261	101	1993	19.7 (2)	38.7	160	4153	26.0 (1)	61.3
Russia	234	139	371	2.7 (20)	59.4	95	1767	18.6 (10)	40.6

SP, single-country publications; CP, internationally collaborated publications; TC/SP, citations per article published by a single country; TC/CP, citations per article published by internationally collaborative countries; SP (%), percentage of single-country outputs; CP (%), percentage of internationally collaborated outputs; R, the rank of citations.

ranking of citations per single-institution produced article with a CPP of 45.3. The University of Wisconsin has the highest citation rate for inter-institutional collaborations with a CPP of 26.0, while the University of Wisconsin and the University of Wageningen & Research Centre outperformed regarding the single-institutional and inter-institutional levels, respectively. Moreover, the average citation rate for articles from a single institution (15.7) was lower than that for institutionally collaborative outputs (17.5), indicating

Table 5. The top 20 productive institutes in soil monitoring research.

Institution	TP	Single-institution				Inter-institution			
		SI	TC	TC/SI (R)	SI (%)	CI	TC	TC/CI (R)	CI (%)
USDA ARS, USA	705	177	2903	16.4 (11)	68.0	528	10,502	19.9 (7)	32.0
Chinese Acad Sci, China	581	149	1174	7.9 (19)	25.6	432	4986	11.5 (19)	74.4
INRA, France	272	47	868	18.5 (9)	17.3	225	4103	18.2 (13)	82.7
Univ Florida, USA	243	77	867	11.3 (17)	31.7	166	2318	14.0 (17)	68.3
CSIC, Spain	228	72	1565	21.7 (5)	31.6	156	3530	22.6 (4)	68.4
US Geol Survey, USA	193	46	855	18.6 (8)	23.8	147	3309	22.5 (5)	76.2
Agr & Agri Food Canada, Canada	183	53	659	12.4 (15)	29.0	130	1660	12.8 (18)	71.0
Univ Calif Davis, USA	167	42	845	20.1 (6)	25.1	125	2398	19.2 (9)	74.9
CNR, Italy	152	29	348	12.0 (16)	19.1	123	2295	18.7 (11)	80.9
US EPA, USA	146	26	413	15.9 (13)	17.8	120	2237	18.6 (12)	82.2
Univ Wisconsin, USA	129	27	739	27.4 (2)	20.9	102	2653	26.0 (1)	79.1
Univ Arizona, USA	128	29	505	17.4 (10)	22.7	99	1944	19.6 (8)	77.3
Swedish Univ Agr Sci, Sweden	128	43	693	16.1 (12)	33.6	85	1827	21.5 (6)	66.4
Colorado State Univ, USA	113	26	490	18.8 (7)	23.0	87	2239	25.7 (2)	77.0
CNRS, France	111	4	181	45.3 (1)	3.6	107	2035	19.0 (10)	96.4
Univ Wageningen & Res Ctr, Netherlands	107	28	720	25.7 (3)	26.2	79	1988	25.2 (3)	73.8
Russian Acad Sci, Russia	107	43	88	2.0 (20)	40.2	64	906	14.2 (16)	59.8
N Carolina State Univ, USA	107	28	406	14.5 (14)	26.2	79	810	10.3 (20)	73.8
Penn State Univ, USA	99	18	431	23.9 (4)	18.2	81	1423	17.6 (14)	81.8
Texas A&M Univ, USA	98	25	219	8.8 (18)	25.5	73	1057	14.5 (15)	74.5

TP, number of citations; TC, total citation count; SI (%), single-institution (the corresponding percentage); CI (%), inter-institutionally collaborated articles (the corresponding percentage).

that inter-institutional collaboration improved the citation rates and the influence of the articles. The top 20 productive institutions were also plotted in a collaboration network (Figure 3). The results showed that the USDA ARS and the Chinese Academy of Sciences cooperate more with other institutions. Collaboration between the INRA and the CNRS was much closer. The institutional productivity values might be biased because over-arching organisations comprised hundreds of affiliates, e.g. the Chinese Academy of Sciences and the Russian Academy of Sciences.

