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Global biodiversity research during 1900–2009: a bibliometric analysis

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Abstract We performed a bibliometric analysis of published biodiversity research for the period of 1900–2009, based on the Science Citation Index (SCI) database. Our analysis reveals the authorial, institutional, spatiotemporal, and categorical patterns in biodiversity research and provides an alternative demonstration of research advancements, which may serve as a potential guide for future research. The growth of article outputs has exploded since the 1990s, along with an increasing collaboration index, references, and citations. Ecology, environmental sciences, biodiversity conservations, and plant science were most frequently used subject categories in biodiversity studies, and *Biological Conservation, Journal of Soil and Water Conservation, Conservation Biology and Biodiversity and Conservation* were most active journals in this field. The United States was the largest contributor in global biodiversity research, as the U.S. produced the most single-country and collaborative articles, had the greatest number of top research institutions, and had a central position in collaboration networks. We perceived an increasing number of both internationally collaborative and inter-institutionally collaborative articles, with the latter form of collaboration being more prevalent than the former. A keyword analysis found several interesting terminology preferences, confirmed conservation's central position as a topic in biodiversity research, revealed the adoption of advanced technologies, and demonstrated keen interest in both the patterns and underlying processes of ecosystems. Our study reveals patterns in scientific outputs and academic collaborations and serves as an alternative and innovative way of revealing global research trends in biodiversity.

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Introduction

Biodiversity refers to variety in life forms and is usually measured at three different levels: genes, species, and ecosystems. Biodiversity is vital for human beings, not only because ecosystems support human beings, but also because individual species all have important roles to play in the ecosystem and can, therefore, greatly impact the environment in which humans live. Biodiversity is closely related to other global environment changes and globalization issues, such as climate change, land use and land cover change, and sustainable development (Vitousek 1994; Thuiller et al. 2005; Gude et al. 2007). However, it has been argued that human activities have been accompanied by a loss in biodiversity and even massive extinction of certain genes, species, and/or ecosystems. Although international organizations and countries have made significant efforts to conserve biodiversity, such as the "Convention on Biological Diversity," the "Census of Marine Life," and "DIVERSITAS" (Glowka et al. 1994; Cropper 1993; Costello et al. 2010), these efforts have not been sufficient, and biodiversity loss has continued (Tisdell 2003; Burns et al. 2009). Biodiversity has been studied from various perspectives, including the spatiotemporal patterns of biodiversity (Gray 1997; Heino et al. 2005), the underlying dynamics of biodiversity changes (Pielke et al. 2002), the methods and technologies for biodiversity research (Hadrys et al. 1992; Muyzer et al. 1993; Mueller and Wolfenbarger 1999; Manzelli et al. 2007) and the practical conservation of biodiversity (Margules and Pressey 2000; Myers et al. 2000). In addition to these studies, a bibliometric analysis of global biodiversity research could serve as an alternative and innovative way of revealing global research trends in biodiversity.

Bibliometric analysis includes a series of visual and quantitative procedures to generalize the patterns and dynamics in scientific publications (Pritchard 1969). Bibliometric analyses have been conducted to reveal the global trends of various research fields (Falagas et al. 2006; Tarkowski 2007; Xie et al. 2008; Li et al. 2008). Whereas conventional bibliometric methods center on citation and content analysis, the newly-developed bibliometric analysis evaluates the scholarly outputs of authors, institutions, and countries, and identifies the temporal evolution of research patterns (Chiu and Ho 2007; Li et al. 2009; Zhang et al. 2009).

In this paper, we perform a bibliometric analysis of published biodiversity research for the period of 1900–2009. More specifically, this article aims at (1) revealing the authorial, institutional, spatiotemporal, and categorical patterns in biodiversity research; (2) summarizing the global research trends from multiple perspectives; and (3) providing an alternative demonstration of research advancements, which may serve as a potential guide for future research.

Data and methods

We gathered academic publications related to biodiversity research based on the Scientific Citation Index (SCI) bibliographic database, which was maintained by the Institute of Scientific Information, USA. SCI is the most frequently-used index in scientific output analysis (Kostoff 2000). We performed bibliographic searches and compiled references using an online version of the SCI database. Seven search terms, including "biodiversity," "biological diversity," "bio-diversity," "genetic diversity," "ecosystem diversity," "species diversity," and "landscape diversity" were used to locate publications that contained these words in publications' titles, abstracts, or keyword lists. These searching terms are designed based on previous bibliometric analysis of biodiversity and related researches (Cameron 2008; Chen et al. 2009). We also gathered all papers that were published in six specialized journals, including *Biodiversity and Conservation*, *Systematics and Biodiversity*, *Biological Conservation*, *Conservation Biology*, *Journal of Soil and Water Conservation*, *Resources Conservation and Recycling*. We then retrieved individual document information, including author name(s), author affiliation(s), subject category(ies), journal name(s), publication title(s), and publication year(s), and eliminated duplicated records. Although we searched documents published between 1900 and 2009, the earliest biodiversity-related publication in the SCI database was published in 1922. Using the above-mentioned searching strategy, a total of 75,860 publications were identified in the SCI database as being biodiversity-related.

As is common in other bibliometric analyses (Ho 2007; Tian et al. 2008; Zhang et al. 2010), research published by authors from England, North Ireland, Scotland, and Wales were labeled as documents originating in the United Kingdom, and publications from Hong Kong were apportioned with those from Mainland China. The collaborations among authors, institutions, or countries were determined based on the complete count strategy, i.e., each signatory on the documents was treated equally. At the author level, "collaborated documents" referred to those publications with two or more signatories. In addition, inter-institutionally collaborative publications and internationally collaborative publications were defined as publications by two or more institutions and countries/territories, respectively.

Seventeen document types were found among the total 75,860 publications, and the most frequent document type was peer-reviewed journal articles (61,418), which were responsible for 81.0% of the total publications. Proceeding papers (4,746; 6.3%), reviews (4,163; 5.5%), editorial materials (2,719; 3.6%), and letters (1,017; 1.3%) also comprised a significant portion of total. Other less significant document types included meeting abstracts (716), bibliographies (3), biographical items (17), book reviews (103), corrections (143), corrections/additions (66), discussions (12), items about individuals (12), news items (320), notes (378), reprints (18), and software reviews (6). The number shown in parentheses indicates the number of papers found for each document type. As consistent with other bibliometric research, we focused on original and peer-reviewed articles and excluded documents of all other types from further analysis.

As for the publishing language, 59,895 or 97.5% of the 61,418 journal articles were written in English. This observation was consistent with the fact that English is the dominant academic language and that most SCI indexed journals are published in English. Other major publication languages included French (396), Spanish (354), Portuguese (259), Russian (234), and German (142). Additionally, Chinese (38), Japanese (25), Polish (22), Czech (10), Finnish (8), Hungarian (7), Croatian (6), Korean (5), Turkish (5), Dutch (4), Italian (4), Lithuanian (2), Slovakian (1), and Swedish (1) were minor publication languages in biodiversity research.

