A bibliometric analysis of research trend in global nitrogen cycle

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Abstract

This study aims at exploring the research characteristics of nitrogen cycle, through quantitatively analysis of related literature gathered from the online version of Science Citation Index-Expanded, the Thomson Reuters Web of Science from 1992-2009. General analysis of scientific output such as subject category, journal, language, and research performance by countries and institutions were presented. Distribution of author keywords, words in title, and KeyWords Plus was analyzed to map the research trend. Results show that articles related to nitrogen cycle grew significantly after 1995 along with more collaboration between countries and institutions. Of all the involved countries, USA possessed a stronger power in nitrogen cycle research. Synthetic analysis of three kinds of keywords showed that "mineralization", "dynamics", "soils", "ecosystems", "nitrification", and "denitrification" were popular research topics, while the responses of "water", "plant", "forest", and "grassland" as well as the climate effect of "N_2O" and "carbon" due to alteration of nitrogen cycle may be new focus in nitrogen cycle research field in the future.

Keywords: Scientometrics, Nitrogen Cycle, SCI, Research Trend

1. Introduction

Nitrogen cycle is a key process of natural biogeochemical cycles, which involves nitrogen fixation, mineralization, nitrification, denitrification, and the mobilization of nitrogen along food chains. Nitrogen fixation is fundamental of nitrogen cycle, since it converts a massive and (to most organism) unavailable pool of nitrogen gas (N_2) to chemical forms of N that are available to most organisms [1]. Estimates of natural nitrogen fixation in terrestrial ecosystems—lighting and biological N fixation, prior to extensive human activity, ranges from 90 to 140 Tg N/yr [2,3]. However, with the fast development of industry and urbanization, global nitrogen cycle has been greatly altered by human via combustion of fossil fuels, production of artificial nitrogen fertilizers, cultivation of nitrogen-fixing legumes, and other actions [4]. In addition to enhancing fixation, human activity liberates N from long-term biological storage pool through biomass burning, land clear and conversion, and wetland drainage [5,6]. It is estimated that human activity causes the fixation of about 187 Tg of new N per year in terrestrial ecosystems and mobilizes perhaps 70 Tg more in total by 2005 [3,7]. The estimate of nitrogen fixation continues to accelerates every year, and will reach as much as 270 Tg by 2050 [3]. Obviously, human activity has greatly enhanced (or more) the transfer of N from the atmosphere to biologically available pools on land [1].

Human alteration of nitrogen source affects every chains of nitrogen cycle, leading to a host of environmental problems. Firstly, combustion of fossil fuels and use of fertilizer have increased emission of trace nitrogen gases [8, 9]. Of worldwide concern is photochemical smog caused by nitric oxides (NO_x) since it first appeared in Los Angeles in 1946. NO_x play a critical role in atmospheric chemistry by affecting the concentration of hydroxyl (OH) radical and contributing to the formation of tropospheric ozone (O_3) [10], thus posing a poisonous effect on human health and plant productivity [11]. In addition to NO_x, greenhouse effect and ozone depletion caused by nitrous oxide (N_2O) is also inconvenient. The greenhouse effect of N_2O is 310 times as strong as that of CO_2 on a per molecule basis over a

100-year period [12] and contributes 6% to the total observed global warming [13]. N_2O is unreactive in troposphere, but is destroyed by photolysis or by reaction with excited oxygen atoms in the stratosphere, where it can catalyze the destruction of stratospheric ozone [14]. Secondly, eutrophication and acidification of terrestrial and aquatic systems caused by nitrogen deposition is another problem holding global attention [15,16]. The increase of nitrogen deposition in forest ecosystem may ultimately lead to a state of "nitrogen saturation" [17,18], causing a series of adverse effects, including nitrogen loss in leachate [19], loss of nutrient cations and increase of acidity of soils [20], nutrient imbalance and reduced productivity in trees [21]. Thirdly, the increase of nitrogen deposition is believed to have caused dramatical changes in dominant species in ecosystems and markedly decrease the overall biodiversity of ecosystems [22]. Moreover, changes in nitrogen cycle can alter the global cycle of carbon, affecting both the increase rate of carbon dioxide in atmosphere and the response of ecosystems to that increase [23]. Atmospheric carbon dioxide (CO_2), which plays a central role in controlling climate [12], has increased by 30% since industrialization due to the burning of fossil fuels and carbon emissions from land-use changes [24]. The deposition of nitrogen that is available to plants can stimulate productivity and enhance uptake of CO_2, which in turn mitigates the effects of climate change. Modeling study by Holland et al. shows that nitrogen deposition on a global scale has increased carbon uptake by 1.4×10^3-2×10^3 Mg C/yr [25,26], while experimental studies by Nadelhoffer et al. suggest that the contribution of nitrogen fertilization to the Northern Hemisphere carbon land sink has been small [27]. However, large uncertainty exists on enhancement of carbon uptake from nitrogen deposition on a global scale and the issue needs more exploration.

The cascade consequences caused by one atom of nitrogen [16], including increase of atmospheric O_3 (human health impact) and fine particulate matter (visibility impact), altered forest and coastal ecosystem productivity, promotion of surface water acidification (biodiversity loss) and coastal eutrophication, and increase of greenhouse potential (via N_2O production), makes the issue of nitrogen cycle an important one to address. Despite of expeditiously increase of papers related to nitrogen cycle, there have been few attempts at gathering systematic data on scientific output of global nitrogen cycle research. It is advised by Garfield that recent research focus could be reflected on its publication output [28]. Bibliometric analysis is a method that analyzes papers quantitatively and provides statistics to describe distribution patterns of articles within a given topic [29], field [30], institute [31], or country [32]. Moreover, Science Citation Index-Expanded (SCI-Expanded), from the Thomson Reuters Web of Science databases, is by far the most authoritative and most widely used source database, providing a broad review of scientific accomplishments in all fields. Conventionally, bibliometric analysis methods often evaluate the research trend by publication outputs of countries, institutions, journals, and research fields [33-35]. However, fluctuation in citation or publications counts of countries or institutions only represents changes in research interests but nothing related to research direction or orientation. A more comprehensive method which has already been applied in bibliometric analysis of some disciplines of science and engineering [36-39] involves the assessment of author keywords, words in title, and KeyWords Plus, which provide closer information to research direction and tendencies [40].