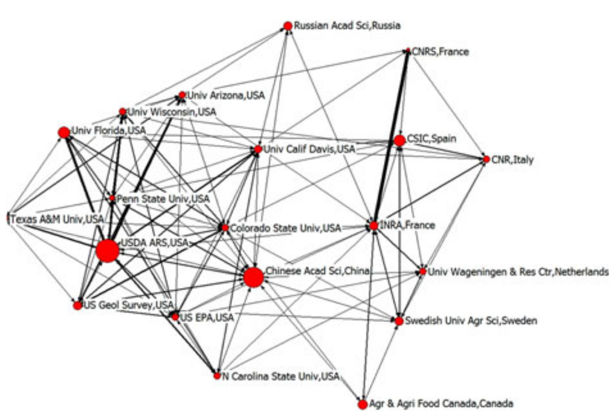

Figure 3. Institutional collaboration network of 20 most central institutions in soil monitoring research (tie strengthen represents the number of co-signed papers by a pair of institutions, and the size of nodes represents the number of single-institution publications).

Hot topics

Keywords were indicators of hot topics for soil monitoring research. We divided the 15-year period into five parts, with 3 years each, then analysed the evolution trends of the author keywords. During the past 15 years, the number of keywords increased dramatically from 5524 in the period of 1999–2001 to 14,424 in the period of 2011–2013. The top 50 most commonly used keywords were shown in Table 6.

Similar to the searching phrases, soil, monitoring, environmental monitoring and soil monitoring occupied a considerable proportion of the total scientific outputs. The total frequency of these search keywords during the five periods were 11.8%, 7.0%, 7.9%, 8.3% and 7.7%, respectively. Due to the scope expansion of research hotspots, the total frequency fluctuated during the 15-year period. The remaining keywords with high frequency were classified into two major groups: soil monitoring objectives and monitoring indicators, soil monitoring techniques and monitoring scales. A contrastive analysis for each group of keywords over the five periods was conducted to reveal the research trends of soil monitoring.

Soil monitoring objectives and indicators

We examined co-occurrence relationships among 39 related keywords and visualised the co-word network

Table 6. The temporal evolution of the most frequently used author keywords.