A bibliometric analysis was performed to reveal the trends in biodiversity studies from the following perspectives: publication outputs, subject categories and major journals, author productivity, geographic and institutional distribution of publications, and keywords analysis.

Results and discussions

Publication outputs

A clear interest in biodiversity research did not emerge until the 1990s, although a few publications related to biodiversity were published previously (Fig. 1a). Along with the development of SCI, biodiversity research continually grew in this long period, started to go up significantly in the year of 1980 and rocketed in the past two decades (Fig. 1a). The United Nations Convention on Biological Diversity (CBD) was signed by 150 government leaders at the 1992 Rio Earth Summit is dedicated to promoting sustainable development. Build on many breakthroughs since 1992, biodiversity research has became one of the most important and dynamic field of environmental and ecological research. Although this growing scientific productivity was commonly ascribed to the increasing amount of SCI-indexed publications, we found that the number of standardized publications on biodiversity, defined as the ratio of the annual number of publications on biodiversity to the annual number of publications in the SCI database, was also increasing (Fig. 1b). This rising number of standardized publications suggested a clear research focus on biodiversity, after controlling for the increasing number of publications being indexed in the SCI database.

We summarized the temporal evolution of major scientific productivity descriptors for the period of 1980–2009 in Table 1. The number of publications on biodiversity exploded from 117 in 1980–7,533 in 2009, and the average length of articles was 10.45 pages. The collaboration index, which was defined as the average number of signatories per publication, increased from 1.85 in 1980–4.45 in 2009. This growing collaboration index suggested that biodiversity studies progressively became more collaborative, whereas the growth rate is on par with collaboration index documented in other bibliometric studies (He et al. 2005; Cameron 2008; Gonzalez-Alcaide et al. 2008). Another example of expanding research in the field of biodiversity was the increasing number of citations and references that were found. The average number of references grew from 21.99 in 1980 to 45.58 in 2009. This growing number of references indicated an expanding accumulation of knowledge about biodiversity. In addition, publications on biodiversity had drawn, on average, 16.30 citations per document. All of these scientific output descriptors revealed solid growth within the research field, in terms of increasing scientific production and research collaboration.

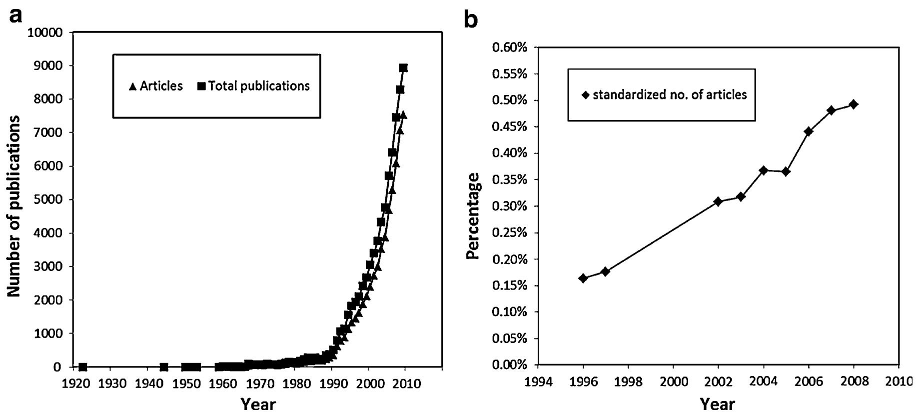

Fig. 1 The growth of absolute and standardized publication outputs

Table 1 Scientific outputs descriptors during 1980–2009

Year	TP	AU	AU/TP	PG	PG/TP	NR	NR/TP	TC	TC/TP
1980	117	217	1.85	1,031	8.81	2,573	21.99	2,360	20.17
1981	134	253	1.89	1,206	9.00	2,358	17.60	2,151	16.05
1982	156	299	1.92	1,428	9.15	3,217	20.62	3,103	19.89
1983	198	405	2.05	1,757	8.87	4,009	20.25	3,471	17.53
1984	171	344	2.01	1,665	9.74	3,456	20.21	2,979	17.42
1985	218	445	2.04	2,175	9.98	4,508	20.68	4,270	19.59
1986	192	400	2.08	2,090	10.89	4,627	24.10	3,539	18.43
1987	190	383	2.02	1,792	9.43	3,980	20.95	2,978	15.67
1988	248	504	2.03	2,192	8.84	4,682	18.88	5,205	20.99
1989	292	687	2.35	2,589	8.87	4,836	16.56	6,368	21.81
1990	358	781	2.18	3,229	9.02	7,104	19.84	8,415	23.51
1991	624	1,476	2.37	6,638	10.64	16,720	26.79	21,357	34.23
1992	787	1,861	2.36	7,740	9.83	19,353	24.59	23,410	29.75
1993	883	2,151	2.44	8,817	9.99	21,487	24.33	32,249	36.52
1994	1,142	3,007	2.63	11,200	9.81	30,326	26.56	36,564	32.02
1995	1,335	3,659	2.74	13,738	10.29	41,454	31.05	40,799	30.56
1996	1,458	4,033	2.77	14,647	10.05	53,917	36.98	45,592	31.27
1997	1,617	4,972	3.07	16,627	10.28	60,731	37.56	52,972	32.76
1998	1,894	5,972	3.15	20,479	10.81	74,042	39.09	58,358	30.81
1999	2,127	6,906	3.25	22,524	10.59	80,565	37.88	59,145	27.81
2000	2,407	8,295	3.45	25,411	10.56	96,522	40.10	73,723	30.63
2001	2,728	9,395	3.44	29,285	10.73	1,10,218	40.40	69,103	25.33
2002	3,009	10,864	3.61	32,328	10.74	1,22,290	40.64	70,624	23.47
2003	3,529	13,378	3.79	38,076	10.79	1,47,817	41.89	71,525	20.27
2004	3,884	14,870	3.83	41,165	10.60	1,65,049	42.49	70,058	18.04
2005	4,704	18,281	3.89	50,985	10.84	2,03,711	43.31	67,599	14.37
2006	5,300	22,026	4.16	57,872	10.92	2,33,255	44.01	58,247	10.99
2007	6,091	25,613	4.21	66,095	10.85	2,73,003	44.82	42,820	7.03
2008	7,071	30,700	4.34	73,105	10.34	3,11,430	44.04	27,276	3.86
2009	7,533	33,556	4.45	79,061	10.50	3,43,382	45.58	9,920	1.32
Total	61,418	2,27,492		6,41,806		24,62,937		1,00,1144	
Average			3.70		10.45		40.10		16.30

TP number of publications, *AU* number of authors, *PG* page count, *NR* cited references, *TC* total citation count; AU/TP, PG/TP, NR/TP, and TC/TP, average of authors, pages, references, and citations in a paper