In this study, we use the combination of traditional bibliometric method and the innovative one to trace the development of nitrogen cycle in the period of 1992 to 2009. Hopefully, the evaluation of related literature from SCI-Expanded will provide some insight into the characteristics of nitrogen cycle research, such as research activities and publication patterns of countries and institutions, and research hotspot tendencies or irregularities. Furthermore, it will help relevant researchers realize current focus of nitrogen cycle, and establish future research direction.

2. Data Source and Methodology

The data used in this study were based on the online database of Science Citation Index-Expanded (SCI-Expanded) retrieved from the Thomson Reuters Web of Science. "Nitrogen cycle", "nitrogen cycling", "nitrogen cycles", "nitrogen cyclings", "N cycle", "N cycles", "N cycling", and "N cyclings" were used as the keywords to search titles, abstract, and keywords from 1992 to 2009. The records were carefully downloaded. Document information included author(s), title, source, abstract, language, document type, keywords, addresses, cited reference count, times cited, publisher information, ISSN, page count, subject category, and citation reports. The SCI-Expended unique article identifier and published year information of data were then examined to rule out duplication and insure the time period of 1992 to 2009. Later, the data were analyzed by Microsoft Excel.

2,759 articles of the original data were used to assess from the following aspects: characteristics of publications outputs; distribution of outputs in subject categories, journals and languages; publication performance including countries, institutions, and collaborations; research emphasis through distribution analysis of author keywords, KeyWords Plus, and word in title. Combination of these three words was then used for research trend analysis.

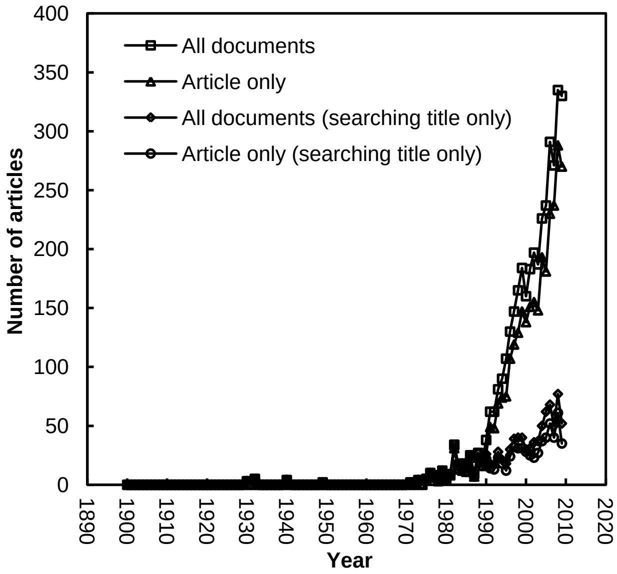
Articles originating from England, Scotland, Northern Ireland, and Wales were grouped together under the UK heading. Articles from Hong Kong were not included in China. Besides, the reported impact factor (IF) of each journal was obtained from 2009 JCR.

3. Results and Discussions

3.1. Characteristics of Publication Outputs

There were 3,383 publications in total satisfying the selection criteria mentioned, comprising of 11 document types. Articles took up 82% of total publication, followed distantly by proceedings papers (305; 9.0%) and reviews (223; 6.6%). Editorial materials (45; 1.3%), meeting abstracts (26; 0.77%), notes (8; 0.24%), corrections (6; 0.18%), news items (6; 0.18%), reprint (2; 0.059%), letters (2; 0.059%), and software review (1; 0.03%) did not appear much and showed less significance. As articles represented the majority of document types that were also peer-reviewed within this field, only the 2,759 original articles were identified and further analyzed in the following study.

Figure 1.World SCI-Expanded publications on nitrogen cycle, 1900-2009



The number of annul publication output from 1900 to 2009 is shown in Fig. 1, by using "nitrogen cycle", "nitrogen cycling", "nitrogen cycles", "nitrogen cyclings", "N cycle", "N cycles", "N cycling", and "N cyclings" to search title words only. There was no articles related to nitrogen cycle until 1930 in SCI-Expanded, and articles before 1970 were rare. The number of articles fluctuated to form a plateau from 1975 to 1990, with an average of 13 per year. Nitrogen cycle research has developed expeditiously in the last two decades, especially after 1995. Since there were no keywords or abstracts with articles before 1991 in SCI-Expanded database, the development trend for all documents and articles, searched by titles, keywords, and abstracts, is also presented in Fig. 1 to avoid limitation. Apparently, there were two phrases of increase of nitrogen cycle research, from 1992 to 1999 and from 2003 to 2009, respectively. The notable growth of academic attention paid to nitrogen cycle after 1992 indicates that the perturbation of nitrogen cycle due to industrialization and urbanization had aroused more and more concern all over the world.

3.2. Distribution of Outputs in Subject Categories, Journals, and Languages

According to the classification of subject categories in Journal Citation Reports (JCR) in 2009, the publication output data of nitrogen cycle research was distributed in 104 SCI subject categories during the period of 1992-

2009. Table 1 listed the top 10 subject categories which containing the most articles. It indicated that ecology (670; 24%), soil science (566; 21%), environmental sciences (560; 20%), multidisciplinary geosciences, (263; 10%), and marine & freshwater biology (248; 9%) were the 5 most popular subject categories. These five most productive subject categories, all of which were branches of ecology and environmental science, produced 2,307 articles in total, accounting for 84% of all nitrogen cycle publications.

In total, 2,759 articles were published in 190 journals. Table 2 shows the top 10 productive journals through the 18 years. Twenty-nine percent of all the articles related to nitrogen cycle reside in these top 10 journals, whereas the remainders reside in other 532 ones. *Soil Biology & Biogeochemistry* ranked first with 156 (5.7%) articles, followed by *Biogeochemistry* with 103 (3.7%) articles; while *Global Change Biology* and *Ecology* had a relatively higher impact factor. All the top 10 journals belong to ecology and environmental science in accordance with the distribution of subject category, indicating that research in ecology and environmental science was the mainstream among all the nitrogen cycle-related fields.

