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Review

Global Research on Artificial Intelligence from 1990–2014: Spatially-Explicit Bibliometric Analysis

Jiqiang Niu [1,*], Wenwu Tang [2,3], Feng Xu [1], Xiaoyan Zhou [4] and Yanan Song [4]

1 School of Urban and Environmental Science, Xinyang Normal University, Xinyang 464000, China; xu-f88@163.com
2 Department of Geography and Earth Sciences, University of North Carolina at Charlotte, Charlotte, NC 28262, USA; WenwuTang@uncc.edu
3 Center for Applied Geographic Information Science, University of North Carolina at Charlotte, Charlotte, NC 28262, USA
4 School of Resource and Environmental Science, Wuhan University, Wuhan 430079, China; zhouxiaoyan@whu.edu.cn (X.Z.); yanansong@whu.edu.cn (Y.S.)
* Correspondence: njq8196@163.com; Tel.: +86-188-3767-2366

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Abstract: In this article, we conducted the evaluation of artificial intelligence research from 1990–2014 by using bibliometric analysis. We introduced spatial analysis and social network analysis as geographic information retrieval methods for spatially-explicit bibliometric analysis. This study is based on the analysis of data obtained from database of the Science Citation Index Expanded (SCI-Expanded) and Conference Proceedings Citation Index-Science (CPCI-S). Our results revealed scientific outputs, subject categories and main journals, author productivity and geographic distribution, international productivity and collaboration, and hot issues and research trends. The growth of article outputs in artificial intelligence research has exploded since the 1990s, along with increasing collaboration, reference, and citations. Computer science and engineering were the most frequently-used subject categories in artificial intelligence studies. The top twenty productive authors are distributed in countries with a high investment of research and development. The United States has the highest number of top research institutions in artificial intelligence, producing most single-country and collaborative articles. Although there is more and more collaboration among institutions, cooperation, especially international ones, are not highly prevalent in artificial intelligence research as expected. The keyword analysis revealed interesting research preferences, confirmed that methods, models, and application are in the central position of artificial intelligence. Further, we found interesting related keywords with high co-occurrence frequencies, which have helped identify new models and application areas in recent years. Bibliometric analysis results from our study will greatly facilitate the understanding of the progress and trends in artificial intelligence, in particular, for those researchers interested in domain-specific AI-driven problem-solving. This will be of great assistance for the applications of AI in alternative fields in general and geographic information science, in particular.

Keywords: Artificial Intelligence; bibliometric analysis; scientific outputs; research trends; SCI-expanded; Conference Proceedings Citation Index-Science

1. Introduction

Artificial Intelligence (AI) is a subject that studies theories, methods, and applications with respect to simulation, extension, and expansion of human intelligence for problem-solving. Application domains of AI include robotics, voice recognition, image recognition, natural language processing, and expert systems [1]. AI, as a branch of computer science, aims to understand the essence of intelligence and design intelligent machines that can act as human behavior. AI has attracted researchers with respect to its theories and principles since the 1956 Dartmouth conference [2,3]. Since the 1960s, AI-related researches have been heavily funded, and many laboratories have been established around the world. However, in the mid-1970s and early 1980s, there are two periods of stagnancy in AI [4]. Until the 1990s, AI achieved its greatest success, which can be confirmed by the scientific articles indexed by the Science Citation Index Expanded (SCI-Expanded) (Figure 1). It is during this period that AI is widely used for logistics, data mining, medical diagnosis, and many other areas throughout industry [2,5]. From the early 21st century, AI research enters a period with numerous research outputs. The success was attributed to several factors: the increasing computational power of computers, a greater emphasis on problem-solving, creation of new ties between AI and other fields working on similar problems, and a new commitment by researchers to solid mathematical methods and rigorous scientific standards [6,7]. Today, AI and its applications play an important role in computer science and its related domains [8].

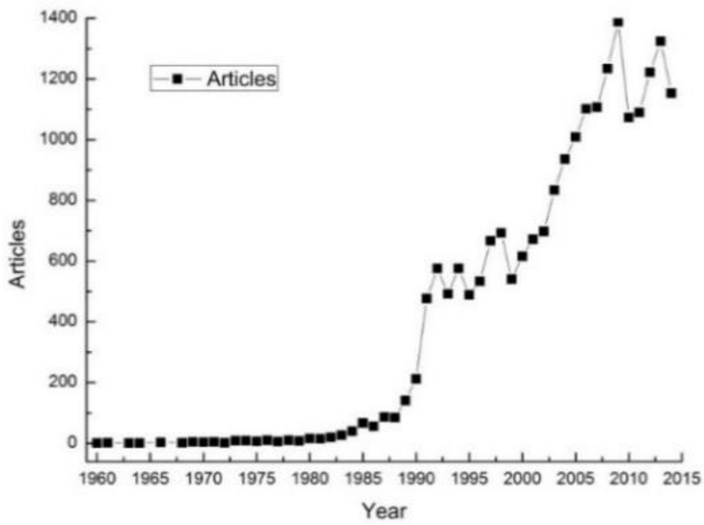

Figure 1. Growth trend of articles in artificial intelligence from 1990–2014.

Bibliometric analysis comprises a series of quantitative and visual procedures or statistics to generalize research patterns, dynamics and trends in scientific publication [9–12]. In recent years, many bibliometric methods were put forward to estimate the scientific outputs or research trend of authors, journals, institutions, and countries, even to identify and quantify international collaboration [13–15]. As the effective method for providing an immediate picture of the actual content of research topics, citation analysis, co-words analysis, and geographic impact factor (GIF) were carried out within the field of bibliometric analysis to enhance the conventional bibliometric methods [16–19]. Recently, correlation analysis was introduced in bibliometrics to explain the phenomenon of research trends [15].

AI is a research domain that includes many branches and methods. While bibliographic data for AI-related studies are increasingly available, how to discover the research patterns and trends in AI based on these bibliographic data represents a challenging research question. Further, bibliographic data are spatially explicit *per se.* However, there is a gap between the use of spatially-explicit methods for analyzing these bibliographic data (*i.e.*, retrieval of geographic information from bibliometrics) and advances in Geographic Information Science (GIScience; [20]), which focuses on the development of these spatially-explicit methods. Therefore, in this study we conduct a bibliometric analysis of AI research for the period of 1990–2014. We proposed an alternative and innovative method, with support from geographic information retrieval technologies, to reveal global research correlation between scientific output and the investment of Research and Development (R and D). Our aims include: (1) multi-angle assessment of research productivity by subject category, journal, author, country, institution, and keywords; (2) analyze the significant publication patterns in the domain of AI research; and (3) summarization of the research directions and trends in the field of AI.

2. Data and Methodology

2.1. Data Sources

The data of this study were collected from the database of the Science Citation Index Expanded (SCI-Expanded), Conference Proceedings Citation Index-Science (CPCI-S) online version of Web of Science published by the Institute for Scientific Information (ISI), Philadelphia, USA, because the SCI-Expanded database is deemed as the most influential database and reliable bibliographic source [18,21], and CPCI-S includes many original theory papers. SCI-Expanded and CPCI-S have been widely applied to reveal bibliographic patterns and research trends in a variety of scientific fields [22,23]. Based on previous bibliometric analysis of AI and related researches, "*artificial intelligence*", which included any word that contain "artificial intelligence", such as "distributed artificial intelligence", "artificial intelligence technique", was used to search for publication with these words in its title, abstract, or keywords in the database of SCI-Expanded and CPCI-S from 1990–2014 (duplicated records were eliminated). The reported impact factor (IF) of the journals was obtained from 2014 Journal Citation Report (JCR) [24]. The data of R and D (Research and Development) investment was collected from the World Bank and the website Wikipedia.

Publications originating from England, Scotland, Wales, and North Ireland were reclassified as from the United Kingdom (UK) [15], and publications from Hong Kong and Taiwan were separated from those from mainland China because there are different research systems in these territories.