Subject categories and major journals

Published biodiversity research covered 185 ISI identified subject categories in the SCI database. The four most common categories were ecology (25,584 articles; accounting for 21.3% of the total), environmental sciences (14,472; 12.0%), biodiversity conservation (11,578; 9.6%), and plant science (6,831; 5.7%). The first two and the fourth subject categories were general topics, while biodiversity conservation focused exclusively on biodiversity-related research. This finding suggested that conservation remained a top priority among the various topics being explored in biodiversity research. Other major

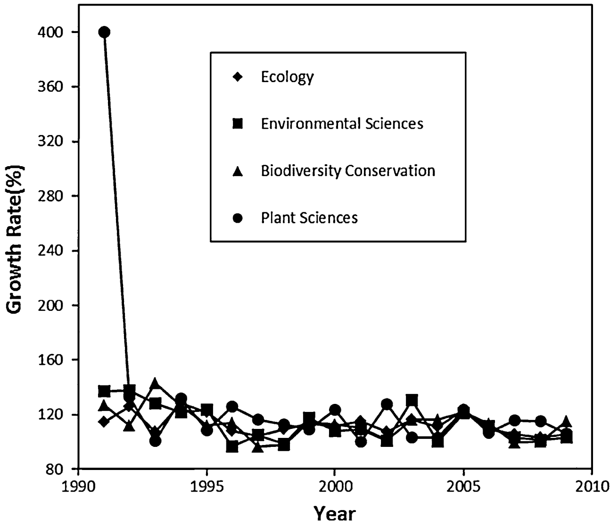

Fig. 2 Annual growth rates of articles in most active subject categories

subject categories in biodiversity research included genetics and heredity, evolutionary biology, marine and freshwater biology, microbiology, agronomy, biochemistry and molecular biology, forestry, biotechnology and applied microbiology, and zoology. However, none of these subject categories accounted for more than 10% of the total articles. We demonstrated the annual growth rates of articles in the top four categories in Fig. 2. Although these four categories enjoyed a continuous growth in the last two decades, their annual growth rates fluctuated widely. These fluctuations in growth rates suggested that the research focus in biodiversity shifted among different subject categories.

Published research on biodiversity appeared in 2,624 journals, and the top 25 most productive journals are summarized in Table 2, along with number of papers that the corresponding journals published, the number of citations that each journal received for these articles. The average citation rate of journals in biodiversity is the most direct indicator for assessing the impacts of journals: The higher the citation rate is, the greater the journal's impact is to this field. There was a high concentration of biodiversity publications in these top journals. These 25, or 0.95% out of the 2,624 journals, had published 22,521 or 36.7% of the total 61,418 articles. *Biological Conservation* ranked first and published 4,558 articles on biodiversity. The *Journal of Soil and Water Conservation* published the second most articles (2,860), followed by *Conservation Biology* (2,674), *Biodiversity and Conservation* (2,181), *Resources Conservation and Recycling* (1,064), *Molecular Ecology* (969), *Forest Ecology and Management* (701), and *Ecology* (608). From the titles and themes of these top journals, we again observed the central position of conservation as a subject in biodiversity research. Biodiversity articles that were published in these journals had received, on average, 21.26 citations, which was greater than the impact factors of these journals. We admit that these citation rates are not directly comparable to journals' impact factors (as the latter are computed with a 2-year window). Therefore, our comparisons focus on the inter-journal differences in citations to biodiversity researches, i.e., the impacts of journals in biodiversity research.

Several journals released a sizeable number of highly cited biodiversity articles, including the following: *Nature* (222 articles on biodiversity with 35,016 citations),

Table 2 The 25 most active journals in biodiversity research

Journal	TP	TP (%)	TC	TC (%)	TC/TP	IF
Biological Conservation	4,558	7.42	90,155	9.01	19.78	3.167
Journal of Soil and Water Conservation	2,860	4.66	23,429	2.34	8.19	1.033
Conservation Biology	2,674	4.35	94,595	9.45	35.38	4.666
Biodiversity and Conservation	2,181	3.55	24,521	2.45	11.24	2.066
Resources Conservation and Recycling	1,064	1.73	8,772	0.88	8.24	1.987
Molecular Ecology	969	1.58	24,894	2.49	25.69	5.960
Forest Ecology and Management	701	1.14	9,297	0.93	13.26	1.950
Ecology	608	0.99	30,384	3.03	49.97	4.411
Theoretical and Applied Genetics	592	0.96	18,042	1.80	30.48	3.363
Genetic Resources and Crop Evolution	564	0.92	3,573	0.36	6.34	1.238
PNAS	504	0.82	29,976	2.99	59.48	9.432
Applied and Environmental Microbiology	463	0.75	21,259	2.12	45.92	3.686
Marine Ecology-Progress Series	437	0.71	7,288	0.73	16.68	2.519
Conservation Genetics	411	0.67	2,352	0.23	5.72	1.849
Journal of Biogeography	408	0.66	7,877	0.79	19.31	4.087
Oikos	397	0.65	10,503	1.05	26.46	3.147
Journal of Clinical Microbiology	384	0.63	9,354	0.93	24.36	4.162
Ecological Applications	384	0.63	15,343	1.53	39.96	3.672
Journal of Applied Ecology	362	0.59	9,476	0.95	26.18	4.197
Crop Science	359	0.58	6,531	0.65	18.19	1.735
Hydrobiologia	356	0.58	3,111	0.31	8.74	1.754
Oecologia	331	0.54	8,184	0.82	24.73	3.129
Agriculture Ecosystems & Environment	328	0.53	4,712	0.47	14.37	3.130
Euphytica	316	0.51	3,499	0.35	11.07	1.405
Ecology Letters	310	0.50	11,698	1.17	37.74	10.318

TP number of publication, *TC* total citation count, *TC/TP* average of citations in a paper, *IF* 2009 ISI Impact factor

Science (186 articles with 27,553 citations), *American Naturalist* (192 articles with 15,015 citations), and *Proceedings of the Royal Society of London Series B-Biological Sciences* (155 articles with 7,729 citations). The ten-most cited articles had been cited 2,111 times on average, and the most cited articles included "Profiling of Complex Microbial-Populations by Denaturing Gradient Gel-Electrophoresis Analysis of Polymerase Chain Reaction-Amplified Genes-Coding for 16s Ribosomal-RNA" (Muyzer et al. 1993) and "*Biodiversity Hotspots for Conservation Priorities*" (Myers et al. 2000) received 3,154 and 2,965 citations, respectively.