Table 1. Distribution of SCI subject categories, 1992-2009

Subject categories	TP	Rank (%)
ecology	670	1 (24)
soil science	566	2 (21)
environmental sciences	560	3 (20)
multidisciplinary geosciences	263	4 (10)
marine & freshwater biology	248	5 (9.0)
oceanography	226	6 (8.2)
plant sciences	224	7 (8.1)
agronomy	188	8 (6.8)
microbiology	171	9 (6.2)
forestry	144	10 (5.2)

TP: total articles

Of all the articles, English is the absolutely predominant language, accounting for 99% of the total article publication. This is understandable since SCI-Expanded is an American-based database, and most of journals are published in English. Moreover, English is the official language of many countries and international conferences, and researchers are more likely to publish their scientific achievements in English to get worldwide discussion and recognition. Other languages that appear include French (12; 0.43%), German (7; 0.25%), Portuguese (4; 0.14%), Chinese (2; 0.072%), Czech (2; 0.072%), Hungarian (1; 0.036%), Spanish (1; 0.036%), and Russian (1; 0.036%).

Table 2. Distribution of the output in journal, 1992-2009

Journals	TP	Rank (%)	IF
Soil Biology & Biochemistry	156	1 (5.7)	2.978
Biogeochemistry	103	2 (3.7)	2.771
Plant and Soil	89	3 (3.2)	2.517
Ecology	83	4 (3.0)	4.411
Oecologia	79	5 (2.9)	3.129
Forest Ecology and Management	76	6 (2.8)	1.95
Global Change Biology	58	7 (2.1)	5.561
Marine Ecology-Progress Series	57	8 (2.1)	2.519
Ecological Applications	55	9 (2.0)	3.672
Global Biogeochemical Cycles	52	10 (1.9)	4.294

TP: total articles; IF: impact factor.

3.3. Publication Performances: Countries, Institutions, and Collaborations

The publication performance analysis of different countries was based on journal articles in which the address and affiliation of at least one author were provided. Of all the 2,750 articles with author address information, 2,041 (74%) articles were single country publications and 709 (26%) articles were collaborative country publications. Table 3 presents the top 20 productive ones of all the 87 countries appeared and is ranked by the number of articles that each country produced. Thirteen of the 20 countries located in Europe, while 2 in North

America, 2 in Asia, 2 in Oceania and one in South America. USA contributed 48% of the total articles with 1,326 publications, followed distantly by UK (263; 9.6%) and Germany (254; 9.2%). USA, which also ranked first in single country publication, collaborative country publication, first author and reprint author publication, played a dominant role in nitrogen cycle research. Europe and North America are the two territories [41], whose nitrogen cycles are severely affected by agriculture production, combustion of fossil fuels and changes of landuse. Programs aiming at exploring the mechanism of long-term nitrogen deposition effect on forest ecosystems, including the Chronic Nitrogen Amendment experiment at the Harvard Forest in central Massachusetts of USA [42] and NITREX (Nitrogen Saturation Experiment) and EXMAN (Experimental Manipulation of Forest Ecosystems in Europe) program in Europe [19, 43] have been carried out for more than 20 year. Researchers have already focused on the sources and consequences of the human alteration of nitrogen cycle [1]. This may provide supporting evidence to the powerful research influence of USA and Europe. Of all the top countries, Austria has the highest collaborative rate (73%), followed by Switzerland (71%) and Belgium (70%).

Table 3. Most productive countries in research on nitrogen cycle, 1992-2009

Country	TP (%)	SPR (%)	CPR (%)	FPR (%)	RPR (%)	%C
USA	1,326 (48)	1 (48)	1 (49)	1 (42)	1 (42)	26
UK	263 (9.6)	2 (6.5)	3 (18)	2 (7.1)	2 (6.6)	50
Germany	254 (9.2)	3 (5.1)	2 (21)	3 (6.0)	3 (6.3)	59
Canada	187 (6.8)	4 (4.8)	4 (13)	4 (4.9)	4 (5.0)	48
France	184 (6.7)	5 (4.7)	5 (13)	5 (4.8)	5 (4.8)	48
Australia	154 (5.6)	6 (3.8)	6 (11)	6 (4.3)	6 (4.2)	49
Netherlands	131 (4.8)	8 (2.9)	7 (10)	7 (3.2)	8 (3.0)	54
Japan	101 (3.7)	7 (3.4)	15 (4.4)	8 (3.1)	7 (3.2)	31
China	98 (3.6)	9 (2.4)	9 (6.9)	9 (2.8)	9 (2.9)	50
Denmark	93 (3.4)	11 (1.7)	8 (8.3)	11 (2.0)	11 (1.9)	63
Spain	81 (2.9)	10 (2.3)	13 (4.9)	10 (2.3)	10 (2.4)	43
Sweden	70 (2.5)	14 (1.1)	10 (6.8)	13 (1.5)	13 (1.6)	69
Italy	65 (2.4)	13 (1.3)	11 (5.4)	14 (1.4)	14 (1.6)	58
New Zealand	59 (2.1)	12 (1.6)	17 (3.8)	12 (1.7)	12 (1.7)	46
Brazil	57 (2.1)	16 (1.0)	12 (5.2)	15 (1.2)	15 (1.2)	65
Switzerland	49 (1.8)	17 (0.69)	13 (4.9)	18 (0.84)	17 (0.87)	71
Austria	40 (1.5)	22 (0.54)	16 (4.1)	17 (0.87)	18 (0.84)	73
Russia	39 (1.4)	14 (1.1)	20 (2.4)	16 (1.0)	16 (1.1)	44
Norway	31 (1.1)	19 (0.59)	19 (2.7)	23 (0.62)	19 (0.76)	61
Belgium	30 (1.1)	25 (0.44)	18 (3.0)	20 (0.65)	22 (0.65)	70