	TP (R)						
Keywords	1999–2001	2002–2004	2005–2007	2008–2010	2011–2013	1999–2013	CPP(R)
Soil	83 (1)	102 (1)	152 (1)	189 (1)	200 (1)	726 (1)	13.5 (29)
Monitoring	74 (2)	83 (2)	104 (2)	118 (2)	149 (2)	528 (2)	13.2 (31)
Heavy metals	40 (3)	52 (3)	70 (3)	108 (3)	132 (3)	402 (3)	15.2 (23)
Soil moisture	21 (11)	38 (6)	46 (7)	88 (4)	125 (4)	318 (4)	16.1 (18)
RS	20 (13)	37 (7)	50 (6)	83 (5)	111 (5)	301 (5)	15.9 (20)
Groundwater	29 (6)	35 (8)	59 (5)	63 (6)	77 (7)	263 (6)	11.7 (43)
Nitrogen	37 (4)	51 (4)	65 (4)	62 (7)	46 (13)	261 (7)	19.2 (10)
Water quality	23 (9)	34 (9)	32 (13)	48 (11)	81 (6)	218 (8)	12.9 (35)
Biodegradation	21 (11)	26 (13)	44 (8)	62 (7)	59 (9)	212 (9)	12.3 (37)
Phosphorus	31 (5)	34 (9)	39 (9)	54 (9)	46 (13)	204 (10)	17.6 (13)
Runoff	18 (15)	31 (11)	35 (11)	46 (12)	48 (10)	178 (11)	12.3 (37)
Bioremediation	24 (7)	28 (12)	35 (11)	42 (15)	42 (17)	171 (12)	14.5 (26)
Nitrate	19 (14)	44 (5)	29 (14)	43 (14)	29 (29)	164 (13)	16.5 (17)
Climate change	6 (44)	9 (45)	20 (32)	53 (10)	68 (8)	156 (14)	23.5 (4)
Modelling	22 (10)	17 (23)	36 (10)	33 (19)	47 (12)	155 (15)	13.5 (29)
Soil erosion	17 (17)	20 (17)	25 (20)	45 (13)	38 (19)	145 (16)	14 (28)
Irrigation	16 (19)	14 (31)	29 (14)	37 (17)	48 (10)	144 (17)	11.2 (44)
GIS	8 (35)	15 (25)	29 (14)	38 (16)	37 (20)	127 (18)	13.1 (32)
Erosion	12 (24)	23 (15)	27 (17)	32 (21)	27 (34)	121 (19)	15.3 (22)
Pesticides	24 (7)	24 (14)	24 (22)	31 (22)	17 (47)	120 (20)	21 (6)
Sediment	8 (35)	18 (21)	26 (18)	35 (18)	30 (26)	117 (21)	21.5 (5)
Evapotranspiration	10 (29)	14 (31)	21 (28)	25 (28)	46 (13)	116 (22)	13.1 (32)
Leaching	10 (29)	19 (19)	23 (25)	27 (24)	34 (22)	113 (23)	10 (47)
Environmental monitoring	14 (22)	14 (31)	21 (28)	23 (32)	40 (18)	112 (24)	12.2 (40)
Pollution	6 (44)	18 (21)	23 (25)	33 (19)	28 (31)	108 (25)	12 (41)
Agriculture	8 (35)	15 (25)	25 (20)	22 (34)	32 (24)	102 (26)	14.1 (27)
Lead	7 (41)	19 (19)	17 (37)	23 (32)	34 (22)	100 (27)	9.7 (49)
Drought	9 (32)	11 (41)	15 (41)	20 (37)	45 (16)	100 (27)	19.9 (8)
Soil quality	13 (23)	14 (31)	15 (41)	26 (25)	30 (26)	98 (29)	20.4 (7)
Hydrology	11 (26)	15 (25)	24 (22)	26 (25)	22 (42)	98 (29)	18.9 (11)
Land use	11 (26)	10 (44)	20 (32)	19 (42)	36 (21)	96 (31)	12.3 (37)
Temperature	7 (41)	17 (23)	13 (46)	25 (28)	32 (24)	94 (32)	13.1 (32)
Radon	8 (35)	7 (49)	18 (36)	29 (23)	27 (34)	89 (33)	8.4 (50)
Restoration	9 (32)	7 (49)	22 (27)	20 (37)	30 (26)	88 (34)	11.8 (42)
Denitrification	9 (32)	15 (25)	15 (41)	22 (34)	27 (34)	88 (34)	14.9 (24)
Soil respiration	7 (41)	21 (16)	15 (41)	20 (37)	24 (40)	87 (36)	28.8 (1)
Nutrients	6 (44)	15 (25)	16 (39)	22 (34)	28 (31)	87 (36)	15.9 (20)
Salinity	5 (48)	13 (36)	19 (34)	24 (31)	25 (38)	86 (38)	9.9 (48)
Microbial biomass	15 (20)	12 (39)	26 (18)	17 (46)	15 (48)	85 (39)	19.3 (9)
Infiltration	8 (35)	20 (17)	17 (37)	25 (28)	15 (48)	85 (39)	17.3 (14)
Carbon dioxide	18 (15)	9 (45)	10 (48)	26 (25)	22 (42)	85 (39)	26.5 (2)
Contamination	11 (26)	9 (45)	21 (28)	19 (42)	23 (41)	83 (42)	14.8 (25)
Degradation	5 (48)	14 (31)	24 (22)	18 (44)	22 (42)	83 (42)	16.1 (18)
Remediation	10 (29)	15 (25)	19 (34)	15 (47)	21 (46)	80 (44)	10.9 (45)
Soil water content	5 (48)	12 (39)	13 (46)	20 (37)	29 (29)	79 (45)	10.8 (46)
Vegetation	12 (24)	11 (41)	9 (50)	20 (37)	26 (37)	78 (46)	18.4 (12)
Soil water	17 (17)	13 (36)	15 (41)	18 (44)	14 (50)	77 (47)	17 (15)
Soil contamination	15 (20)	13 (36)	10 (48)	13 (48)	25 (38)	76 (48)	12.5 (36)
Grassland	8 (35)	9 (45)	16 (39)	11 (50)	28 (31)	72 (49)	16.8 (16)
Soil organic matter	6 (44)	11 (41)	21 (28)	12 (49)	22 (42)	72 (49)	26.5 (2)

TP, number of publications; CPP, citations per publication; R, rank for an item.