2.2. Methodology

Bibliometric analysis provides support for quantitative analysis of scientific knowledge by employing mathematical, statistical, and visual approaches to generalize research patterns and trends in scientific publication. Most of the analysis can be performed by Microsoft Excel 2010 (Redmond, Washington, USA) and CiteSpace 2.2 R11 (Philadelphia, Pennsylvania, USA), such as scientific outputs, subject categories, and journals. However, scientific publication has a spatial component, such as the location(s) of authors or institutes. The analysis of this spatial component through geographic information retrieval methods may offer more insight into the research pattern and trends across spatial scale (e.g., regional, country, or continental). In this study, we introduced GIS-based spatial analysis into the field of bibliometric analysis for the retrieval and discovery of geographic information in bibliometrics—*i.e.*, spatially-explicit bibliometric analysis. We focus on the use of kernel density analysis and social network analysis here.

2.2.1. Kernel Density Analysis

In order to perform the kernel density analysis, we first introduced kernel density estimation (KDE; see [25]) to visualize the worldwide geographic distribution of authors. We defined the kernel density estimator to represent the worldwide geographic distribution of authors. Let $(x_1, x_2, \ldots, x_n)$ be the spatial coordinates of authors in the field of AI, which is a distribution with unknown density. Its kernel density estimator can be described as follows:

$$\hat{f}_h(x) = \frac{1}{n}\sum_{i=1}^{n} K_h(x - x_i) = \frac{1}{nh}\sum_{i=1}^{n} K_h\left(\frac{x - x_i}{h}\right)$$

where $K(\cdot)$ is the kernel, and h is a smoothing parameter often referred to as the bandwidth. By means of the kernel density estimator, we can obtain a continuous surface generated by the quantity of authors all over the world based on the original data. Then the worldwide geographic distribution of authors can be overlaid with the world map to visualize the hotspot area of AI research.

2.2.2. Social Network Analysis

Social network analysis is the method of investigating social structures based on the theory of networks and graphs [26]. In this study, this method is applied into bibliometric analysis to visualize the networks in which nodes are represented as points and edges are represented as lines. These networks are often visualized through structure and relation of such aspects as authors, countries, institutes, and keywords. We performed the social network analysis by defining the following two elements. Nodes can be used to represent the entity in the real world. In bibliometric analysis, it can be the authors, countries, institutes, and keywords. Edges show the relationship or interactions between nodes. For example, edges can explain the collaboration between authors or co-occurrence keywords in the literature. The size of nodes can show the degree of importance of an entity, while the width of edges shows the degree of relationship in the network.

In this study, the method of social network analysis was employed to reveal bibliographic patterns in AI research. The collaboration type was determined by the addresses of authors, where the term "single country/institution" was assigned if researchers were from the same country/institution and the term "international/inter-institutionally collaboration" was assigned if an article was co-authored by researchers from multiple countries/institutions. We geocoded authors, countries, institutes, and keywords using CiteSpace 2.2 R11, and we use the software Ucinet 6 (Irvine, California, USA), one of the prevalent social network analysis software platforms, to measure the relative importance of each individual country/territory in the collaboration network and each word in the co-word analysis.

3. Results and Discussion

3.1. Publication Outputs

From this study, 21 document types were found in a total of 22,072 publications related to AI issued during the past 25 years. Article (20,715), including the article published as proceeding papers (8806) or book chapters (6), was the most common type (occupying 93.85% of the total publications), followed by reviews (528 or 2.39%) and editorial material (508 or 2.3%). Among these publications, 20,715 articles on AI were further analyzed. 98.49% of all articles were published in English. Twenty-one other languages appeared, the most frequent of which were Chinese (59), Spanish (51), French (51), German (41), and Portuguese (39). The numbers of publications categorized by year were reported in Table 1. The annual publications increased from 212 in 1990 to 1153 in 2014, illustrating a significant increase in AI research over the past 25 years. Meanwhile, articles remained as the dominant type throughout this period.

The artificial intelligence research has experienced a rapid growth over the last decades. Figure 2 shows that AI publications, both indexed by SCI-Expanded and CPCI-S, increased rapidly from early 1990s. However, from 2010, the number of publications in AI is unstable. The most important reason is that the publication indexed by CPCI-S exhibits a decreasing pattern, and the total publication output remains stable. Table 1 provides more information in addition to Figure 2. The number of authors per paper increased from 2.1 to 3.4 in the period of 1990–2014, which is likely caused by the higher quality of research involving more researchers from different fields. Meanwhile, the number of articles cited per paper increased from 9.2 to 34.5, which, as we know, was brought about by more and more research outputs on AI and citing from other related fields. From Table 1, an interesting finding is that the earlier the articles were published, the lower their times of being cited before the 2000s, and after that, another interesting finding is that the later articles were published, the lower their times of being cited. Thus, the less research output limited the number of citations before the 2000s, and after that, the rule of citation does work [27,28].

Table 1. Summary scientific outputs from 1990–2014.

Year	TA	AU	AU/TA	NR	NR/TA	PG	PG/TA	TC	CPA
1990	212	437	2.1	1948	9.2	2017	9.5	706	3.3
1991	477	1002	2.1	8166	17.1	5477	11.5	7029	14.7
1992	576	1357	2.4	8226	14.3	6062	10.5	5403	9.4
1993	492	1231	2.5	7985	16.2	5217	10.6	4332	8.8
1994	576	1407	2.4	12,576	21.8	12,082	21.0	4667	8.1
1995	489	1161	2.4	10,344	21.2	6257	12.8	7015	14.3
1996	534	1335	2.5	9482	17.8	5691	10.7	3868	7.2
1997	667	1676	2.5	10,833	16.2	8653	13.0	7946	11.9
1998	693	1808	2.6	12,930	18.7	7337	10.6	7868	11.4
1999	541	1371	2.5	11,742	21.7	6378	11.8	5619	10.4
2000	616	1713	2.8	12,514	20.3	6722	10.9	6932	11.3
2001	672	1869	2.8	14,530	21.6	7359	11.0	10,498	15.6
2002	698	1828	2.6	14,199	20.3	7040	10.1	5991	8.6
2003	834	2354	2.8	16,697	20.0	8491	10.2	6830	8.2
2004	936	2719	2.9	19,442	20.8	9497	10.1	8267	8.8
2005	1009	2826	2.8	18,833	18.7	9573	9.5	5839	5.8
2006	1102	3248	2.9	23,748	21.5	10,788	9.8	6276	5.7
2007	1107	3163	2.9	23,692	21.4	10,926	9.9	7360	6.6
2008	1234	3543	2.9	26,857	21.8	11,344	9.2	6412	5.2
2009	1388	4104	3	30,768	22.2	12,685	9.1	6906	5.0
2010	1073	3338	3.1	26,878	25.0	11,111	10.4	4928	4.6
2011	1090	3445	3.2	28,424	26.1	11,498	10.5	4391	4.0
2012	1222	3959	3.2	35,036	28.7	12,476	10.2	3376	2.8
2013	1324	4437	3.4	38,571	29.1	13,241	10.0	1824	1.4
2014	1153	3971	3.4	39,783	34.5	13,623	11.8	767	0.7
Total	20,715	59,302	/	464,204	/	221,545	/	141,050	/
Average	/	2965	3.4	23,210	26.3	11,077	13.7	7053	9.7

TA: Total articles; AU: number of authors; NR: cited references; PG page count; TC: total citation counts; CPA: citations per article; TU/TA, NR/TA and PG/TA: average of authors, references, and pages per article, respectively.