Author productivity

An author productivity analysis revealed that a small group of productive authors have contributed a large number of publications on biodiversity. Among the 119,720 authors who (co)authored at least one biodiversity paper, 117,715 or 98.3% contributed less than ten papers, while the top 2,005 or 1.7% authors produced 30,788 or 50.1% of the total articles. The most productive authors in biodiversity research were Gaston and Nevo with

Table 3 The 20 most productive authors and major collaborators

Author	TP	CP	AU	CO	AU/TP	DC	DC/TP	MC
Gaston, KJ	141	133	630	489	4.47	218	1.55	Blackburn, TM (17)
Nevo, E	135	132	588	453	4.36	236	1.75	Belies, A (38)
Lindenmayer, DB	83	81	386	303	4.65	156	1.88	Fischer, J (24)
Possingham, HP	83	82	419	336	5.05	209	2.52	Wilson, KA (18)
Tscharntke, T	77	76	356	279	4.62	126	1.64	Steffan-Dewenter, I (32)
Hamrick, JL	77	77	210	133	2.73	79	1.03	Godt, MJW (22)
Schmid, B	75	74	390	315	5.20	151	2.01	Roscher, C (12)
Cowling, RM	63	63	374	311	5.94	192	3.05	Rouget, M (17)
Tilman, D	60	53	245	185	4.08	103	1.72	Reich, PB (9)
Samways, MJ	56	50	139	83	2.48	66	1.18	Grant, PBC (4)
Hebert, PDN	55	55	258	203	4.69	148	2.69	Hallwachs, W (6)
Hyde, KD	55	53	210	155	3.82	75	1.36	McKenzie, EHC (12)
Melchinger, AE	53	53	295	242	5.57	88	1.66	Warburton, ML (13)
Chung, MG	53	48	156	103	2.94	33	0.62	Chung, MY (29)
Hermy, M	52	52	259	207	4.98	113	2.17	Honnay, O (14)
Li, Y	51	50	346	295	6.78	252	4.94	Shi, YS (4)
Macdonald, DW	50	50	320	270	6.40	212	4.24	Feber, RE (5)
Zhang, Y	50	50	320	270	6.40	243	4.86	Yu, Y (6)
Mac Nally, R	49	43	154	105	3.14	51	1.04	Fleishman, E (13)
Vendramin, GG	49	49	312	263	6.37	166	3.39	Sebastiani, F (13)

TP total publications, *CP* collaborated publications, *AU* signatories on publications or number of authors, *CO* co-authorships, *DC* distinct collaborators, *MC* major collaborator and number of collaborated publications

141 and 135 articles, respectively. Other prolific authors included Lindenmayer with 83 papers, Possingham with 83, Tscharntke with 77, and Hamrick with 77. There were 35 authors who wrote over 40 articles each. In Table 3, we present the article output descriptors of the 20 most productive authors and their major collaborators. We noticed that several authors tended to cooperate with a small group of collaborators, i.e., setting smaller values of distinct collaborators per article and signatories per article. This type of author included Samways and Hamrick, averaging 2.48 and 2.73 signatories on their papers, respectively. In contrast, some authors collaborated with a relatively large group of co-authors. For example, Macdonald and Vendramin averaged 6.40 and 6.37 signatories on their papers, respectively, while the average number of authors per article for all biodiversity articles was 3.70.

We geocoded the affiliations of authors using CiteSpace (Chen 2004) and plotted the world-wide geographic distribution of authors (Fig. 3a). We could distinguish the major spatial clusters of authors in North America, Europe, and Japan and several minor clusters in other parts of the world. A close view of the spatial distributions of authors in North America and Europe (Fig. 3b and c) revealed the sub-clusters of authors within these geographic regions. For example, there were two clusters of authors on the east and west coasts of the United States and another two clusters of authors near London, UK and Paris, France. These clusters of authors were consistent with the fact that these regions house a large number of universities, e.g., the northeastern part of United States, and that certain

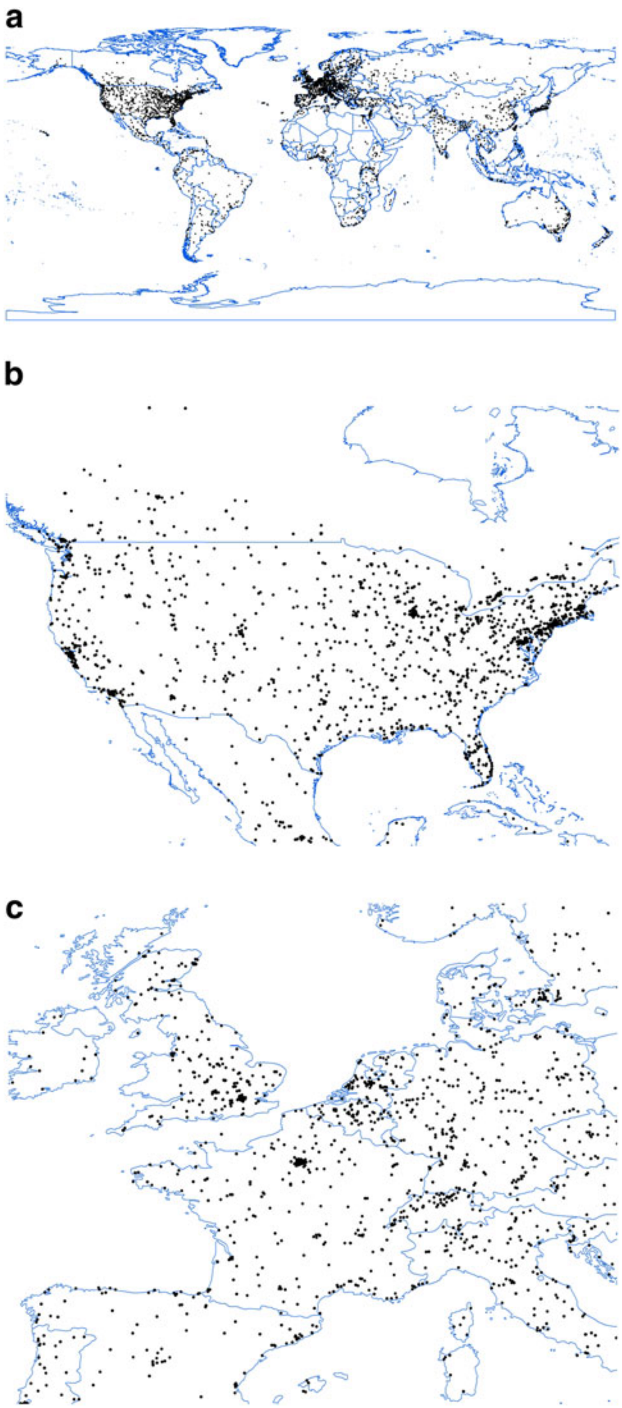

Fig. 3 **a** Global geographic distribution of authors. **b** Spatial clusters of authors in North America. **c** Spatial cluster of authors in west Europe

universities/research institutions made substantial contributions to biodiversity publications, such as the University of Oxford's contribution to the author cluster near London.

