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Research paper

A bibliometric and visual analysis of global geo-ontology research

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A R T I C L E I N F O

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A B S T R A C T

In this paper, the results of a bibliometric and visual analysis of geo-ontology research articles collected from the Web of Science (WOS) database between 1999 and 2014 are presented. The numbers of national institutions and published papers are visualized and a global research heat map is drawn, illustrating an overview of global geo-ontology research. In addition, we present a chord diagram of countries and perform a visual cluster analysis of a knowledge co-citation network of references, disclosing potential academic communities and identifying key points, main research areas, and future research trends. The *International Journal of Geographical Information Science*, *Progress in Human Geography*, and *Computers & Geosciences* are the most active journals. The USA makes the largest contributions to geo-ontology research by virtue of its highest numbers of independent and collaborative papers, and its dominance was also confirmed in the country chord diagram. The majority of institutions are in the USA, Western Europe, and Eastern Asia. Wuhan University, University of Munster, and the Chinese Academy of Sciences are notable geo-ontology institutions. Keywords such as “Semantic Web,” “GIS,” and “space” have attracted a great deal of attention. “Semantic granularity in ontology-driven geographic information systems, “Ontologies in support of activities in geographical space” and “A translation approach to portable ontology specifications” have the highest cited centrality. Geographical space, computer-human interaction, and ontology cognition are the three main research areas of geo-ontology. The semantic mismatch between the producers and users of ontology data as well as error propagation in interdisciplinary and cross-linguistic data reuse needs to be solved. In addition, the development of geo-ontology modeling primitives based on OWL (Web Ontology Language) and finding methods to automatically rework data in Semantic Web are needed. Furthermore, the topological relations between geographical entities still require further study.

1. Introduction

Ontology was originally a philosophical concept that describes research on the essence of the objective world. Ontology was founded, defined, and finally came into being during humanity's process of understanding nature. It is a cognitive activity directed toward the natural world and based on human ideology, and its main forms are judgment and inference through the medium of language (Chidamber and Kemerer, 1994). In the 1990s, ontology was introduced into geographic information science, and geo-ontology was formed as an extension and application of ontology into the field of geo-spatial information science. Moreover, geo-ontology is an explicit and formal specification of the shared conceptual models in the geographic information field (Kuhn, 2001). At the same time, the geographic information field needs geo-ontology to be the principal theory for its development, especially for the semantics-based technologies of the Internet, modeling, and integration. Through the introduction of the idea of ontology, existing data, knowledge, and information can be formed into a reasonable semantic system from object-oriented, process-oriented and other forms, which is easy for computers to process and users to share (Buccella et al., 2009).

In the past 20 years, many researchers have been dedicated to geo-ontology studies and published thousands of papers, most of which are primarily focused on a specific subdomain or subject of geo-ontology, such as the properties of geo-ontology (Smith and Mark, 1998, 2001), formal geo-ontology (Guarino, 1998; Li et al., 2008), geo-ontology integration (Hu et al., 2011; Kavouras and Kokla, 2002). These studies deepen our insight into geo-ontology. Geo-ontology has already become an important research topic in geographic information science. A summary analysis of its development will be helpful for orienting

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future studies in the field. Researchers have previously created summaries containing qualitative analysis (Li et al., 2015). In library and information science and scientific measurement, a qualitative review reflects a researcher's understanding and is suitable for the description and analysis of a topic at a micro level. In contrast, a quantitative review focuses more on the results of data analysis and is suitable for the large-scale investigation and prediction of these topics at the macro level (Frenken et al., 2009; Hood and Wilson, 2001). They emphasize a different focus. Using epistemology, researchers can obtain more reliable results from a qualitative analysis of topics (Bamberger, 2000; Gao, 2008; Hofer, 2000). Therefore, we make a summary of geo-ontology research based on quantitative bibliometric analysis. This summary not only supplements qualitative reviews, but also enables researchers to look at geographic research at macro and micro levels and provide an overview of its status and reference for further research.

Initially, bibliometrics was only a tool utilizing mathematical and statistical methods to quantitatively analyze science communication (Niu et al., 2014). Currently, bibliometrics can be used to quantitatively analyze and research risk assessments of not only papers of certain domains, authors, or journals but also specific papers. In the process of analyzing the communication and cognition of scientific knowledge, bibliometrics supervises its developments and determines emerging subject areas and knowledge structure (Liu et al., 2015; Raan, 1996; Silva and Teixeira, 2008). Bibliometrics can not only facilitate historical research retrospectives but also help us explore hotspots and trends in disciplines objectively from macro and micro perspectives, which can usefully supplement the views of subject specialists (Zhu et al., 2015).