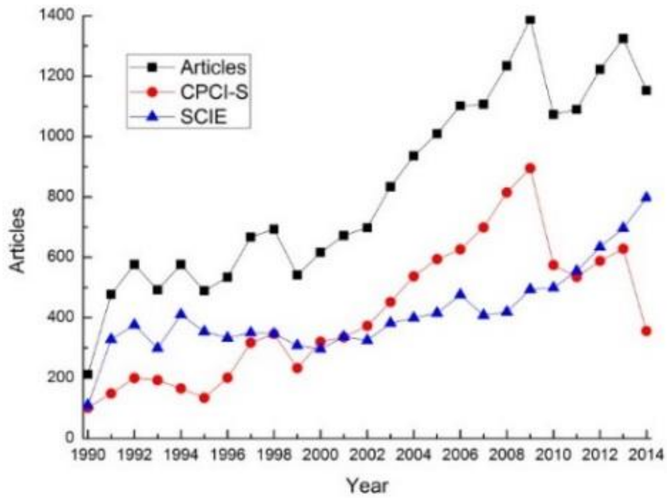

Figure 2. Temporal patterns of artificial intelligence-related articles.

3.2. Subject Categories and Major Journals

According to the classification of SCI/SSCI subject categories in 2014, AI research covered 138 categories. Top 10 subject categories include computer science (12,575; 35.2%), engineering (7884; 22.1%), automation and control systems (1714; 4.8%), operations research and management science (1185; 3.3%), mathematics (911; 2.5%), telecommunications (714; 2%), materials science (700; 2%), robotics (642; 1.8%), instruments and instrumentation (484; 1.4%), and physics (444; 1.2%). These top categories also suggest AI research is becoming a high-priority theme. The method of AI has been widely used in various applications including games, automation, medical and process control [3]. More and more researchers and scientists began to engage in this hot theme.

Articles on AI were published on 2599 journals and 958 proceedings (see Table 2 for the 20 most productive journals). There was a high concentration of artificial intelligence articles in these journals. These 20 journals (0.6% of 3557 journals) or proceedings accounted for 1,976 articles, or 9.5% of the total articles. Obviously, *Expert Systems with Applications* published the most articles on AI (344), followed by *Engineering Applications of Artificial Intelligence* (161), *AI Magazine* (161), *Artificial Intelligence* (126), and *Knowledge-based Systems* (103). AI-related articles published in these journals have received, on average, 13.3 citations, indicating that these articles have substantial influences on these subjects. Furthermore, several journals published a considerable number of highly cited articles, including *Artificial Intelligence* (126 articles with 7341 citations) and *IEEE Transactions on Information Theory* (seven articles with 4524 citations).

Table 2. Most productive journals in artificial intelligence research.

Journal	TA (R; %)	TC (R; %)	CPA (R)	IF (R)
Expert Systems with Applications	344(1;1.7)	3643(2;2.6)	10.6(9)	2.24(7)
Engineering Applications of Artificial Intelligence	161(2;0.8)	1650(4;1.2)	10.2(11)	2.207(9)
AI Magazine	161(3;0.8)	1220(7;0.9)	7.6(15)	0.595(17)
Artificial Intelligence	126(4;0.6)	7341(1;5.2)	58.3(1)	3.371(2)
Knowledge-based Systems	103(5;0.5)	1218(8;0.9)	11.8(8)	2.947(3)
Kybernetes	96(6; 0.5)	150(20;0.1)	1.6(20)	0.429(20)
Applied Artificial Intelligence	89(7;0.4)	562(15;0.4)	6.3(18)	0.527(19)
European Journal of Operational Research	84(8; 0.4)	1499(5;1.1)	17.8(5)	2.358(5)
Minds and Machines	81(9; 0.4)	375(19;0.3)	4.6(19)	0.568(18)
Artificial Intelligence Review	77(10; 0.4)	677(12;0.5)	8.8(13)	2.111(10)
Artificial Intelligence in Medicine	72(11; 0.3)	1318(6;0.9)	18.3(4)	2.019(12)
Journal of Intelligent Manufacturing	71(12; 0.3)	639(14;0.5)	9(12)	1.731(14)
Journal of Materials Processing Technology	68(13; 0.3)	833(11;0.6)	12.3(7)	2.236(8)
Information Sciences	68(14; 0.3)	965(10;0.7)	14.2(6)	4.038(1)
Applied Soft Computing	68(15; 0.3)	1693(3;1.2)	24.9(2)	2.81(4)
Computers in Industry	64(16; 0.3)	663(13;0.5)	10.4(10)	1.287(16)
Decision Support Systems	62(17; 0.3)	1151(9;0.8)	18.6(3)	2.313(6)
Computers & industrial Engineering	62(18; 0.3)	412(17;0.3)	6.6(17)	1.783(13)
Neurocomputing	60(19; 0.3)	404(18;0.3)	6.7(16)	2.083(11)
International Journal of Advanced Manufacturing Technology	59(20;0.3)	463(16;0.3)	7.8(14)	1.458(15)

TA: total articles; TC: total citation; CPA: citations per article; IF: 2014 ISI impact factor; R: rank in the list.

3.3. Author Productivity and Geographic Distribution

Table 3 presents the result of the author productivity analysis. Twenty authors were the most productive during the period of 1990–2014. It is evident that these top productivity authors have made great achievement on AI research. Of these authors, J. Neves produced the largest number (35) of articles [29], but G. Klopman received the highest rate of citations (35.6) [30,31]. For individual authors, it seems that their productivity is negatively related to their academic value. The pursuit for high-level research might be at the cost of research quantity [32]. We found the authors mainly cooperated with colleagues in national-level institutions rather than international cooperation by analyzing the data of authors: M. Ogiela published 14 articles with R. Tadeusiewicz, and G. Klopman has 11 articles with H. Rosenkranz. These data suggest that the cooperation tends to not be prevalent in AI research, and this cooperation is far less than that in other fields [15,33].

We geocoded cities of authors in the database, and mapped the distribution of authors in AI research by using ArcGIS 10.1, a GIS software package. Then, we employed the method of kernel density estimation (KDE) to visualize the geographic distribution of authors (Figure 3). As Figure 3 shows, major spatial clusters of authors are in U.S., Europe, and East Asia. In USA and China, most of the authors were located in east coast instead of west. The clusters of European authors were mainly located in UK, Spain, France, Germany, Italy, Poland, Greece, Netherlands, and Romania. China, Japan, and South Korea were the major distribution areas of authors in East Asia. There are spatial clusters of authors distributed in Canada, India, Brazil, Iran, and Turkey, but an exception is India: distribution of authors did not form a cluster, although there are many authors with productive output. Figure 4 shows the distribution of authors and investment of R and D (also see Table 4). By comparing the two figures, we found there is a strong spatial correlation between the geographic distribution of authors and investment of R and D. Most of the authors are distributed in the developed countries and developing countries with high investment of R and D. In these countries, research institutions and universities receive a significant amount of R and D investment. Therefore, authors in those countries produce more articles. For individual countries, productive authors are clustered in those regions with more universities and research institutes, such as the east part of USA, Beijing in China, Paris in France, London in UK, and Tokyo in Japan. Support in these institutions and universities provide more opportunities for researchers.

Table 3. Top 20 productive authors from 1990–2014.