(Figure 4). The size of the nodes was proportional to the occurrence frequency of keywords. The lines represented the relationship between two words, the connection strength of which was shown by the thickness. Heavy metals appeared most frequently, which had the largest cooperation frequency with pollution, indicating the importance of conducting soil monitoring. Groundwater, soil moisture, nitrate, nitrogen, phosphorus, land use, climate change were highly related to soil ecosystem during the study

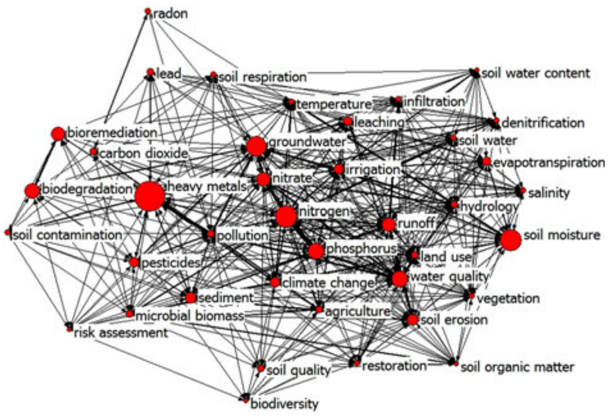

Figure 4. Co-word network of high-frequency keywords in monitoring objectives and monitoring indicators.

period. Additionally, bioremediation and biodegradation had been the effective measures to restore the changes of ecosystem. We divided these keywords into four parts to discuss the research patterns, respectively.

(1) Monitoring of soil change

Keywords in this section included biodegradation, bioremediation, soil erosion, soil quality, restoration, denitrification, soil respiration, salinity and soil contamination. Figure 5 showed that the research interest has been attached to biodegradation and bioremediation, ranking the 9th and the 12th among the total keywords, respectively. Bioremediation provides a cost-effective clean-up technology that accelerates naturally occurring biodegradation compared to traditional site remediation approaches (Margesin et al. 2000). Currently, an insight of the metabolic cooperation among microbial communities is required to analyse the numerous driving factors of microbial biodegradation (Megharaj et al. 2011). In addition, soil respiration, as one of biological parameters reflecting the mineralisation of soil organic matter (SOM), has been widely utilised to measure the carbon dynamics of soil and evaluate the carbon budget in various ecosystems (Kuzyakov & Larionova 2005).

Researchers paid more and more attentions to the effects of heavy metals on soil quality during the periods of 1999–2013 (Figure 6). Not only would high concentration of heavy metals be detrimental towards agricultural products, but these conditions were also adverse to the microorganisms in soil, thus increasing the risk of metal adulteration in food chains (McLaughlin et al. 1999). Heavy metal pollution had also been found in soil near industrial complexes, e.g. lead contamination has caused repercussions due to its unfavourable effects on human health (Lin 2002; Velea et al. 2009). Various methods had been developed to monitor the heavy metal contents in soils, e.g. sampling tests with extraction methods (Romkens et al. 2009), the integration of satellite and ground-based techniques (D'Emilio et al. 2012).

(2) Monitoring of ecosystems related to the soil

Climate change, irrigation, pollution, agriculture, land use, vegetation, risk assessment and biodiversity were monitoring objectives related to soil environmental factors. Climate change maintained an upward topic and tops the occurrence frequency of keywords in the period from 2011 to 2013 (Figure 7). It affected the structure and function of terrestrial ecosystems as an imperative environmental and political concern in the twenty-first century (Rustad 2008). Soil monitoring provided a basis for the analysis of the relationship between soil carbon and climate change via measuring the total amount and the change of SOM and dissolved organic carbon (Worrall et al. 2004; Feng & Simpson 2011). Additionally, a slight increasing trend was also observed during the evolution of land use, agriculture and risk assessment. Many soil monitoring techniques, for example, were employed to guarantee the agricultural production, including molecular genetic techniques for real-time monitoring of soil and plant health (Amarger 2002) and environmental probes based on nano-sensors for agro-ecosystem monitoring (Welbaum et al. 2004).