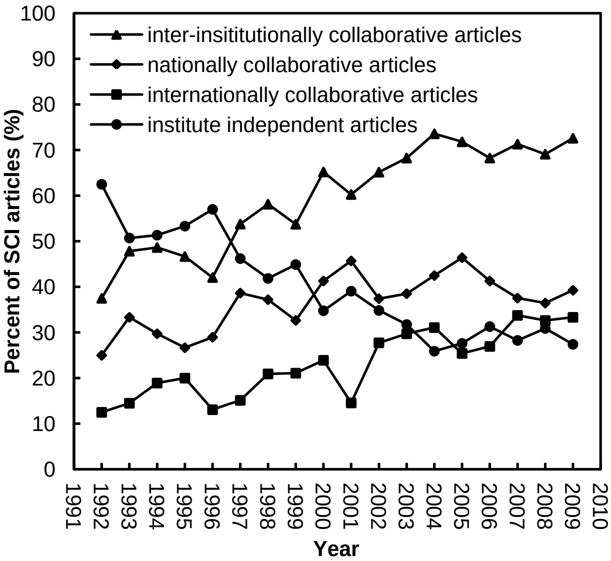
TP: total articles; SPR: single institution publication rank; CPR: inter-institutionally collaborative publication rank; FPR: first author publication rank; RPR: reprint author publication rank; %C: collaborative percent of TP.

There are 1,884 institutions in total of the 2,750 articles related to nitrogen cycle research. Table 4 presents the top 20 productive institutions and is ranked by the number of articles each institute produced. Eighteen of the 20 institutions listed are in the USA, while the remaining two is National Institute for Agricultural Research (INRA) in France and Chinese Academy of Science (CAS) in China. Since CAS is made up of branches in different cities, results for institutions would be different if publications are divided among branches. Of all the institutions, University Colorado in the USA ranked first, contributing 63 articles in total, followed by University of California Berkeley (USA; 61; 2.2%), United States Department of Agriculture, Agricultural Research Service (USA; 61; 2.2%), Colorado State University (USA; 54; 2.0%), and University of Minnesota (USA; 53; 2.2). It is obvious that USA possesses a stronger research power in nitrogen cycle field. All of the top 20 institutions have more collaborative publications than independent ones, especially

United States Forest Service (USFS) and Princeton University with collaborative rate 97% and 95% respectively. However, a bias appeared because the Chinese Academy of Sciences has over 100 branches in different cities [40]. At present, the publications of the institute were pooled as one heading, and publications divided into branches would result in different rankings.

Of the 2,750 articles with address information, 36% were published by single institute, and the remaining 64% were all inter-institutional articles, either nationally or internationally collaborative works. It is evident that collaboration now plays an important role in contemporary nitrogen cycle research. Figure 2 shows the independent and collaborative share of articles during 1992 to 2009. As could be seen, inter-institutional collaborative articles were becoming more prevalent in recent years, while share of institute independent articles was in a trend of decrease. Collaborative rates rose from 38% in 1992 to 73% in 2009, and shares of both national and international collaborative rates were also in ascending trend, though not as apparent as collaborative rates. As collaborative productivity among countries gradually caught up with nationally collaborative works, it is predicted that collaborative work of nitrogen cycle research will shifted from domestic inter-institute to international collaborations.

Figure 2. Independent and collaborative share of articles per year, 1992-2009



3.4. Research Emphasis: Author Keywords, Words in Title, and KeyWords Plus

Author Keywords

Author keywords supply information of research trend that is concerned by researchers throughout the world. Bibliometric method of author keyword analysis appeared in recent years and has been only used several times for trend analysis [38,44]. Author keywords that appeared in the related articles of nitrogen cycle from 1992-2009 were counted and ranked in 3 six-year period. Of all the articles examined, 5,534 keywords were used. Among them, 4,211 (76%) keywords appeared only once, while 619 (11%) appeared twice. The large number of once-only author keywords probably indicates a lack of continuity in research and a wide disparity in research focus. Furthermore, these keywords might not be standard or widely accepted by researchers [45]. Table 5 presents the most active 30 keywords during the last 18 years. Except for “nitrogen cycle”, “nitrogen cycling”, “N cycling” which were used for searching words in this study, “nitrification”, “denitrification”, “mineralization”, “decomposition”, and “nitrogen fixation” were also frequently used keywords, indicating that segment processes of the nitrogen cycle were still attracting great attention due to the existence of uncertainties, while the “stable isotope”- “N-15” was always used to quantify the fate of nitrogen in the cycle. Also, “anammox”, which is the anaerobic process of denitrification, is also attracting research attention, ranking to 25 during 2004-2009 with no related articles before 2004. Rank of “climate change” ascended from 32 in 1992-1997 to 19 in 2004-2009, and ranks of “soil” and “nitrate leaching” both rose markedly from 73 and 195 to 17 and 31. It is inferred that human alteration of nitrogen cycle is tightly linked to “climate change” [1]. Particularly, “soil” of forest ecosystems can uptake and store carbon from atmosphere under the fertilizer effect of nitrogen deposition and in turn may alleviate climate change, while “nitrate leaching” to streams, groundwater, and atmosphere leads to the disappearance of continued C storage [46]. Some compounds such as “nitrate”, “nitrous oxide”, “ammonium”, “dissolved organic nitrogen”, as well as “carbon” had higher growing rates too. The rank and percentage of “nitrous oxide” went up from 20 (2.2%) in 1992-1997 to 14 (2.8%) in 2004-2009, “carbon” from 32 (1.5%) in 1992-1997 to 10 (3.3%) in

2004-2009, "dissolved organic nitrogen" from 73 (0.73%) in 1992-1997 to 20 (1.7%) in 2004-2009, in accordance with the attention given to nitrogen- or carbon-containing chemicals in the past decade because of their impact on global climate change. On the contrary, rank and percentage of words like "nutrient cycling", "amino acid", "elevated CO_2", and "soil organic matter" descended during 1992-2009, either because of replacing by more specific or definite single words or falling out of the mainstream of nitrogen cycle research.