Author name	Institute	Total Outputs			First Author			Corresponding Author		
		TA	TC	CPA (R)	FAP	TC	TC/FAP (R)	CP	TC	CPA (R)
J. Neves	Univ Minho	35	63	1.3(17)	3	0	0.0(19)	3	0	0(16)
G. Klopman	Case Western Reserv Univ	30	1,068	35.6(1)	12	664	55.3(1)	14	697	49.8(1)
C. Chen	Natl Pingtung Univ Educ	28	321	13.5(7)	11	114	10.4(8)	22	295	13.4(5)
K. Chau	Hong Kong Polytech Univ	28	633	18.6(6)	26	601	23.1(4)	28	633	22.6(3)
R. Tadeusiewicz	AGH Univ Sci & Technol	26	172	6.6(11)	4	26	6.5(12)	4	32	8(9)
M. Cheng	Natl Taiwan Univ Sci & Technol	25	114	4.6(14)	15	71	4.7(13)	1	0	0(16)
M. Ogiela	AGH Univ Sci & Technol	22	163	7.4(10)	15	131	8.7(10)	16	137	8.6(8)
H. Rosenkranz	Univ Pittsburgh	21	702	33.4(2)	4	56	14.0(7)	6	78	13(6)
L. Lai	City Univ London	18	437	24.3(4)	10	359	35.9(2)	11	359	32.6(2)
S. Chien	Caltech,Jet Propuls Lab	18	20	1.1(18)	5	19	3.8(15)	5	19	3.8(12)
P. Novais	Univ Minho	18	20	1.1(18)	1	3	3.0(17)	6	8	1.3(14)
Y. Xu	Shanghai Jiao Tong Univ	17	92	5.4(12)	3	48	16.0(6)	5	48	9.6(7)
M. Juhola	Univ Tampere	17	65	3.8(15)	2	0	0.0(19)	2	0	0(16)
U. Cortes	Tech Univ Catalonia	17	396	23.3(5)	4	16	4.0(14)	4	16	4(11)
O. Kisi	Canik Basari	17	208	12.7(9)	2	19	9.5(9)	0	0	0(16)
B. Shih	Natl Pingtung Univ Educ	16	211	13.2(8)	10	166	16.6(5)	0	0	0(16)
M. Majewski	Koszalin Univ Technol	16	23	1.4(16)	3	11	3.7(16)	3	11	3.7(13)
B. Goertzel	Novamente LLC	14	14	1.0(20)	5	3	0.6(18)	11	9	0.8(15)
E. Corchado	Univ Salamanca	14	66	4.7(13)	6	47	7.8(11)	6	47	7.8(10)
Y. Hsu	Chung Hua Univ	14	368	26.3(3)	7	188	26.9(3)	9	195	21.7(4)

TA: total articles; TC: total citation counts; FAP: number of articles published as the first author; CP: number of articles published as the corresponding author; CPA: citations per article; R: rank in the list.

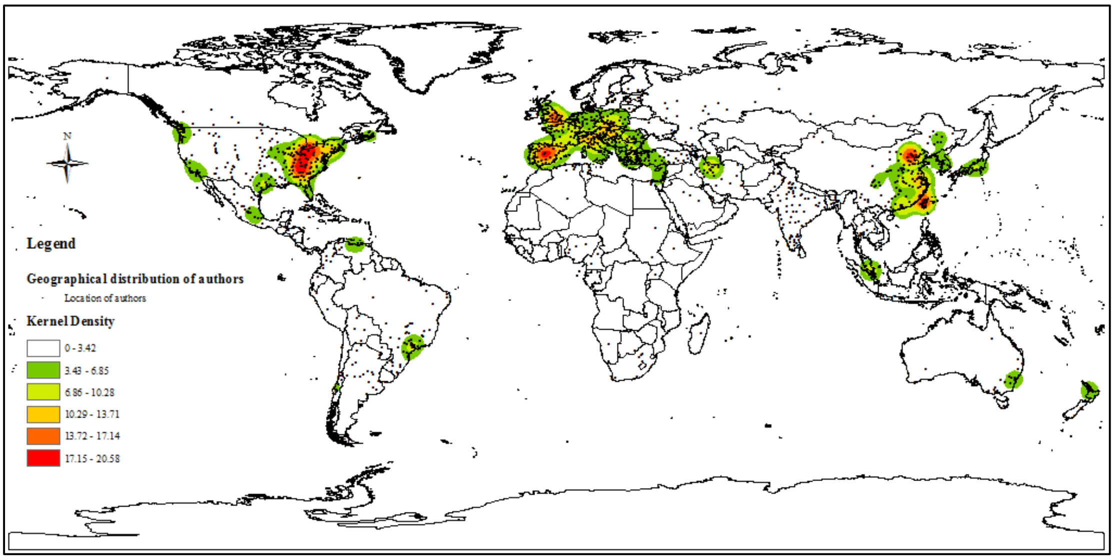

Figure 3. Kernel density estimation for the geographic distribution of authors.

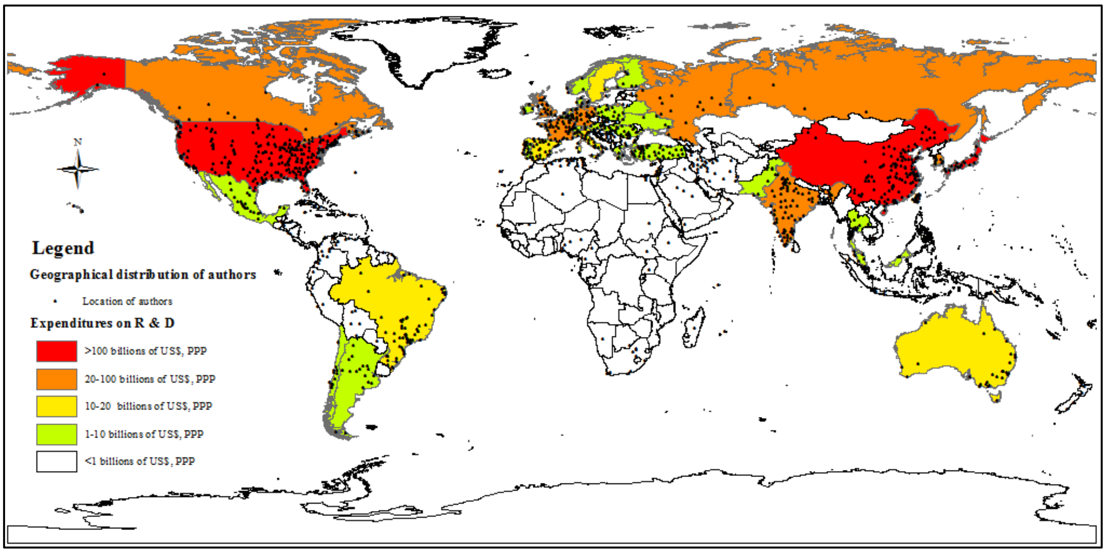

Figure 4. Relation between geographic distribution of authors and investment on R and D.

Table 4. Twenty most productive countries/territories in artificial intelligence research.

	TA	Single-country				Internationally Collaborated				R&D	TA/I(1 million)
		SA	TC	CPA (R)	SA (%)	CA	TC	CPA(R)	CA(%)		
USA	4144	3432	42,233	12.3(2)	82.8	712	15,032	21.1(2)	17.2	405.3	13.2
China	2392	2157	4432	2.1(19)	90.2	235	2282	9.7(13)	9.8	337.5	1.8
UK	1718	1312	11,996	9.1(3)	76.4	406	5939	14.6(5)	23.6	38.4	27.4
Spain	1073	888	4215	4.7(12)	82.8	185	1315	7.1(18)	17.2	17.2	22.9
France	869	650	3068	4.7(12)	74.8	219	3205	14.6(6)	25.2	42.2	13.3
Germany	830	655	3978	6.1(6)	78.9	175	1718	9.8(12)	21.1	69.5	10.2
Canada	823	565	3237	5.7(9)	68.7	258	6790	26.3(1)	31.3	24.3	24.2
Italy	797	615	3339	5.4(10)	77.2	182	3109	17.1(3)	22.8	19	13.1
India	643	575	2175	3.8(15)	89.4	68	675	9.9(10)	10.6	36.1	0.5
Japan	613	510	1890	3.7(16)	83.2	103	1200	11.7(8)	16.8	160.3	4.8
Brazil	593	521	1384	2.7(18)	87.9	72	759	10.5(9)	12.1	19.4	2.9
Australia	590	432	2181	5.0(11)	73.2	158	1130	7.2(17)	26.8	15.9	27.1
Taiwan	506	461	3740	8.1(4)	91.1	45	646	14.4(7)	8.9	19	21.5
Poland	470	423	1383	3.3(17)	90.0	47	370	7.9(16)	10.0	6.9	12.2
Iran	412	326	1260	3.9(14)	79.1	86	479	5.6(20)	20.9	0.7	5.3
Turkey	359	288	4206	14.6(1)	80.2	71	673	9.5(14)	19.8	7.3	4.6
South Korea	317	276	1642	5.9(7)	87.1	41	390	9.5(15)	12.9	65.4	6.5
Greece	307	258	1485	5.8(8)	84.0	49	485	9.9(11)	16.0	1.7	28.4
Netherlands	304	196	1401	7.1(5)	64.5	108	1696	15.7(4)	35.5	10.8	18.1
Romania	270	251	491	2.0(20)	93.0	19	116	6.1(19)	7.0	1.3	12.3

TA: total articles; TC: total citation counts; SA: single-country articles; CA: internationally-collaborated articles; CPA: citations per article; R and D: investment of research and development, 1 billion; TA/I: number of articles per million inhabitants; R: rank in the list.