(3) Physicochemical indicators of soil

Nitrogen, phosphorous, nitrate, sediment, leaching, temperature, radon, microbial biomass, carbon dioxide and SOM are parts of the physicochemical soil attributes. Figure 8 showed that nitrogen and nitrate still maintained high numbers of total outputs though the number of related publications decreased after the peak of annual publications from 2002 to 2004 and from 2011 to 2013, the number of outputs on phosphorous surpassed that of nitrogen. In fact, environmental pollution resulted from the overuse of fertilisers triggered more concerns about soil nitrogen and phosphorous. On-site monitoring of

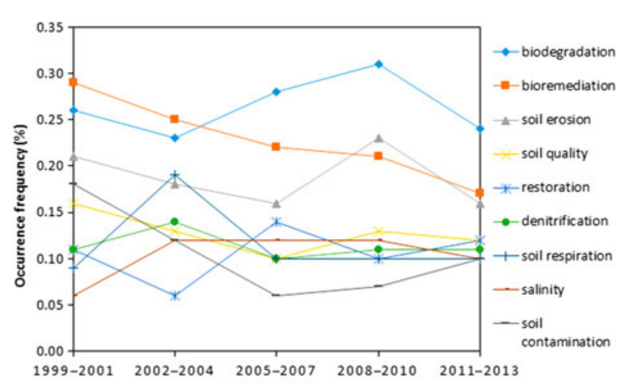

Figure 5. Keywords belonging to monitoring of changes in the soil.

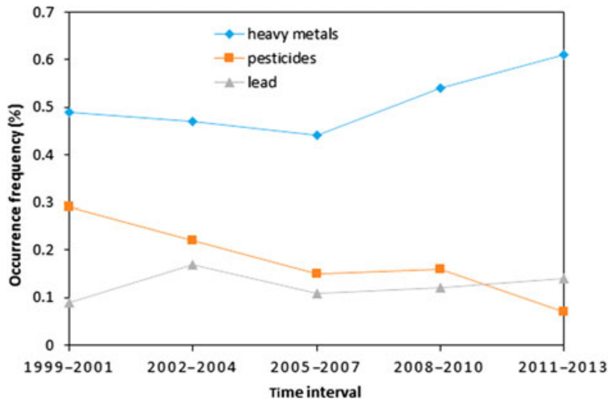

Figure 6. Keywords belonging to soil contamination.

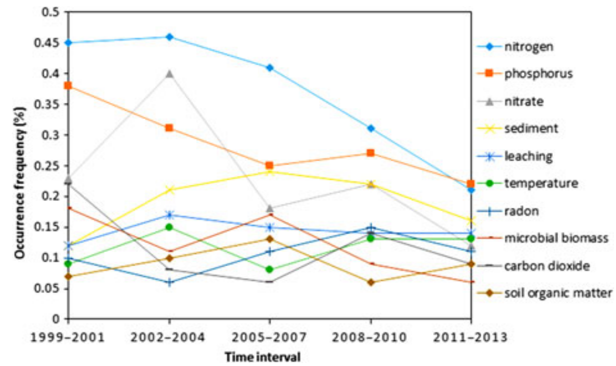

Figure 8. Keywords belonging to the physicochemical indicators of soil.

nitrogen and phosphorous nutrients is highly popular due to the high density of measurements available at low costs, the adoption of which would be energised if precise sampling and rapid extraction of the macronutrients in the sample could be fulfilled in a real-time system (Kim et al. 2009). The monitoring of other experimentally detectable and informative soil indicators, e.g. microbial biodiversity and soil carbon, revealed their relationships with functioning ecosystems related to soils and assesses the feedback between soil carbon and climate change (Ranjard et al. 2010; Smith et al. 2012).

(4) Water-related indicators

Soil moisture, groundwater, water quality, runoff, evapotranspiration, hydrology, infiltration, soil water content and soil water are water-related keywords. Soil moisture, groundwater and water quality showed an obvious increasing trend (Figure 9). Soil moisture, from both climate and hydrologic cycle perspectives, was critical in agricultural and natural systems. A shortage of soil moisture limited the plant respiration and productivity, while the extremes in soil moisture levels could cause drought or flooding and lead to deleterious effects on crop yields. To maintain the sustainability of agriculture production system and ecosystem, soil and water must remain harmonious with each other. Groundwater, for instance, was defined in biological and hydrological contexts and the effects of spatial and temporal heterogeneity of groundwater on fauna distribution system were discussed (Schmidt & Hahn 2012). Runoff dynamics from green roof performances within soil-vegetation systems also indicated that additional critical studies should be undertaken to monitor soil functions in a watershed environment and meet ecological needs (Berndtsson 2010).