Geographic and institutional distribution of publications

We generated the data on the geographic and institutional distributions of publications based on the affiliation information of authors. The 30 most productive countries/territories are summarized in Table 4, in terms of the number of total publications and total citations for single country articles and international collaborations, respectively. Out of these

Table 4 The 30 most productive countries/territories in biodiversity research

Country	TP	Single-country				Internationally-collaborated			
		SP	TC	TC/SP	SP (%)	CP	TC	TC/CP	CP (%)
USA	20,558	14,076	3,14,816	22.37	68.47	6,482	15,2280	23.49	31.53
UK	6,710	3,207	70,768	22.07	47.79	3,503	84,373	24.09	52.21
France	4,111	1,765	27,151	15.38	42.93	2,346	46,635	19.88	57.07
Australia	3,764	2,301	45,178	19.63	61.13	1,463	31,926	21.82	38.87
Canada	3,614	2,087	32,294	15.47	57.75	1,527	37,050	24.26	42.25
Germany	3,355	1,409	20,303	14.41	42.00	1,946	34,817	17.89	58.00
China	2,775	1,584	6,803	4.29	57.08	1,009	10,577	10.48	36.36
Spain	2,593	1,442	16,416	11.38	55.61	1,333	21,482	16.12	51.41
Brazil	2,308	1,484	9,115	6.14	64.30	824	13,960	16.94	35.70
Italy	2,219	1,193	10,995	9.22	53.76	1,026	16,859	16.43	46.24
India	1,973	1,513	7,059	4.67	76.69	460	5,898	12.82	23.31
Japan	1,909	1,158	11,823	10.21	60.66	751	11,074	14.75	39.34
Sweden	1,676	801	16,431	20.51	47.79	812	19,065	23.48	48.45
Netherlands	1,613	676	16,133	23.87	41.91	1,000	22,656	22.66	62.00
Switzerland	1,376	495	12,779	25.82	35.97	881	17,996	20.43	64.03
Mexico	1,298	576	5,189	9.01	44.38	676	13,002	19.23	52.08
South Africa	1,252	721	8,538	11.84	57.59	577	12,686	21.99	46.09
Belgium	1,096	428	5,442	12.71	39.05	668	12,340	18.47	60.95
Finland	1,013	561	9,465	16.87	55.38	430	7,787	18.11	42.45
Russia	1,005	659	1,690	2.56	65.57	354	5,308	14.99	35.22
New Zealand	991	481	7,591	15.78	48.54	524	9,480	18.09	52.88
Argentina	778	376	2,501	6.65	48.33	322	5,231	16.25	41.39
Norway	762	326	5,218	16.01	42.78	436	10,768	24.70	57.22
Denmark	698	288	4,827	16.76	41.26	490	11,547	23.57	70.20
Israel	614	261	3,853	14.76	42.51	323	6,263	19.39	52.61
Portugal	584	199	1,494	7.51	34.08	415	7,058	17.01	71.06
Poland	561	352	1,526	4.34	62.75	209	2,421	11.58	37.25
South Korea	512	267	1,287	4.82	52.15	218	1,755	8.05	42.58
Turkey	485	255	781	3.06	52.58	149	1,638	10.99	30.72
Czech Republic	466	208	1,641	7.89	44.64	258	3,674	14.24	55.36

TP total publication, *SP* single-country publication, *CP* internationally collaborated publication, *TC* citations

30 countries, 17 were from Europe, 3 were from North America, 2 were from South America, 5 were from Asia, 2 were from Oceania, and 1 was from Africa.

The productivity ranking of countries was headed by the U.S., which was responsible for the most single-country (14,076) and internationally collaborative articles (6,482). The UK published the second highest number of articles (6,710), followed by France (4,111), Australia (3,764), Canada (3,614), and Germany (3,355). There were 24,845 single-country articles from these six countries, which were responsible for 40.1% of the total 61,418 articles. As is consistent with other bibliometric analyses (Xie et al. 2008; Tarkowski 2007; Zhang et al. 2010), economic developments were correlated with the academic outputs: the seven industrialized countries (G7 group: Canada, France, Germany, Italy, Japan, the UK, and the USA) and four major developing countries ("BRIC": Brazil, Russia, India, and China) were all among the top list of thirty countries. Although both single-country and internationally collaborative articles increased in the last three decades, the proportion of single-country articles decreased from 90% in the early 1980s to approximately 70% in 2009. The change in the percentage of internationally-collaborative articles suggested that the academic communities of biodiversity research became more internationally connected (Fig. 4). Another observation on the academic exchange would be that internationally collaborative articles generally drew more citations than those produced by individual countries.

Applying a threshold to the network centralities in the collaboration network of countries/territories, we visualized a core group of countries in the collaboration network using NetDraw (Borgatti 2002). Network centrality measures the relative importance of nodes within networks and could be viewed as an indicator of countries' positions within the collaboration network in our case. The United States took the central position in the collaboration network, as it was the principal collaborator with majorly productive countries, such as the UK and Germany (Fig. 5).

Among the 23,989 institutions that participated in biodiversity research, the Chinese Academy of Sciences led institutional productivity with 912 papers, followed by USDA ARS with 852, the University of California-Davis with 752, the Institut National de la Recherche Agronomique (INRA) with 694, the Spanish National Research Council (CSIC)

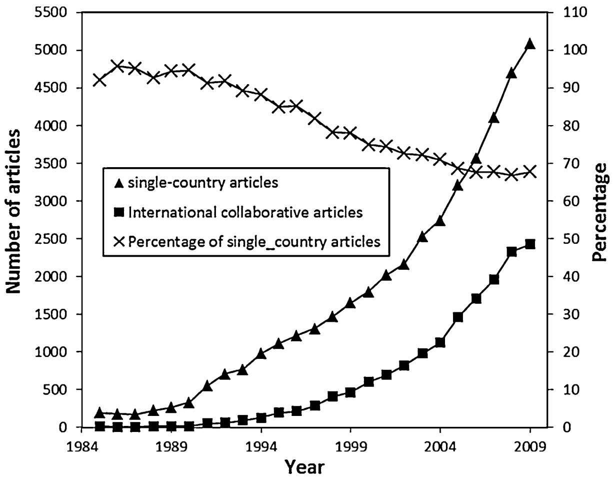

Fig. 4 International collaborative and single-country articles in biodiversity research