3.4. International Productivity and Collaboration

The total number of articles for the distribution analysis of country and institute publications was 28,565 (2537 articles without author affiliation information were excluded). Based on the analysis of the author affiliation, there were 122 countries/territories participated in AI research. The top 20 countries/territories were ranked based on the total number of articles (Table 4). Out of these 20 countries, nine were from Europe, seven were from Asia, two were from North America, one was from South America, and one was from Oceania. The results are similar to the geographic distribution of authors. Table 4 shows that USA was responsible for the most internationally-collaborative and single-country articles—*i.e.*, USA can be seen as the most productive country for AI studies. In addition to the citation, the ranking of countries was led by USA. China published the second highest number of articles (2392), followed by UK (1718), Spain (1073), France (869), Germany (830), and Canada (823).

To a certain degree, R and D investment can be linked to academic output. Therefore, it is instructive to compare the number of publications per country relative to population and R and D investment. Table 4 also lists the amount of investment of R and D and number of population of top 20 countries/territories. In terms of investment of R and D, USA ranked first, and Iran ranked last. With respect to the article intensity per million inhabitants, Greece ranked first, and India ranked last. Although USA published the largest number of articles, it ranked 17th and ninth among the top 20 after taking population and R and D into consideration. To quantify the relationship between R and D and academic outputs, correlation analysis was performed using the data for top 20 countries. The number of articles is highly correlated with the investment of R and D (r^2 = 0.88).

At the country/regional level, 17,969 (86.7%) were single-country articles and 2,746 (13.3%) were internationally-collaborated publications, indicating that independent research dominated in these countries/territories. Highly-cited articles that are internationally-collaborated are more than those from single countries. For example, the citation of single-country articles in 20 most productive countries/territories is 6.7, while the citation of internationally collaborated articles is 14.8. This phenomenon explains that international collaboration can lead to more high-level research achievement and articles.

At the institution level, there were 28,566 research institutes participated in AI research. USA's dominance in AI research has extended to the institutional level. Among top 20 institutions in Table 5, seven were in USA, and other 13 were from China, Singapore, Canada, Spain, India, Italy, Brazil, Iran, and Greece. Chinese Academy of Sciences led institutional productivity with 123 articles, followed by Massachusetts Institute of Technology (MIT) with 118, and Hong Kong Polytech University with 118. MIT topped in the ranking of citations per single-institution produced articles with 63.2. The University of Toronto has the highest citation rate for inter-institutional collaborations with a CPP of 110.9, while Nanyang Technological University and Chinese Academy of Sciences outperformed regarding single-institutional and inter-institutional levels. Moreover, the average citation rate for articles from a single institution (12.4) was lower than that for institutionally-collaborated outputs (18.2), indicating that inter-institutional collaboration improved the citation rates and the influence of the articles. The results showed that University of Pittsburgh, Islamic Azad University, the Chinese Academy of Sciences, and Georgia Institute Technology are the top four with more single-institutional papers than international collaboration, and the University Alberta, National Technology University of Athens, Nanyang Technological University, and the University Polytechnic of Valencia were the top four with more international collaboration papers than single-institution.

Table 5. Top productive institutions in artificial intelligence research.

Institution	TA	TC	Single-institution				Inter-institution			
			SI	TC	CPA (R)	SI (%)	CI	TC	CPA (R)	CI (%)
Chinese Acad Sci, China	123	769	45	92	2(17)	36.6	78	677	8.7(13)	63.4
MIT, USA	118	5684	69	4,359	63.2(1)	58.5	49	1,325	27(4)	41.5
Hong Kong Polytech Univ, Hongkong	118	1302	67	526	7.9(10)	56.8	51	776	15.2(7)	43.2
Nanyang Technol Univ, Singapore	111	1039	70	586	8.4(9)	63.1	41	453	11(10)	36.9
Islamic Azad Univ, Iran	104	361	31	75	2.4(16)	29.8	73	286	3.9(19)	70.2
Carnegie Mellon Univ, USA	102	1547	57	1,044	18.3(3)	55.9	45	503	11.2(9)	44.1
Univ Sao Paulo, Brazil	100	346	55	75	1.4(20)	55.0	45	271	6(17)	45.0
Stanford Univ, USA	95	2526	48	795	16.6(4)	50.5	47	1731	36.8(2)	49.5
Indian Inst Technol, India	94	600	54	290	5.4(13)	57.4	40	310	7.8(16)	42.6
Natl Univ Singapore, Singapore	92	790	51	352	6.9(12)	55.4	41	438	10.7(11)	44.6
Univ Pittsburgh, USA	88	2436	24	496	20.7(2)	27.3	64	1940	30.3(3)	72.7
Univ Toronto, Canada	77	5187	34	419	12.3(7)	44.2	43	4768	110.9(1)	55.8
Univ SO Calif, USA	77	1100	42	545	13(6)	54.5	35	555	15.9(5)	45.5
Univ Politecn Valencia, Spain	76	320	46	81	1.8(18)	60.5	30	239	8(15)	39.5
Natl Tech Univ Athens, Greece	76	763	49	497	10.1(8)	64.5	27	266	9.9(12)	35.5
Univ Genoa, Italy	75	393	44	128	2.9(15)	58.7	31	265	8.5(14)	41.3
Univ Poliecn Madrid, Spain	74	184	33	57	1.7(19)	44.6	41	127	3.1(20)	55.4
Univ Arizona, USA	72	875	32	246	7.7(11)	44.4	40	629	15.7(6)	55.6
Univ Alberta, Canada	66	688	34	507	14.9(5)	51.5	32	181	5.7(18)	48.5
Georgia Inst Technol, USA	66	605	25	114	4.6(14)	37.9	41	491	12(8)	62.1

TA: total articles; TC: total citation counts; SI: single-institution articles; CI: inter-institutionally collaborated articles; CPA: citations per article; R: rank in the list.

It is apparent that international collaboration was not prevalent in AI research (Figure 5). Among 19,963 articles with address information, 14,798 (74.1%) were independent articles published by single institutions, and the other articles were inter-institutional collaboration work, including both national (16.5%) and international (9.4%) collaborations. Thu, in order to strengthen AI research, cooperation, especially international cooperation, among institutions should be paid more attention.