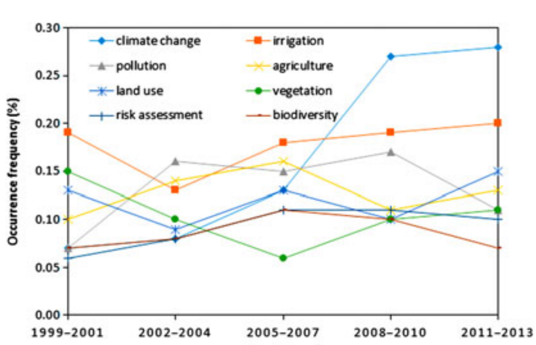

Figure 7. Keywords belonging to ecosystems related to the soil.

Soil monitoring techniques and scales

Soil monitoring techniques experienced three stages, i.e. spatial statistics (sampling), maths modelling and the integration of '3S'. Meanwhile, the monitoring scales changed from point scale to regional scale, and data acquisition became more efficient. Figure 10 displayed the changes of soil monitoring techniques. RS dominated the total five periods with an increasing trend. GIS, modelling, geostatistics, Soil and Water Assessment Tool (SWAT) and GPS shared a similar pattern of fluctuation.

Models play a key role in simulation and prediction of the soil change (Urban 2000). As Figure 10 showed, increasing attention had been paid on the

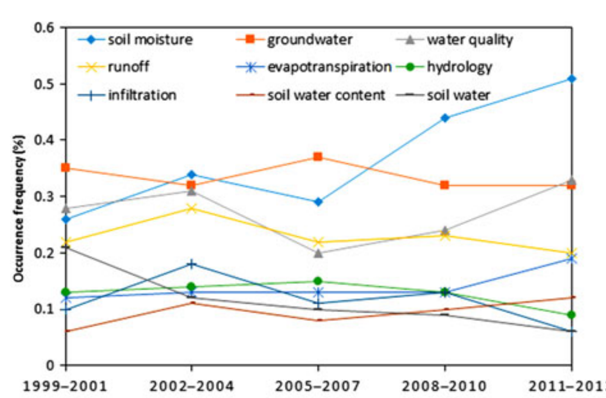

Figure 9. Keywords belonging to water-related indicators.

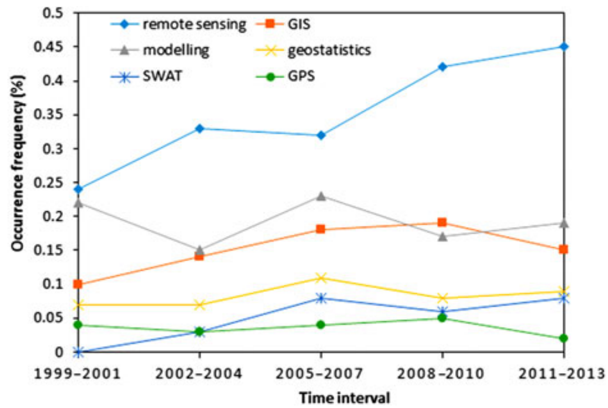

Figure 10. Keywords belonging to monitoring techniques.

SWAT, which was used to simulate all relevant procedures influencing water-related problems in catchment and watershed scales (Abbaspour et al. 2007). Due to its availability and user-friendliness, SWAT enabled the identification of the sensitive parameters and the major hydrological control factors related to the soil change. Additionally, numerous geostatistical space-time models had been used to improve the predictions accuracy of mapping soil variables (Schroder et al. 2006; Lacarce et al. 2012), including soil carbon (Rantakari et al. 2012), soil moisture (Sun et al. 2012), soil salinity (Wang, Li et al. 2012) and soil chemical elements (Bossa et al. 2012).