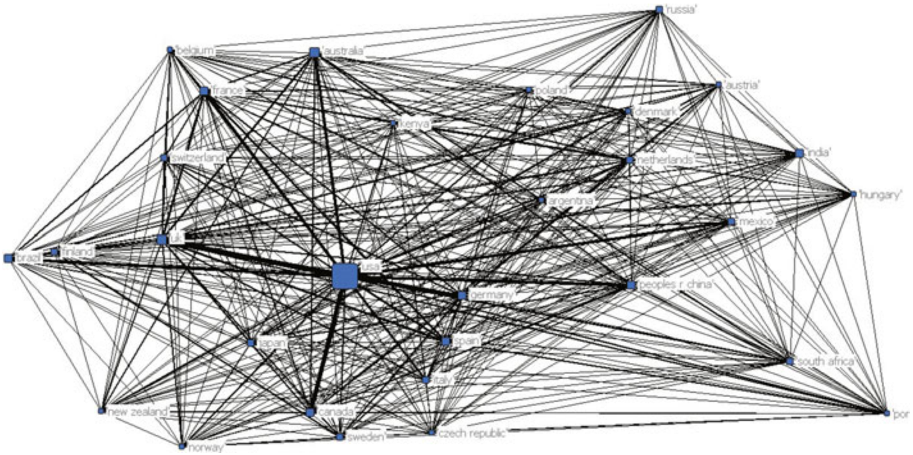

Fig. 5 Core international collaboration network (The *thickness of links* represents the strength of collaborations, and the *size of nodes* represents the amount of single-country publications)

with 652, the University of Wisconsin with 631, the Russian Academy of Sciences with 567, and the University of Georgia with 530. Of the 30 most prolific institutions in biodiversity research, 17 were from the U.S. (Table 5). The institutional productivity values could be biased by the fact that the Chinese Academy of Sciences and Russian Academy of Sciences are over-arching institutions that each house hundreds of branches.

Inter-institutional collaboration was more prevalent than international collaboration, as the average number of institutions per article increased from 2.0 in 1970s to 3.1 in 2009 (Fig. 6) and the 30 most productive institutions were characterized by inter-institutional collaboration on 60% of their papers (Table 5). Additionally, the number of inter-institutionally collaborative articles exceeded the number of single-institution articles around 1995. Applying a threshold to the network centralities in the collaboration network of the 500 most productive institutions, we identified a cluster of 20 of the most central institutions to the collaboration network (Fig. 7). Institutions in the U.S., especially those affiliated with the University of California system, tended to collaborate more with each other. In contrast, although the Chinese Academy of Sciences produced a substantial amount of publications, its links with other central programs were fewer. Moreover, collaboration could improve an article's influence, as the citations to inter-institutionally collaborative articles were generally greater than those from individual institutions.

Temporal evolution of keyword frequencies

We used a keywords analysis to demonstrate the biodiversity research trends and frontiers (Chiu and Ho 2007; Xie et al. 2008; Malarvizhi et al. 2010). The keywords analysis in our study utilized author keywords and keywords plus and could provide a relatively comprehensive overview of research trends (Table 6). The author keywords were provided by article authors as parts of the articles, and the keywords plus were produced by ISI based on each article's citations and references. Both author keywords and keywords plus are termed keywords for simplicity.

The 61,418 articles had 121,207 unique keywords, which appeared 647,011 times. However, 79,546 or 65.63% out of these 121,207 keywords appeared in one paper, and

Table 5 The 30 most productive research institutions in biodiversity research

Institution	TP	Single-institution				Inter-institutional			
		SI	TC	TC/SI	SI (%)	CI	TC	TC/CI	CI (%)
Chinese Academy of Sciences, China	912	268	1,685	6.29	29.39	644	5,088	7.90	70.61
USDA ARS, USA	852	230	3,917	17.03	27.00	622	10,584	17.02	73.00
University of California-Davis, USA	752	208	5,428	26.10	27.66	544	12,956	23.82	72.34
INRA, France	694	181	3,251	17.96	26.08	513	10,858	21.17	73.92
CSIC, Spain	652	159	2,879	18.11	24.39	493	7,888	16.00	75.61
University of Wisconsin, USA	631	188	5,015	26.68	29.79	443	10,969	24.76	70.21
Russian Academy of Sciences, Russia	567	295	895	3.03	52.03	272	2,748	10.10	47.97
University of Georgia, USA	530	142	3,585	25.25	26.79	388	9,791	25.23	73.21
USDA, USA	520	188	1,712	9.11	36.15	332	4,976	14.99	63.85
Swedish University of Agricultural Science, Sweden	505	182	4,365	23.98	36.04	323	5,721	17.71	63.96
Oregon State University, USA	504	135	4,739	35.10	26.79	369	11,108	30.10	73.21
University of California-Berkeley, USA	487	105	3,675	35.00	21.56	382	11,313	29.62	78.44
University of Oxford, UK	484	92	2,594	28.20	19.01	392	11,942	30.46	80.99
University Nacional Autonoma, Mexico	474	154	1,957	12.71	32.49	320	6,284	19.64	67.51
University of Minnesota, USA	473	115	6,945	60.39	24.31	358	14,539	40.61	75.69
CNRS, France	465	61	1,337	21.92	13.12	404	8,844	21.89	86.88
University of Florida, USA	464	117	2,358	20.15	25.22	347	6,752	19.46	74.78
US Forest Service, USA	461	126	2,270	18.02	27.33	335	8,248	24.62	72.67
Colorado State University, USA	457	100	3,154	31.54	21.88	357	10,355	29.01	78.12
University of Helsinki, Finland	429	121	2,647	21.88	28.21	308	5,210	16.92	71.79
University of British Columbia, Canada	412	117	1,868	15.97	28.40	295	6,409	21.73	71.60
University of Washington, USA	399	91	3,693	40.58	22.81	308	9,419	30.58	77.19
University of Queensland, Australia	388	77	1,491	19.36	19.85	311	5,127	16.49	80.15
Stanford University, USA	367	77	4,038	52.44	20.98	290	16,117	55.58	79.02
University of Illinois, USA	361	110	2,186	19.87	30.47	251	4,625	18.43	69.53
Colorado State University, USA	361	77	1,503	19.52	21.33	284	6,609	23.27	78.67
CSIRO, Australia	357	121	7,515	62.11	33.89	236	7,902	33.48	66.11
USGS, USA	351	78	1,832	23.49	22.22	273	4,878	17.87	77.78
Harvard University, USA	333	66	2,201	33.35	19.82	267	9,814	36.76	80.18
University of Cambridge, UK	325	46	818	17.78	14.15	279	7,307	26.19	85.85

TP total publication, *SI* single-institution publication, *CI* inter-institutionally collaborated articles, *TC* total citations

113,771 (93.87%) keywords appeared in less than 10 papers. We present the 50 most frequently used keywords within each of the 5-year intervals during 1990–2009 in Table 6. During this period, 50 or 0.04% of the 121,207 keywords appeared 109,612 times and, thus, were responsible for 16.9% of the total keyword occurrences. The frequency of keywords and their ranks follows the power-law distribution: there is a small group of keywords that are widely-used, whereas most keywords are not employed frequently. This power-law distribution has also been discovered in other bibliometric studies (Li et al. 2008).