This study analyzes papers from the Web of Science (WOS) database published from 1999 to 2014 that focus on geo-ontology. Specifically, the purpose of our analysis is to (1) identify general patterns for document types, publishing language, and journals in geo-ontology research; (2) visualize the number of nations and institutions, evaluate national and institutional research performance, and reveal the characteristics of international collaboration and geographical distribution of global institutions; (3) distinguish references that are the most cited and have the highest centrality; (4) provide an analysis of keywords, term words, and references, which may be a potential guide for researchers, especially newcomers in the geo-ontology field, and develop a reference for research focus and direction in the future.

2. Data and methodology

2.1. Data collection

The research data resource is the WOS for the period 1999–2014, and we created the data set using the following steps. First, “geo* AND ontolog*” was used as a search subject term and the document information search range included titles, abstracts, and keywords. Second, we deleted replicated data. By checking the title, author, institution, and publication date of the papers, we were able to find repeated results and delete them. Third, we eliminated irrelevant data. This was accomplished by checking the title, abstract, and keywords.

2.2. Methods of data analysis

Excel 2013 was used to analyze scientific outputs, journals, authors, countries, institutes, and keywords, and CiteSpace was used to map knowledge domains and extract the geographic coordinates of the institutions with which the authors are affiliated. Those coordinates were imported into ArcGIS to form a global research heat map. Moreover, CorelDraw was used to draw the thematic map of the spatial distribution of global institutions and paper quantities, and Echarts was used to draw the chord diagrams of the 20 most productive countries.

Publications from England, Scotland, Northern Ireland, and Wales were all treated as publications from the UK (Zhuang et al., 2013). However, publications from Hong Kong and Taiwan were not treated as Chinese publications but were independently counted. All journal data were obtained from the 2014 Journal Citation Reports (JCR), and the data for the global Gross Domestic Products (GDPs) in 2014 are from statistics published by the World Bank.

3. Results

3.1. Document types

Five types of documents were found among the 1357 publications published from 1999 to 2014. The most common document type is article (1309), which includes articles published as proceedings papers or book chapters, making up 89.78% of the total publications. Articles were followed by reviews (33 documents, 2.43% of the total), editorial materials (11, 0.81%), and book reviews (4, 0.29%). For consistency with other bibliometric research results (Zhang et al., 2010), this study was based on the 1309 original and peer-reviewed articles.

3.2. Characteristics of journals

With respect to the source journals, from 1999 to 2014, 698 journals published papers related to geo-ontology research. Table 1 shows the top 15 journals in publication volume, which represents 2.14% of the total journals and are mainly assigned to the topic of computer science and geography. Of these, nine are from the UK, four are from the USA, and the other are two from Germany and the Netherlands. In these journals, 327 articles were published, which accounts for 24.98% of the total articles. The *International Journal of Geographical Information Science* (51 articles, 3.90% of the total),

Table 1
Fifteen most active journals in geo-ontology.

Journal titles	SC	TA	TC	CPA	IF	Country
International Journal Of Geographical Information Science	CS;G1; PG; IS & LS	51	851	16.69	1.655	UK
Progress In Human Geography	G1	34	1051	30.91	5.01	UK
Computers & Geosciences	CS;G2	26	414	15.92	2.054	UK
Environment And Planning A	ES & E; G1	25	238	9.15	1.604	USA
Geospatial Semantics, Proceedings	CS	25	123	4.92	0	Germany
Environment And Planning D-Society & Space	ES & E; G1	23	507	22.04	1.515	UK
Transactions Of The Institute Of British Geographers	G1	22	1023	46.5	3.636	USA
Geoforum	G1	19	249	13.11	1.759	UK
Geoinformatica	CS;PG	18	174	9.67	0.745	Netherlands
Annals Of The Association Of American Geographers	G1	16	241	15.06	2.291	UK
Transactions In GIS	G1	16	63	3.94	1.398	USA
Antipode	G1	15	224	14.93	2.104	USA
Cultural Geographies	ES & E; G1	13	70	5.38	1.887	UK
Expert Systems With Applications	CS;E; OR & MS	12	108	9	2.241	UK
Social & Cultural Geography	G1	11	119	10.82	1.315	UK