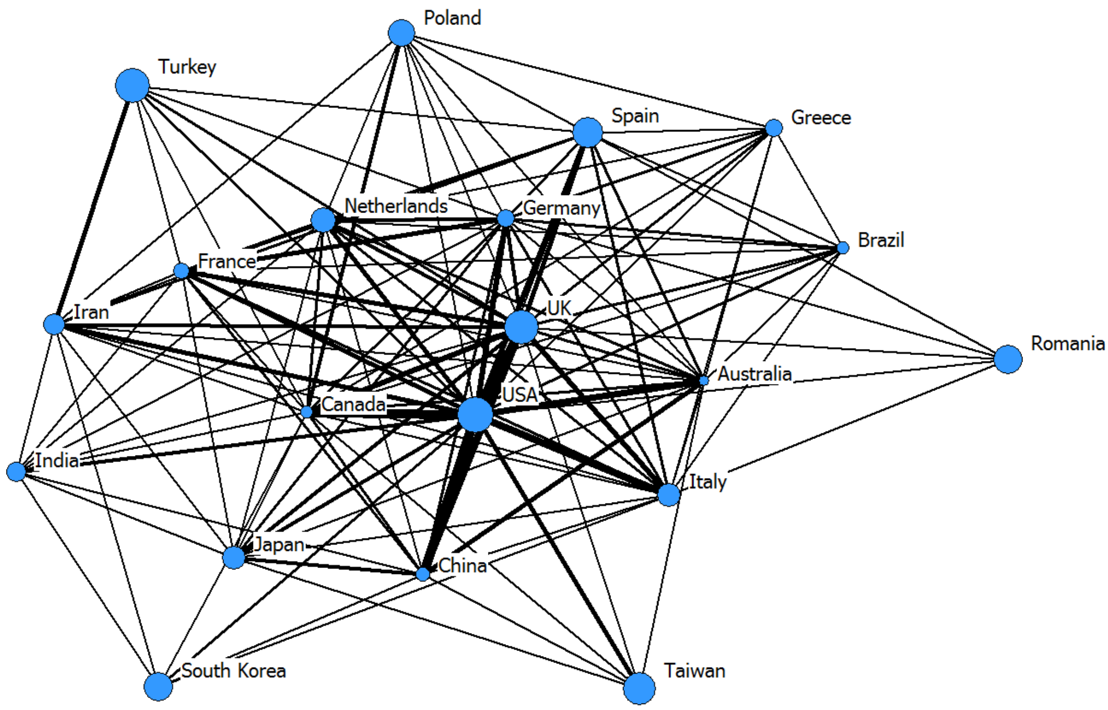

Figure 5. Core international collaboration networks.

3.5. Key Words, Hot Issues, and Research Trend Analysis

Keyword analysis can be considered as an important tool for analyzing hot topics and research trend. We carried out the keyword analysis by the author keywords and keywords plus. There are 4001 articles without author keywords and keywords plus, and the other articles (16,714) contained 36,049 unique keywords with 108,850 occurrences. However, 25,144 (69.7%) keywords appeared only once. It implied that there are many research fields in AI research, and many scholars study the AI research in various fields with different methods. However, due to various reasons, most scholars lack continuous research [34]. Only 1137 (3.2%) keywords were used over 10 times in articles of AI, and these keywords were considered as the hot topic in AI research. In order to analyze the macroscopic development of AI research, the 25-year period of AI research is divided into five stages with an interval of five years. The results show that, in the past 25 years, the number of keywords increases from 5692 during 1990–1994 to 24,183 during 2010–2014. The top 30 high-frequency keywords were listed in Table 6. We can conclude the hot issues and research trends of AI as follows:

Keywords, except the search word "artificial intelligence", can be classified into two groups, "method and model" and "applications" in AI research. In order to find the hot issues and research trends, we conducted comparative analysis of each group of keywords in five stages.

First, artificial neural network (ANN), genetic algorithm (GA), fuzzy logic (FL), support vector machine (SVM), machine learning (ML), swarm intelligence (SI), particle swarm optimization (PSO), distributed artificial intelligence (DAI), computational intelligence (CI), and ontology can be organized to the class of "methods and models". Figure 6 depicts the changes and trends of every five-year article output of the "methods and models" from 1990 to 2014. As an important approach in AI, ANN attracted continual attention. Thus, the frequency of occurrence on ANN is about triple that on GA, and much higher than other keywords throughout the study period [35–37]. The article output of ANN maintained rapid growth. This implies that ANN will still deserve extensive research in the future [38]. We noticed that there is a significant growth in mid-2000s with respect to the output of ANN because of advancement in ANNs. One possible reason is the advance in computational resources. Therefore, more and more researchers have opportunities to leverage high-performance computing resources for data handling, analysis, and visualization [39,40]. Another reason is the rise of "deep learning" research in late 2000s as "recurrent neural networks" and "deep feedforward neural networks" (based on the use of many hidden layers, instead of one or two) have been developed. GA is another important method in AI research, but, there are some limited factors on the use of GA, for example, fitness function evaluation, decision problems, and global optimization. As a booming field, AI mainly undeniably relies on numerous methods, such as SVM, SI, CI, and PSO. Albeit these methods do not have a large number of applications, many scholars suggested these methods will have more and more applications, and become more important in AI [41–44].

Table 6. Temporal pattern of frequently used keywords.

keyword	TA(R)						CPA(R)
	1990–1994	1995–1999	2000–2004	2005–2009	2010–2014	1990–2014	
Artificial Intelligence(AI)	915(1)	879(1)	950(1)	1487(1)	1,610(1)	5,841(1)	6.8(25)
Artificial Neural network(ANN)	114(3)	310(2)	472(2)	966(2)	1,419(2)	3,281(2)	8.3(17)
Genetic algorithm(GA)	16(18)	82(5)	178(4)	315(3)	493(3)	1,084(3)	9.2(11)
Expert System (ES)	399(2)	196(3)	181(3)	170(5)	132(14)	1,078(4)	6.9(23)
Optimization	19(15)	57(8)	92(6)	168(6)	366(4)	702(5)	7.9(19)
Prediction	13(22)	22(20)	57(12)	132(9)	300(5)	524(6)	9.2(11)
Classification	18(16)	43(15)	60(11)	179(4)	223(8)	523(7)	10.6(6)
Design	42(10)	45(14)	79(8)	120(11)	223(8)	509(8)	9.9(8)
Fuzzy Logic (FL)	20(13)	52(12)	101(5)	138(8)	185(11)	496(9)	8(18)
Multi-agent system(MAS)	9(23)	42(17)	84(7)	158(7)	141(12)	434(10)	10.6(6)
Simulation	52(6)	43(15)	69(9)	104(12)	120(15)	388(11)	7.2(20)
Support Vector Machine(SVM)	0(27)	0(29)	15(28)	86(15)	264(6)	365(12)	7.2(20)
Machine Learning(ML)	22(12)	48(13)	56(13)	92(13)	138(13)	356(13)	6.6(26)
Diagnosis	46(8)	61(7)	63(10)	72(19)	90(18)	332(14)	13.1(3)
Data mining	1(25)	11(25)	52(14)	131(10)	118(16)	313(15)	6.5(27)
Swarm intelligence(SI)	0(27)	1(28)	16(26)	73(17)	215(10)	305(16)	15.4(1)
Particle swarm optimization (PSO)	0(27)	0(29)	3(30)	52(25)	238(7)	293(17)	11.6(5)
Decision support system(DSS)	34(11)	53(11)	52(14)	80(16)	65(26)	284(18)	8.8(14)
Pattern recognition	46(8)	56(9)	36(22)	73(17)	64(27)	275(19)	9.4(10)
Knowledge-based system(KBS)	68(4)	78(6)	49(17)	41(29)	26(30)	262(20)	6.4(28)
Case-based reasoning(CBR)	8(24)	39(18)	50(16)	91(14)	74(21)	262(20)	9(13)
Distributed artificial Intelligence(DAI)	57(5)	93(4)	43(19)	37(30)	29(29)	259(22)	7(22)
Knowledge representation(KR)	50(7)	54(10)	49(17)	66(20)	37(28)	256(23)	5.6(30)
Management	15(20)	20(22)	38(21)	54(23)	78(20)	205(24)	14.7(2)
Identification	15(20)	17(24)	33(23)	59(22)	80(19)	204(25)	9.7(9)
Decision making	16(18)	30(19)	23(25)	52(25)	72(22)	193(26)	6.9(23)
Fault Diagnosis	20(13)	21(21)	39(20)	43(28)	66(25)	189(27)	8.4(16)
Computational intelligence(CI)	0(27)	11(25)	16(26)	53(24)	103(17)	183(28)	8.6(15)
Recognition	18(16)	20(22)	15(28)	49(27)	72(22)	174(29)	12.1(4)
Ontology	1(25)	10(27)	24(24)	62(21)	69(24)	166(30)	6.3(29)

TA: total articles; CPA: citations per article; R rank in the list.