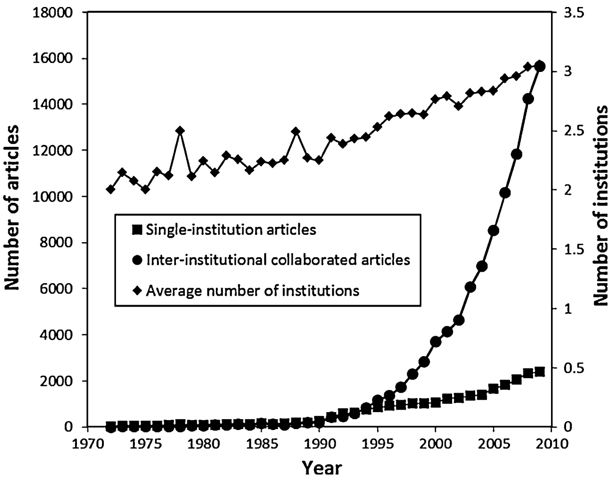

Fig. 6 Inter-institutionally collaborative and single-institution articles

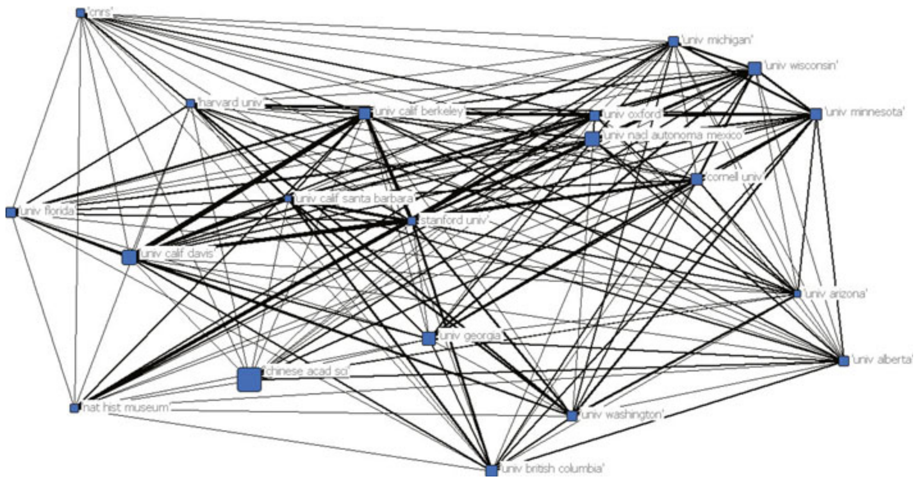

Fig. 7 Core inter-institutional collaboration network (The *thickness of links* represents the strength of collaborations, and the *size of nodes* represents the amount of single-institution publications)

Ranked among these 50 most frequently used keywords were "biodiversity," "genetic diversity," and "species diversity," which were the search terms in the data retrieval process. However, "biological diversity," "bio-diversity," "ecosystem diversity," and "landscape diversity," which were also used as search terms, were not listed among the 50 most commonly used keywords. "Species-diversity" also ranked 15th, and the online SCI search engine treated "species-diversity" and "species diversity" equally. The temporal evolution of ranks of the keywords "species richness" and "species diversity" revealed an interesting terminology preference: "species diversity" ranked 9th during 1990–1994, whereas its rank decreased to 53rd by 2009. In contrast, the rank of "species richness" increased from 37th to 6th in the last two decades. This change in terminology preference suggested that recent studies prefer "species richness" to "species diversity." Additionally, the keyword "diversity" ranked 3rd and indicates that many authors used this broad

Table 6 The temporal evolution of most frequently used keywords

Keywords	1990–1994		1995–1999		2000–2004		2005–2009		Total		RC	TC	TC/TP
	Cnt	Rank	Cnt	Rank	Cnt	Rank	Cnt	Rank	Cnt	Rank			
Biodiversity	137	5	1,126	1	3,399	1	8,127	1	12,789	1	4	20,1505	15.76
Genetic diversity	301	1	932	3	2,250	3	5,180	2	8,663	2	2	1,46,986	16.97
Diversity	265	2	1,024	2	2,298	2	4,906	3	8,493	3	1	1,10,077	12.96
Conservation	176	3	867	4	1,891	4	4,058	4	6,992	4	1	1,09,574	15.67
Patterns	125	6	436	6	1,011	6	1,912	5	3,484	5	1	66,876	19.20
Populations	147	4	506	5	1,025	5	1,689	7	3,367	6	3	56,150	16.68
Species richness ↑	36	37	228	19	781	7	1,883	6	2,928	7	31	52,590	17.96
Evolution	110	7	350	7	709	10	1,560	8	2,729	8	3	52,171	19.12
Communities	77	12	293	9	761	8	1,503	10	2,634	9	4	49,015	18.61
Management ↑	43	30	274	12	680	11	1,538	9	2,535	10	21	43,821	17.29
Identification	69	15	255	16	737	9	1,347	12	2,408	11	7	43,005	17.86
Ecology	89	9	258	14	674	12	1,367	11	2,388	12	5	42,258	17.70
Vegetation	76	13	292	10	608	15	1,141	14	2,117	13	5	38,623	18.24
DNA	65	20	277	11	659	13	1,093	15	2,094	14	9	36,753	17.55
Species-diversity	110	7	269	13	550	17	1,142	13	2,071	15	10	35,848	17.31
Dynamics	64	22	304	8	649	14	1,031	16	2,048	16	14	34,432	16.81
Markers	29	53	214	21	555	16	990	17	1,788	17	37	34,332	19.20
Abundance	49	25	187	26	537	18	941	18	1,714	18	8	34,054	19.87
Disturbance	69	15	257	15	498	19	867	19	1,691	19	4	33,957	20.08
Population	75	14	232	17	437	22	845	21	1,589	20	8	31,044	19.54
Differentiation	69	15	226	20	447	21	752	26	1,494	21	11	30,170	20.19
RAPD ↑	20	94	187	26	483	20	743	27	1,433	22	74	27,586	19.25

Table 6 continued

Keywords	1990–1994		1995–1999		2000–2004		2005–2009		Total		RC	TC	TC/TP
	Cnt	Rank	Cnt	Rank	Cnt	Rank	Cnt	Rank	Cnt	Rank			
Habitat	33	43	156	32	402	25	801	23	1,392	23	20	27,024	19.41
Forest	37	36	191	25	424	23	714	29	1,366	24	13	26,832	19.64
Community structure	40	31	153	33	356	31	814	22	1,363	25	11	26,151	19.19
Growth	65	20	200	23	386	26	685	32	1,336	26	12	24,712	18.50
Extinction	36	37	187	26	415	24	682	34	1,320	27	13	24,421	18.50
Dispersal	21	90	109	49	362	29	797	24	1,289	28	66	23,943	18.57
Variability ↓	83	11	214	21	358	30	632	38	1,287	29	27	23,309	18.11
Polymorphism	60	23	174	29	363	28	675	35	1,272	30	12	21,586	16.97
Microsatellites ↑	2	1,239	64	105	346	33	846	20	1,258	31	1219	21,463	17.06
Species diversity ↓	89	9	229	18	374	27	551	53	1,243	32	44	21,306	17.14
Competition	68	18	195	24	346	33	609	39	1,218	33	21	21,300	17.49
Strains	46	26	168	30	344	35	605	41	1,163	34	15	21,261	18.28
Landscape	7	322	56	125	268	49	784	25	1,115	35	297	21,197	19.01
Richness	19	101	79	84	293	41	697	31	1,088	36	70	21,194	19.48
Plants	51	24	148	35	327	36	562	50	1,088	36	26	20,838	19.15
Habitat fragmentation	8	287	82	79	288	44	704	30	1,082	38	257	20,687	19.12
Birds	32	44	140	37	352	32	557	52	1,081	39	20	20,392	18.86
Selection	46	26	157	31	290	43	580	47	1073	40	21	2,0054	18.69
Biogeography	30	47	112	48	259	51	651	36	1,052	41	15	19,966	18.98
Population-structure	21	90	52	136	234	57	741	28	1,048	42	108	19,771	18.87
Ecosystems	25	65	132	39	311	38	570	49	1038	43	27	19,469	18.76
Fragmentation	20	94	114	46	301	40	596	44	1,031	44	54	19,328	18.75