Table 5. Top 30 most used author keywords, 1992-2009

Author keywords	TP	92-09 R (%)	92-97 R (%)	98-03 R (%)	04-09 R (%)
nitrogen cycling	281	1 (14)	1 (18)	1 (15)	1 (13)
nitrogen	217	2 (11)	2 (14)	2 (12)	5 (10)
nitrogen cycle	217	2 (11)	3 (12)	3 (11)	2 (11)
nitrification	205	4 (11)	4 (11)	4 (10)	4 (11)
denitrification	175	5 (9.0)	7 (7.3)	5 (6.5)	3 (11)
nitrate	100	6 (5.1)	12 (3.3)	6 (5.4)	6 (5.4)
N-15	87	7 (4.5)	5 (7.7)	7 (4.9)	10 (3.3)
mineralization	86	8 (4.4)	5 (7.7)	9 (3.7)	7 (4.0)
N cycling	77	9 (3.9)	11 (3.7)	8 (4.6)	9 (3.6)
microbial biomass	70	10 (3.6)	8 (4.4)	11 (2.9)	8 (3.8)
ammonium	60	11 (3.1)	13 (2.9)	11 (2.9)	12 (3.2)
nitrogen mineralization	57	12 (2.9)	10 (4.0)	9 (3.7)	17 (2.2)
carbon	53	13 (2.7)	32 (1.5)	19 (2.2)	10 (3.3)
decomposition	50	14 (2.6)	23 (1.8)	16 (2.4)	13 (2.9)
nitrous oxide	49	15 (2.5)	20 (2.2)	19 (2.2)	14 (2.8)
stable isotopes	48	16 (2.5)	23 (1.8)	19 (2.2)	14 (2.8)
nitrogen fixation	48	16 (2.5)	73 (0.73)	11 (2.9)	16 (2.7)
nutrient cycling	45	18 (2.3)	8 (4.4)	16 (2.4)	20 (1.7)
climate change	39	19 (2.0)	32 (1.5)	14 (2.5)	19 (1.8)
n mineralization	37	20 (1.9)	20 (2.2)	16 (2.4)	25 (1.5)
amino acids	37	20 (1.9)	13 (2.9)	22 (2.1)	25 (1.5)
soil respiration	33	22 (1.7)	13 (2.9)	43 (1.1)	20 (1.7)
soil	32	23 (1.6)	73 (0.73)	43 (1.1)	17 (2.2)
elevated CO_2	32	23 (1.6)	20 (2.2)	30 (1.4)	24 (1.6)
grassland	31	25 (1.6)	32 (1.5)	30 (1.4)	20 (1.7)
biogeochemistry	31	25 (1.6)	45 (1.1)	14 (2.5)	40 (1.1)
soil organic matter	30	27 (1.5)	13 (2.9)	30 (1.4)	34 (1.2)
dissolved organic nitrogen	29	28 (1.5)	73 (0.73)	30 (1.4)	20 (1.7)
nitrate leaching	28	29 (1.4)	195 (0.37)	22 (2.1)	31 (1.3)
sediment	26	30 (1.3)	23 (1.8)	60 (1.0)	28 (1.4)

TP: total articles; R (%): rank (percentage of keywords in total articles)

Words in Article Title

Title of an article always includes the key information that the author would most like to express to readers [47]. In our study, distribution of words in title was analyzed by bibliometreic method to map the focus of research subjective. Prepositions include "of", "in", "at", "on", "with", and etc., were discarded since they were meaningless for further analysis. As a result, the most frequently used substantives in title were listed in Table 6. Unlike preserving the precise words the authors wanted to transmit in keywords analysis, titles in this analysis were segmenting into single words. Hence, phrases appeared in author keywords may show in the form of single words in title. Eighteen of the top 30 most used words in title also appeared in the top 30 of author keywords, which reflected consistence in research direction. Except for words that appeared in author keywords, "forest/forests", "effects", "dynamics", "ecosystem/ecosystems", "model", "plant", "production", "species", and "atmospheric" only ranked high in words in title. Of particular concern, rank and percentage of "forests" and "species" rose markedly. It is indicated that much research focused on the "dynamics" of nitrogen cycle and its "effects" on "ecosystems", especially towards the ability of "forest" ecosystem to retain nitrogen, stimulation on "production" potential of "plant" and disturbance on "species" diversity. Meanwhile, atmospheric simulation of nitrogen cycle calls for "model" studies.

Table 6. Top 30 most used words in title, 1992-2009

Word in title	TP	92-09 R (%)	92-97 R (%)	98-03 R (%)	04-09 R (%)
nitrogen	1,300	1 (47)	1 (45)	1 (50)	1 (46)
soil	581	2 (21)	3 (17)	2 (20)	2 (23)
cycling	438	3 (16)	2 (20)	3 (14)	3 (16)
forest	286	4 (10)	5 (8.1)	4 (13)	5 (9.6)
N	280	5 (10)	9 (6.1)	5 (9.7)	4 (12)
effects	254	6 (9.2)	4 (8.5)	6 (9.3)	6 (9.4)
carbon	235	7 (8.5)	7 (7.7)	8 (8.2)	7 (9.0)
soils	198	8 (7.2)	6 (7.9)	9 (7.3)	9 (6.9)
dynamics	198	8 (7.2)	8 (7.3)	7 (8.3)	10 (6.4)
microbial	168	10 (6.1)	15 (3.9)	12 (5.5)	8 (7.2)
ecosystem	156	11 (5.7)	12 (4.7)	11 (6.1)	12 (5.7)
organic	151	12 (5.5)	21 (3.3)	12 (5.5)	11 (6.2)
nitrate	134	13 (4.9)	10 (5.3)	15 (4.5)	13 (4.9)
model	126	14 (4.6)	16 (3.7)	10 (6.6)	19 (3.6)
cycle	126	14 (4.6)	21 (3.3)	14 (5.2)	15 (4.6)
plant	114	16 (4.1)	16 (3.7)	15 (4.5)	17 (4.1)
N-15	110	17 (4.0)	34 (2.4)	18 (3.7)	14 (4.7)
forests	100	18 (3.6)	58 (1.8)	21 (3.6)	16 (4.3)
CO_2	100	18 (3.6)	21 (3.3)	15 (4.5)	22 (3.2)
denitrification	93	20 (3.4)	21 (3.3)	32 (2.6)	18 (3.9)
nutrient	83	21 (3.0)	21 (3.3)	38 (2.5)	22 (3.2)
mineralization	83	21 (3.0)	11 (4.9)	26 (2.8)	35 (2.5)
production	83	21 (3.0)	14 (4.1)	18 (3.7)	47 (2.2)
species	77	24 (2.8)	129 (1.0)	32 (2.6)	20 (3.5)
grassland	77	24 (2.8)	39 (2.2)	26 (2.8)	25 (3.0)
changes	77	24 (2.8)	39 (2.2)	26 (2.8)	25 (3.0)
nitrification	74	27 (2.7)	21 (3.3)	23 (3.1)	47 (2.2)
elevated	70	28 (2.5)	69 (1.6)	21 (3.6)	47 (2.2)
atmospheric	70	28 (2.5)	39 (2.2)	18 (3.7)	68 (1.9)
ecosystems	69	30 (2.5)	12 (4.7)	59 (2.0)	60 (2.1)