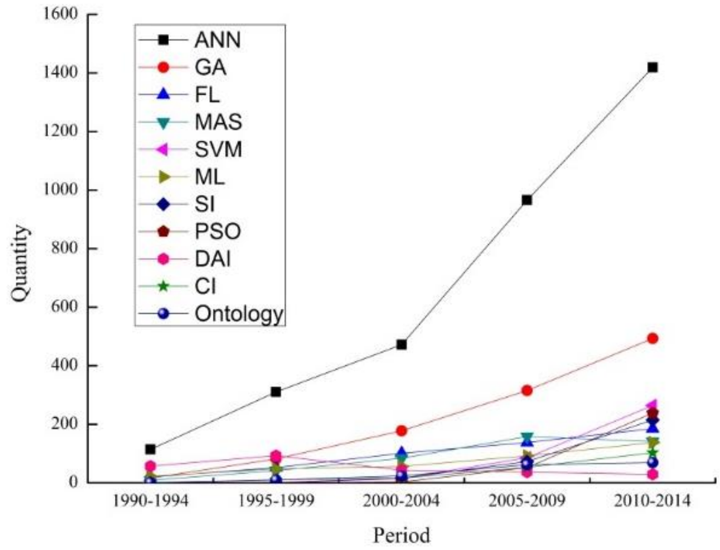

Figure 6. Trends of keywords with respect to method and model.

Second, AI is an application-driven discipline [45]. So the method and model of AI have been widely applied in many fields [46], such as expert system (ES), optimization, classification, design, prediction, multi-agent system (MAS), simulation, diagnosis, decision support system (DSS), pattern recognition, knowledge-based system (KBS), case-based reasoning (CBR), knowledge representation (KR), management, identification, decision-making, fault diagnosis, recognition, and data mining. Figure 7 shows the trend in the applications of AI research over the past 25 years (five year intervals). AI has great advantage in reasoning, learning [47], data processing and application-specific problem-solving [48–51]. In addition to these aspects, it has been well acknowledged that AI can solve domain application problems efficiently and effectively [52,53]. Researchers studied the application of AI from two main aspects. (1) designing and realizing the prototype system and experimental system, such as ES, DSS, KBS, MAS, by the method and model to solve the application problems; (2) employing the method, model, or algorithm of AI to solve practical applications in some fields. Based on the analysis of academic output, the number of articles increased substantially in most application fields in which optimization, prediction, classification, and data mining play an important role. On the other hand, although some fields had the highest frequency before the 2000s, fewer and fewer scholars paid attention to these fields in recent years. For instance, the ES-related articles in 2010–2014 are only one-third of the articles from 1990-1994, which is the same as in the field of pattern recognition.

The keywords of articles was dominated by AI, ANN, GA, ES, optimization, and prediction. In order to achieve a deep understanding of the hot issues and patterns of AI research, the method of co-word analysis was performed by using top 30 frequent keywords (Figure 8). It is worth noting that "AI" obtained the high frequencies of co-occurrence with "ANN", "ES", "GA", and "Simulation", indicating that these keywords are important in the AI research. Another important keyword is ANN, which has high frequencies of co-occurrence with "ES" and "AI", "prediction", "GA", "fuzzy logic", "SVM", and "CI", showing that ANN is the essential and important algorithm in AI research. By using new methods, in recent years, many scholars have been intent to improve ANN and enhance the efficiency of ANN by coupling with other algorithm, such as GA, and fuzzy logic [54–59]. In addition, the close relationship of AI with ANN and ES indicates that many scholars are dedicated to related research and published numerous articles.

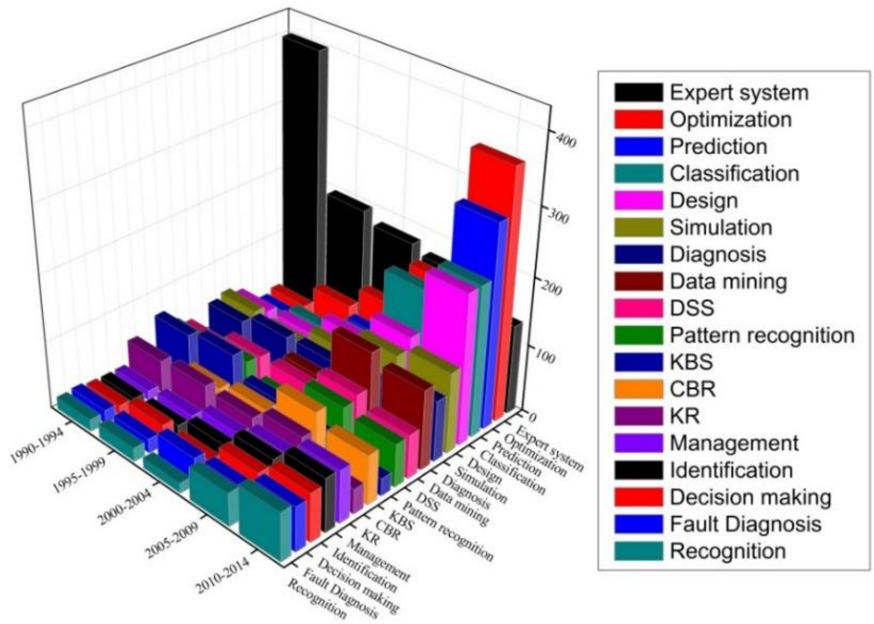

Figure 7. Trend of keywords with respect to application of artificial intelligence (DSS: decision support system; KBS: knowledge-based system; CBR: case-based reasoning; KR: knowledge representation).

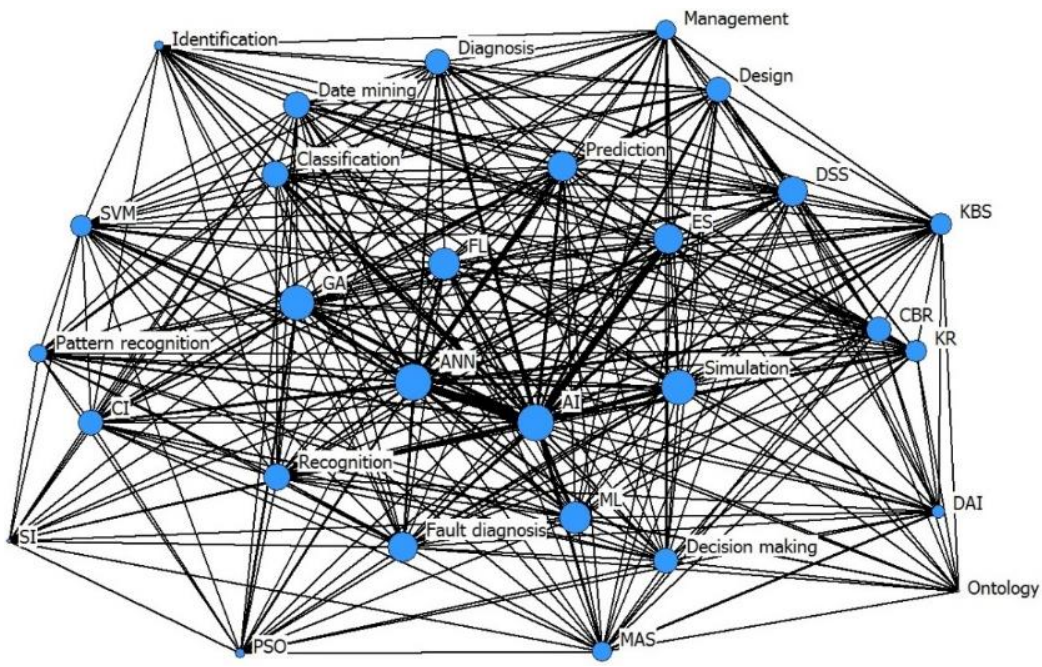

Figure 8. Co-word network of top 30 high-frequency keywords in artificial intelligence.