Table 6 continued

Keywords	1990–1994		1995–1999		2000–2004		2005–2009		Total		RC	TC	TC/TP
	Cnt	Rank	Cnt	Rank	Cnt	Rank	Cnt	Rank	Cnt	Rank			
Productivity	20	94	92	64	322	37	595	45	1,029	45	57	18,384	17.87
Community	38	34	135	38	274	47	562	50	1,009	46	16	16,748	16.60
AFLP ↑	0	8789	35	225	285	45	685	32	1,005	47	8,757	16,578	16.50
Phylogeny	23	72	103	53	270	48	606	40	1,002	48	32	16,273	16.24
Sequences	30	47	107	50	308	39	533	55	978	49	16	15,864	16.22
Consequences	15	145	85	75	259	51	578	48	937	50	97	15,616	16.67

Cnt count of occurrences, *R* rank, *RC* change in rank, *TC* total citations of papers that have the corresponding keywords, *TP* total number of papers that have the corresponding keywords term instead of specific diversity types. According to studies on changes in plant species diversity of aquatic ecosystems in the agricultural landscape in West Poland during the last 30 years, Goldyn (2010) indicated that the species diversity of the whole landscape declined. The number of species, as well as Shannon and Simpson diversity indices were calculated from 157 sampling quadrats to identify whether the relationships among the relationships among landscape characteristics and plant diversity in tropical forests could be used to predict biodiversity (Hernandez-Stefanoni 2006).

There were high-ranking keywords representing three different levels of biodiversity: genetic diversity, such as "DNA"; species diversity, such as the previously mentioned "species richness"; and ecosystem diversity, such as "ecosystems." We also found words that were included in the definition of biodiversity ranked high in our keyword list. "Populations," "population," "communities," and "ecosystems" ranked 6th, 20th, 9th, and 43rd in our list, respectively. Although biodiversity studies the variation of life forms in ecosystems, the rank of "variability" decreased from 11th to 29th in the last two decades. Meanwhile, "polymorphism" ranked consistently around 30th. As for the types of ecosystems, more research tended to focus on terrestrial ecosystems, although surveys of marine biodiversity were conducted in recent years. "Vegetation," "forest," and "plants" were among the 50 most common keywords, while no keywords that represent marine and freshwater ecosystems were found in the list. Tree species diversity of four tropical forest vegetation types is investigated in Xishuangbanna and southwestern China, while the results reveal the long-tailed rank/abundance diagrams of these forests (Cao and Zhang 1997).

"Conservation" was the keyword with the highest rank, apart from our search terms. Two possible reasons can be used to explain this result. First, conservation is a significant target on various biodiversity research fields. Second, the biodiversity of soils underpins many crucial ecosystem services which support the plants and animals typically targeted by conservation efforts (Parker 2010). This observation again confirmed our previous conjecture that conservation held a central position in biodiversity studies. Biodiversity research focused on both the patterns and underlying processes of ecosystems, as "patterns," "evolution," "dynamics," and "growth" ranked consistently high at 5th, 8th, 16th, and 26th, respectively, in the last two decades. High-ranking keywords related to ecological patterns also included "community structure" and "population structure," while keywords related to ecological processes included "disturbance," "competition," and "dispersal." "Management" ranked 10th during 1990–2009, and we conjectured that another aim of biodiversity would be the management of natural resources.

Marking technologies were widely applied in biodiversity research at various levels. "Markers" ranked 17th in 1990–2009. Additionally, three marking technology terms were among the keywords that enjoyed the greatest rank advancements in the last two decades (Hadrys et al. 1992; Mueller and Wolfenbarger 1999; Manzelli et al. 2007): "Microsatellites" ranked 1239th in 1990–1994, and its rank soared to 20th by 2009; "AFLP" ranked 8789th and was found in no papers in 1990–1994, while its rank grew to 32nd in 2005–2009; and "RAPD" was adopted earlier than the other two and ranked 94th in 1990–1994, whereas it ranked 27th in 2005–2009.

Conclusions

In this paper, we provide an alternative perspective on the global research trends in biodiversity studies. We conducted a bibliometric analysis of the patterns of authorship, journal and subject categories, geographic and institutional distributions, and temporal evolutions of keyword frequencies. Our study suggests that there has been steady growth in the scientific outputs in biodiversity research and confirms the dynamic collaborations in this field. The scientific outputs in biodiversity research enjoyed substantial growth during the last century, with increasing publications, collaboration index, references, and citations.

Ecology, environmental sciences, biodiversity conservations and plant science were most frequently used subject categories in biodiversity studies. *Biological Conservation, Journal of Soil and Water Conservation, Conservation Biology and Biodiversity and Conservation* published most articles on biodiversity, and top 25 journals were responsible for 36.7% of the total biodiversity papers. A small group of productive authors contributed a substantial amount of papers, as the top 1.7% of the productive authors published 50.1% of the total articles. Gaston and Nevo were the most prolific authors in biodiversity research, and 35 of the authors have produced more than 40 papers. The spatial distribution of authors and several spatial clusters of authors were also visualized.

At the country level, the U.S. attained a dominant position in global biodiversity research by contributing the largest number of single-country and internationally collaborative articles. The scientific outputs were related to economic developments, as fully developed and fast-developing countries were all among the list of productive countries. At institutional level, Chinese Academy of Sciences, USDA ARS, University of California-Davis, Institut National de la Recherche Agronomique (INRA) and Spanish National Research Council (CSIC) were the five most productive institutions. Additionally, inter-institutional collaborations were more prevalent than international collaborations. Moreover, collaborative works drew more citations than single-country or single-institution publications.

A keywords analysis found several interesting terminology preferences, confirmed conservation's central position in biodiversity research, revealed the adoption of advanced technologies, and demonstrated keen interest in both the patterns and underlying processes of ecosystems.

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