TP: total articles; R (%): rank (percentage of keywords in total articles)

KeyWords Plus

KeyWords Plus provides additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes [48], which substantially augments words in title and author keywords indexing [49,50]. Table 7 presents the distribution of KeyWords Plus with their rank and percentage in different periods. Of all the KeyWords Plus, "dynamics" ranked first during the last 18-year period. As it is in author keywords, "nitrogen", "nitrification", and "denitrification" also ranks high in distribution of KeyWords Plus, which again reflects the hotspot in nitrogen cycle research. KeyWords Plus are words or phrases that frequently appear in the title of an article's references, but do not necessarily appear in the title of the article itself [36]. Twenty of the top 30 most used KeyWords Plus appeared in either the top 30 of author keywords or words in title. As KeyWords Plus may include important terms that are not listed in title or author keywords [36], it can be concluded that additional spikes of attention were given to "growth", "water", "availability", "deposition", "phytoplankton", "response", "phosphorus", "diversity", "marine-sediments", and "bacteria", which appeared only in top 30 of KeyWords Plus. Given human-caused acceleration of nitrogen “fixation” and nitrogen “deposition” and increase of nitrogen “availability” in nitrogen-limiting system, more ecosystems including “water” and “marine” systems are affected by eutrophication and acidification [21]. Therefore research on “responses” of plant “growth”, “bacteria”, “sediments”, and biological “diversity” in different ecosystems are attracting special attention. Moreover, interactions between nitrogen cycle and other biogeochemical cycles like “carbon” and “phosphorus” are calling for a global perspective of the earth system.

Table 7. Top 30 most used KeyWords Plus, 1992-2009

KeyWords Plus	TP	92-09 R (%)	92-97 R (%)	98-03 R (%)	04-09 R (%)
dynamics	301	1 (12)	4 (11)	1 (12)	1 (11)
carbon	280	2 (11)	1 (11)	2 (10)	2 (11)
nitrogen	256	3 (9.8)	6 (10)	2 (10)	4 (9.4)
denitrification	236	4 (9.1)	3 (11)	7 (8.4)	5 (8.9)
nitrification	233	5 (9.0)	4 (11)	6 (8.8)	7 (8.5)
soil	228	6 (8.8)	7 (10)	9 (8.1)	6 (8.8)
organic-matter	217	7 (8.3)	14 (6.1)	10 (7.2)	3 (9.7)
nitrate	215	8 (8.3)	8 (9.8)	4 (9.3)	8 (7.1)
ecosystems	205	9 (7.9)	10 (9.1)	5 (8.9)	9 (6.8)
mineralization	199	10 (7.6)	2 (11)	8 (8.2)	10 (6.3)
growth	150	11 (5.8)	9 (9.6)	11 (6.0)	14 (4.4)
microbial biomass	130	12 (5.0)	16 (5.1)	16 (3.9)	11 (5.6)
water	124	13 (4.8)	12 (6.8)	13 (5.1)	18 (3.9)
decomposition	122	14 (4.7)	13 (6.3)	14 (4.5)	15 (4.3)
forest	121	15 (4.6)	18 (4.9)	12 (5.3)	16 (4.2)
ecosystem	116	16 (4.5)	22 (4.0)	17 (3.7)	12 (5.1)
availability	108	17 (4.1)	16 (5.1)	17 (3.7)	17 (4.1)
deposition	99	18 (3.8)	18 (4.9)	14 (4.5)	29 (3.0)
biomass	94	19 (3.6)	21 (4.4)	25 (3.3)	20 (3.5)
ammonium	91	20 (3.5)	11 (7.9)	21 (3.5)	50 (2.1)
plants	90	21 (3.5)	15 (5.4)	17 (3.7)	31 (2.7)
nitrogen mineralization	89	22 (3.4)	26 (3.5)	21 (3.5)	21 (3.3)
phytoplankton	82	23 (3.2)	18 (4.9)	17 (3.7)	36 (2.3)
responses	79	24 (3.0)	32 (3.0)	29 (2.8)	24 (3.2)
phosphorus	79	24 (3.0)	22 (4.0)	37 (2.4)	27 (3.1)
diversity	78	26 (3.0)	N/A	72 (1.6)	13 (4.8)
marine-sediments	75	27 (2.9)	44 (2.3)	76 (1.5)	18 (3.9)
bacteria	73	28 (2.8)	26 (3.5)	42 (2.2)	30 (2.9)
soils	70	29 (2.7)	24 (3.7)	27 (3.1)	44 (2.1)
plant	70	29 (2.7)	31 (3.3)	27 (3.1)	36 (2.3)

TP: total articles; R (%): rank (percentage of keywords in total articles); N/A: not applicable

3.5. Analysis of Research Trend

Weak points exist in the separate analysis of author keywords, words in title and KeyWords Plus, since a lack of overall situation. Combination analysis of three kinds of words has been reported [47]. Synonymic single words and congeneric phrases from above table were summed and grouped into categories, so as to analyze the historical development of the science and programs more completely and precisely, and more importantly, to discover the directions the science is taking. Based on the top words analysis of author keywords, words in title, and KeyWords plus, hotspot of nitrogen cycle research could be classified into three categories – segmental processes involved in nitrogen cycle, manifold environmental items influenced by human alteration of nitrogen cycle, and important elements or chemicals coupled with nitrogen cycle. The words listed in Figs. 3-5 all include their plural forms, abbreviations, and other transformations, as well as words with similar meanings.