'3S' techniques include RS, GIS and GPS. Satellite RS provided enormous potential for soil monitoring owing to its synoptic data and accessible imagery archives. It had overcome the limitations of information from conventional 'point' measurements by graduating to 'surface' information, enabling quantitative analyses of land surface factors (Shi et al. 2012). Accordingly, RS was applied to monitor different soil attributes, e.g. soil moisture (Cosh et al. 2008), land–atmosphere CO_2 exchange (Kimball et al. 2009), soil salinity (Metternicht & Zinck 2003) and soil erosion (d'Oleire-Oltmanns et al. 2012). Future research could focus on the combination of proximal and RS, employing scaling-based methods to capitalise on all accessible data sources to improve the soil monitoring efficiency (Mulder et al. 2011). GIS, a computer system designed to capture, store, manipulate, analyse, manage and display all the geographically referenced information (Lin et al. 2002), has advanced the development of statistically based approaches and models that transfer soil properties to digital environmental data (Greve et al. 2012). The GPS was used to locate the position on surface of the Earth in a three-dimensional scale. In recent years, researchers had enabled the generation of vertical geometric coordinates, and enhanced the accuracy for detecting small movements, including monitoring soil subsidence (dos Santos et al. 2012). The integration of '3S' techniques utilised the advantages of each technique while overcome their deficiencies. Examples included monitoring soil ecology and biodiversity (Wang et al. 2010), soil water content (Ju et al. 2010), pasture soil types (Turner et al. 2000) and soil erosion (Ozsoy et al. 2012).

Keywords related to regional scales occurred more frequently during the period of 1999–2013 (Figure 11). Due to the spatio-temporal variability of soil attributes, future developments in soil monitoring would focus on large areas over long time periods (Brocca et al. 2012) and accuracy related to the scale-up of point scale towards the coarse resolution of satellite estimates (Loew & Schlenz 2011). Non-point source pollution referred to water/soil pollution from abundant sources, which degrade both soil and water quality (Dietz et al. 2004). Researchers have employed watershed-scale methods to monitor nutrients or microorganisms in soils to assist the policy making of soil management (O'Donnell 2012).

Conclusions

In this study, we employed a bibliometric method to analyse the research trends of soil monitoring field from 1999 to 2013. The publications on soil monitoring presented a solid growth with an increasing number of articles, collaboration index, citations and references.

A total of 18,940 articles were listed in 169 subject categories and 2004 journals. The fields of environmental sciences, soil science, water resources, multidisciplinary geosciences and ecology published the most number of articles on soil monitoring. Journals including Science of The Total Environment, Journal of Environmental Quality, Journal of Hydrology, Soil Biology & Biochemistry, Environmental Science

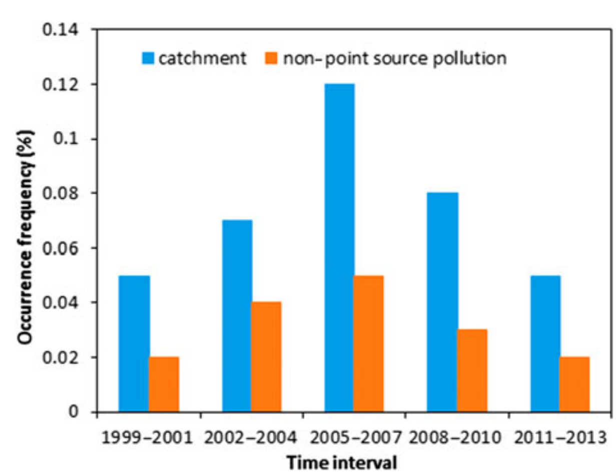

Figure 11. Keywords belonging to monitoring scales.

& Technology were the most productive in the field, and the top 20 journals had published a total of 4191, occupying 22.1% of all papers. The USDA ARS, the Chinese Academy of Sciences and the INRA were the three most prolific institutions. Collaborative works performed better in CPP than single-country or single-institute publications.

The contrast analyses of related hot topics revealed the reason why soil monitoring is important and how it should be conducted. Heavy metal pollution had been the most concerned problem on soil quality during the investigated period. More environmentally friendly policies should be made to regulate effective supervision mechanism to control the concentration of the detrimental contents. Biodegradation and bioremediation were widely applied methods to restore the changes in microbial communities, soil water quality, SOM and inorganic matter. What is more, the integration of '3S' techniques guaranteed the improvement of soil monitoring efficiency and accuracy, which, at a catchment/regional scale, even facilitated soil mapping and its spatio-temporal pattern analysis. The results provided a basis for simulation and prediction of soil change and policy making.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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