From the early 2000s, with the resurgence of AI research, more and more methods and models were put forward, such as ant colony optimization (ACO), artificial immune system (AIS), and artificial bee colony algorithms (ABC). These methods and models were applied to more fields, and even some new fields emerged (Table 7). Based on various aspects of ant foraging behavior, ACO was originally proposed for numerical problems, and was used to solve the optimization problem in many fields [60,61]. Currently, there are many studies on the AIS [62] and ABC algorithms [63,64]. These methods and models typically emulate the biological characteristics of response, memory, and learning to domain-specific problem-solving. As an important method in computer science, a rough set has been applied in the field of AI [65,66]. The latest research in AI methods is the artificial endocrine system (AES), which is introduced into the field of AI [6,67–69]. It is foreseeable that AES will become an important method of AI in computer science and related domains. In general, these methods are not only applied to solve the problem of AI independently, but also integrated with the existing methods to solve application problems [60,70–72]. On the other hand, the theory and method of AI are applied to solve new problems. There have been some studies reported with respect to applications in mobile robot and reinforcement learning since the late 1990s (see Table 7).

Table 7. New methods, models and applications in artificial intelligence research.

Keyword	Type	TA(R)					CPA (R)
		1995–1999	2000–2004	2005–2009	2010–2014	1995–2014	
Artificial Bee Colony (ABC)	Method and model	0(5)	0(6)	5(6)	156(1)	161(1)	14.2(2)
Ant Colony Optimization (ACO)	Method and model	1(4)	5(4)	31(4)	62(2)	99(4)	15.5(1)
Artificial Immune System (AIS)	Method and model	0(5)	4(5)	37(3)	53(3)	94(6)	9.0(4)
Artificial endocrine system (AES)	Method and model	0(5)	0(6)	0(7)	4(7)	4(7)	3.3(7)
Rough set	Method and model	5(3)	17(2)	49(1)	32(6)	103(3)	7.3(6)
Mobile robot	Application	9(1)	25(1)	30(5)	33(5)	97(5)	12.7(3)
Reinforcement learning	Application	7(2)	14(3)	48(2)	54(4)	123(2)	8.95(5)

TA: total articles; CPA: citations per article; R: rank in the list.

In the past decades, AI made rapid progress not only in the theory, method, and model, but also in its application. As mentioned above, AI is an application-driven discipline. Many specific application problems in the field of geoscience (broadly includes a suite of domains, for example, geographic information science, geography, earth science, and environmental science) contribute to the development of AI (e.g., to support spatial optimization, image classification) [36,73]. Scholars of geoscience are engaged in the field of applied research in AI, and this is the case particularly as the emergence of geocomputation in the 1990s [74,75]. We analyzed the 1482 articles related to geoscience in AI research, including 4819 keywords, in which only 219 keywords were used more than five times. In addition to the keyword in Table 8, some keywords, such as land use and virtual reality caught the attention from scholars in recent years. However, the output and status in the field of geoscience do not attract enough attention. The reason may come from two aspects: one is that part of researchers believed AI and its application does not belong to the domain of geoscience; the other reason is that there are many problems needed to overcome in the theory, method, and model of AI. For example, many unresolved issues in AIS limited the applied research. In fact, the lack of research in the field of geoscience has a certain relationship with these two reasons, especially for the latter. With the development of computational hardware and computational power in recent years, many problems of AI have been resolved. A growing number of scholars engaged in interdisciplinary research, especially as vigorous development of Geographic Information Science (GIScience; see [20]) and the blossoming of big data studies [76]. As scholars proposed extensively to carry out the interdisciplinary collaborative research, AI research and related discipline will enter a new era. A number of research problems to which conventional statistical models may be ill-suited, AI (e.g., machine learning) may provide alternative or novel support for the resolution of these problems, in particular, in the face of handling large amounts of data.

Table 8. Most frequently used keywords in geoscience.

Keyword	TA(R)						CPA(R)
	1990–1994	1995–1999	2000–2004	2005–2009	2010–2014	1990–2014	
River	0(5)	0(2)	2(4)	13(2)	16(1)	31(1)	20.8(4)
GIS	0(5)	0(2)	2(4)	14(1)	12(2)	28(2)	4.9(9)
Remote sensing	1(4)	0(2)	6(2)	9(3)	8(3)	24(3)	14.2(5)
Wastewater treatment	2(3)	0(2)	7(1)	9(3)	2(7)	20(4)	28.8(1)
Water quality	0(5)	3(1)	0(7)	6(7)	8(3)	17(5)	7.2(7)
Hydrology	4(1)	0(2)	0(7)	1(8)	6(5)	11(6)	5.4(8)
Risk assessment	3(2)	0(2)	3(3)	0(9)	4(6)	10(7)	12(6)
Rainfall runoff models	0(5)	0(2)	0(7)	8(5)	2(7)	10(7)	27.2(2)
Flood forecasting	0(5)	0(2)	1(6)	8(5)	1(9)	10(7)	24.1(3)

TA total articles; CPA citations per article; R rank in the list. GIS: Geographic Information Systems.

4. Conclusions

By employing the method of bibliometric analysis, a clear understanding of the global trends in AI research patterns during 1990–2014 was developed in this study. The amount of AI publication presented a solid growth with an increasing number of articles. This can be seen as a new research upsurge in AI after the rapid development from the 1990s. "Computer science" and "engineering" were the two major subject categories. *Artificial Intelligence* is the most important journal with the highest number of citations per article. The top 20 productive authors are identified. We noticed a pattern that cooperation was not prevalent in AI research. The geographic information visualization approach is employed to represent the worldwide geographic distribution of authors in AI. Results show the authors are mainly distributed in USA, West Europe, and East Asia, highly correlated with the investment of R and D and population density. From the country/territory and institute level, we analyzed the international productivity and collaboration. USA and Chinese Academy of Sciences produced the largest number of single-country and internationally-collaborated articles. Network analysis suggested that USA was in the central position of international collaboration network. However, based on the analysis on the citation, MIT is the top institute in the research of artificial intelligence. Additionally, both national and international collaboration are not prevalent in AI research. With the keywords analysis, we analyzed the research patterns by categorized the key words into two groups: method and model, application, and the prevalent research topic patterns were also ascertained in these two fields. In terms of co-word analysis, we found several interesting keywords with high co-occurrence frequencies. Based on the recent research in artificial intelligence, we analyzed the future research trends in the field of AI, and more and more methods and models can be applied to solve the application in the future. Our study reveals patterns in scientific outputs and academic collaborations related to AI, and serves as an alternative and innovative way of revealing global research trends. The method and result of this article may serve for future research as an alternative demonstration of research advancements.

In this study, we aimed to reveal the research pattern and trends of AI studies from different perspectives. For future study, we will focus on the improvement of bibliometric analysis. First, we will use more bibliometric indicators to further strengthen the bibliometric analysis. Second, more methods in spatial analysis, geovisualization, and social network analysis will be introduced to bibliometric analysis within a spatially-explicit context. In this study, we used geocoding and KDE as geospatial approaches to support the spatially-explicit bibliometric analysis of AI studies. In future work, we will use, for example, spatial autocorrelation approaches to analyze spatially-dependent characteristics in bibliometric data at alternative levels (e.g., country, state/province). Further, point pattern analysis can be recruited to identify the spatial arrangement of bibliometric data (e.g., clustered, random, or regular). These future directions, as we believe, will further advance the study of bibliometric analysis within spatially-explicit contexts. This need is timely, with the increasing availability of bibliometric data and the rapid and continual development of GIS and spatial analysis.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SCI-Expanded	Science Citation Index Expanded
CPCI-S	Conference Proceedings Citation Index-Science
IF	impact factor
KDE	Kernel Density Estimation
JCR	Journal Citation Report
R&D	Research and Development

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