Figure 3. Comparison of trends of nitrogen cycle processes, including "dynamics", "mineralization", "nitrification", "denitrification", "decomposition", and "deposition".

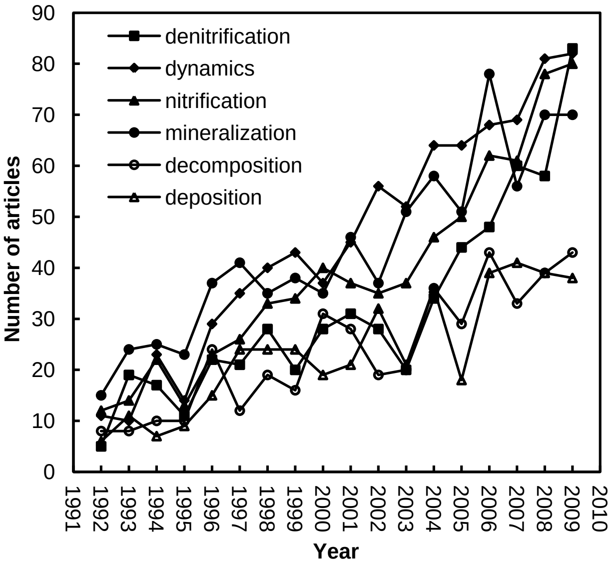
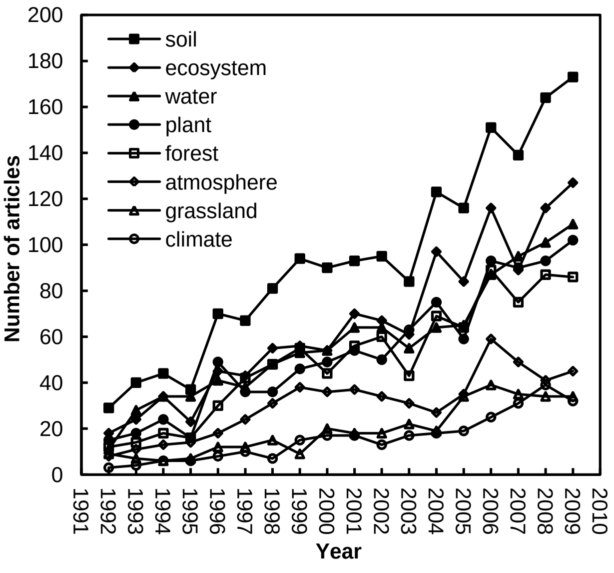
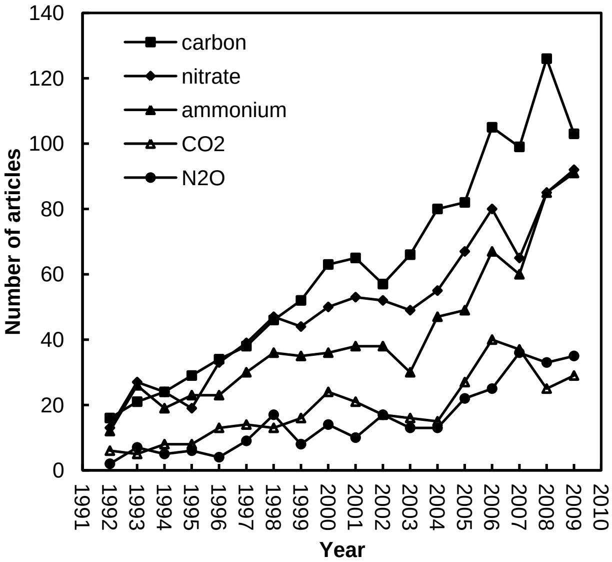


Figure 4. Comparison of trends of influenced items by human alteration of nitrogen cycle, including "soil", "ecosystem", "water", "plant", "forest", "atmosphere", "grassland", and "climate".



"Dynamics" and "mineralization" are the most popular studied processes of nitrogen cycle, while articles related to "nitrification" and "denitrification" grew quickly after 2005, even surpassed "dynamics" and "mineralization" in 2009 (Fig. 3). Nitrification and denitrification are two central processes of the global nitrogen cycle [51]. Data on the fate of 65% reactive nitrogen inputs to terrestrial biosphere was unclear and denitrification was believed to be an important reactive nitrogen sink on earth [52]. Due to the large uncertainties in measuring nitrification and denirification rates in upland terrestrial system, the two central processes were continually drawing research attention [53]. Articles related to "deposition" grew gradually from 6 in 1992 to 36 in 2004, and changed little until 2009. This might be attributed to the fact that the mechanism of nitrogen deposition was already clear; whereas, attention has rocketed in the research which looked into the effects and responses of different ecosystems to nitrogen deposition. From above analysis, it is predicted that one of nitrogen cycle research trends will lie in the exploration of nitrification and denitrification mechanism until more definite data or more convincing method shows up.

Figure 5. Comparison of trends of important elements or chemicals coupled with nitrogen cycle, including "carbon", "nitrate", "ammonium", "CO_2", and "N_2O".



Another hotspot is the study of ecological response to alteration of nitrogen cycle. It is evident that manifold ecological items are influenced by perturbation of nitrogen cycle, including soil, atmosphere, forest, plant, and etc. Comparison of research trends (Fig. 4) showed that "soil" had a higher incidence than other items, being involved in 1690 articles, which accounts for more than 50% of all the articles related. Soils contain the largest near-surface reservoir of terrestrial carbon [54], and knowledge of the factors controlling soil carbon storage and turnover is essential for understanding the global climate change [23]. However, there remains large uncertainty in the potential response of soil dynamics to the rapid increase of reactive nitrogen and much attention has been focused on understanding the mechanism of soil C response to changing N availability and more accurate SOM (soil organic matter) carbon measurement techniques [55,41]. Except for "soil", the higher incidence of "ecosystems", "water", "plant", and "forest" indicates the most heavily influenced items under human alteration of nitrogen cycle. More than 80% of denitrification is occurring in soils and freshwater systems (groundwater, rivers, lakes and reservoirs). "Soil" and "water", being the main place for nitrification and denitrification and directly influenced by acidification and eutrophication, play a critical role in nitrogen cycle. "Ecosystems", especially "forest" and "grassland", and even different factors of ecosystems, like "plant" and "climate", are all under the cascading effects of human changed global nitrogen cycle. Articles related to "atmosphere" peaked in 2006, and then decreased little in 2007-2009 and "climate" research in nitrogen cycle increased continually during the period. In all, alteration of nitrogen cycle makes the once limited nitrogen supply reach a new high level. The performance of organism and ecosystems under such conditions will be another continually trend of nitrogen cycle research.

When comparing the chemicals or elements studied, it is interesting to note that research related to "carbon" was investigated most in nitrogen cycle and study related to "CO_2" in nitrogen cycle also attracted much attention (Fig. 5). Topics including "N_2O" peaked in 2007, which could partly be interpreted as due to Climate Change 2007 [12]. Historically, N_2O has undergone large changes that were synchronized with climate variation [56, 57]. Besides, changes in marine nitrogen cycle were suggested to be a leading cause of the observed variations in the concentration of atmospheric CO_2 [58]. Despite lack of understanding of the underlying processes forcing these changes, the close correspondence between atmospheric CO_2 levels, temperature and atmospheric N_2O concentrations demonstrate that nitrogen cycle is closely coupled to variations in the climate system and in the carbon cycle [24]. Research on interactions between nitrogen cycle and carbon cycle will also be a hot trend as concern over climate change rockets. "Nitrate" and "ammonium", which are the main forms of organic nitrogen, were important chemicals studied in nitrogen cycle and number of articles related to them increased steadily. Nitrogen additions have led to increased nitrate mobility shown by experiments, which further results in a series of increases of nitrate concentrations in soils, lakes, and streams [59]. Of particular concern, nitrate in drinking water were causing universal attention due to human health concern [60].

4. Conclusion

In this study on research trend in nitrogen cycle based on related literature from SCI-Expanded, some significant points on the research performance during the period of 1992 to 2009 have been obtained. Articles related to nitrogen cycle grow up expeditiously after 1995. The main distribution field of nitrogen cycle was in ecology, soil science, and environmental sciences, while *Soil Biology & Biochemistry* published most of the articles. English was by far the predominant language; while other 8 languages also appeared, indicating the global concern over nitrogen cycle research. Of all the participating countries, USA was the most productive country, followed distinctly by UK and Germany. University Colorado in the USA, University of California Berkeley, and United States Department of Agriculture- Agricultural Research Service, were the top three productive institutions. Research outputs of institutions and countries show that research collaborative articles have shifted from national inter-institutional to international collaboration. Through synthetically and innovatively analysis of distribution in author keywords, words in title, and KeyWords Plus, the development and trend of research on nitrogen cycle was roughly found. It can be concluded that nitrogen cycle research related to "soil", "ecosystem", "water", "carbon", "dynamics", "nitrification", and "denitrification" may be major directions of nitrogen cycle research in future. The result analysis by this bibliometric method can help relevant researchers to realize current focus of nitrogen cycle, and establish future research direction.

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Table 4. Most productive institutions in research on nitrogen cycle, 1992-2009

Institutions	TP (%)	SPR (%)	CPR (%)	FPR (%)	RPR (%)	%C
University of Colorado, USA	62 (2.3)	2 (1.7)	7 (2.6)	1 (1.4)	2 (1.2)	73
University of California Berkeley, USA	61 (2.2)	7 (1.2)	2 (2.8)	2 (1.3)	4 (1.1)	80
United States Department of Agriculture, Agricultural Research Service (USDA ARS), USA	61 (2.2)	3 (1.3)	4 (2.7)	5 (1.2)	1 (1.4)	79
Colorado State University, USA	54 (2.0)	44 (0.4)	1 (2.8)	13 (0.73)	25 (0.53)	93
University of Minnesota, USA	53 (1.9)	17 (0.71)	6 (2.6)	13 (0.73)	25 (0.53)	87
Institute of Ecosystem Studies, USA	53 (1.9)	44 (0.4)	2 (2.8)	20 (0.65)	10 (0.84)	92
National Institute for Agricultural Research (INRA), France	52 (1.9)	3 (1.3)	11 (2.2)	7 (0.91)	6 (1.0)	75
University of New Hampshire, USA	51 (1.9)	44 (0.4)	5 (2.7)	10 (0.87)	8 (0.91)	92
Chinese Academy of Science, China	51 (1.9)	7 (1.2)	11 (2.2)	3 (1.2)	2 (1.2)	76
University of California Davis, USA	49 (1.8)	1 (1.9)	22 (1.7)	3 (1.2)	4 (1.1)	61
Cornell University, USA	49 (1.8)	13 (0.91)	9 (2.3)	7 (0.91)	15 (0.72)	82
University of Wisconsin, USA	48 (1.7)	7 (1.2)	14 (2.0)	11 (0.76)	10 (0.84)	75
Marine Biological Lab, USA	47 (1.7)	17 (0.71)	9 (2.3)	16 (0.69)	9 (0.87)	85
University of Michigan, USA	44 (1.6)	65 (0.30)	8 (2.3)	7 (0.91)	13 (0.76)	93
Oregon State University, USA	43 (1.6)	10 (1.1)	18 (1.8)	6 (1.1)	7 (1.0)	74
Duke University, USA	40 (1.5)	30 (0.51)	15 (2.0)	24 (0.62)	18 (0.65)	88
University of Georgia, USA	39 (1.4)	30 (0.51)	17 (1.9)	16 (0.69)	20 (0.57)	87
Princeton University, USA	39 (1.4)	97 (0.20)	13 (2.1)	13 (0.73)	13 (0.76)	95
United States Geological Survey (USGS), USA	38 (1.4)	24 (0.61)	18 (1.8)	16 (0.69)	10 (0.84)	84
United States Forest Service (USFS), USA	36 (1.3)	171 (0.10)	15 (2.0)	78 (0.25)	71 (0.27)	97

TP: total articles; SPR: single country publication rank; CPR: internationally collaborative publication rank; FPR: first author publication rank; RPR: reprint author publication rank; %C: collaborative percent of TP.