SC: Subject Category; ***TA:*** total articles; ***TC:*** total citation count; ***CPA:*** average number of citations per article; ***IF:*** impact factor;***G1*** : Geography ; ***PG:*** Physical Geography ; ***IS & LS:*** Information Science & Library Science ; ***ES & E*** : Environmental Sciences & Ecology ; ***E:*** Engineering ; ***PG*** : Physical Geography ; ***G2*** : Geology; ***CS*** : Computer Science; ***OR & MS:*** Operations Research & Management Science

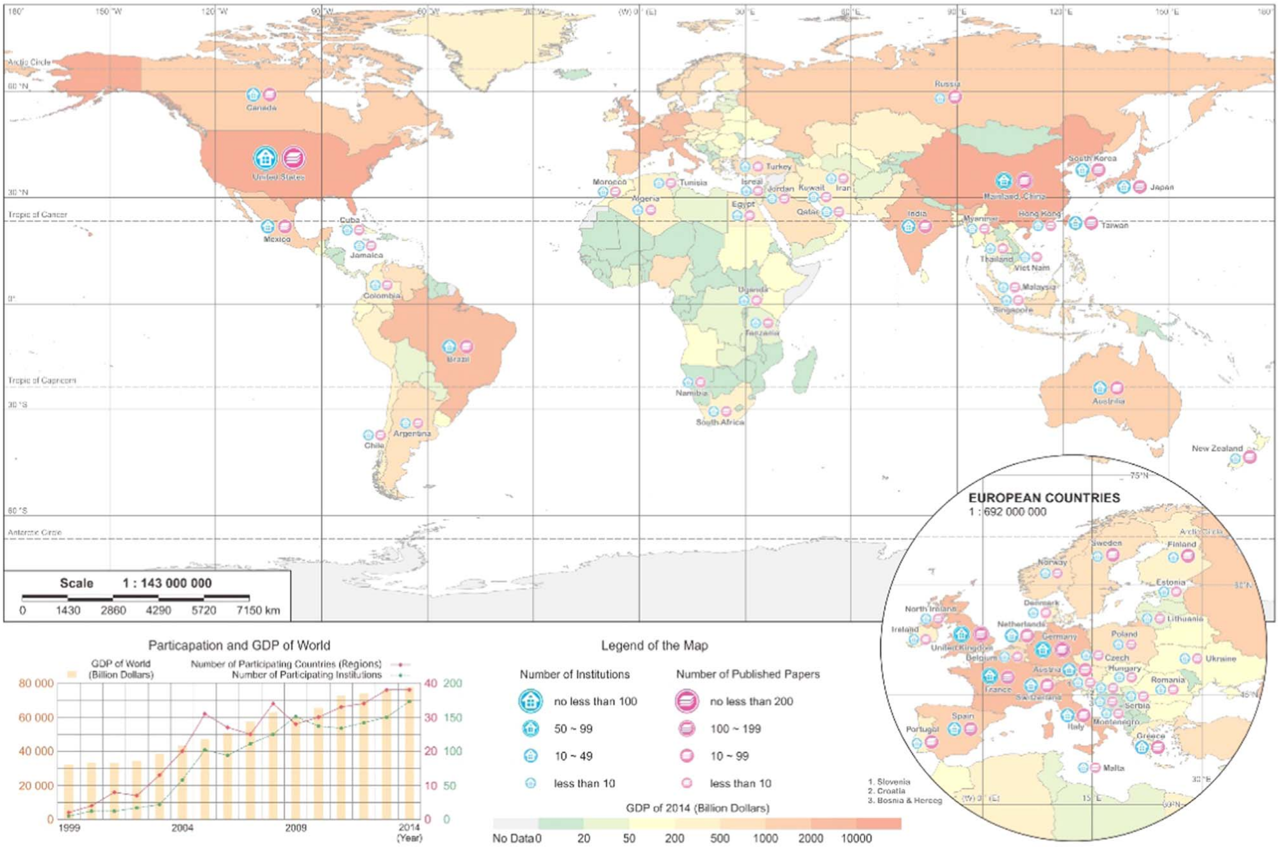

Fig. 1. Map of the number of institutions, published geo-ontology articles, and GDP (USD) of different countries in 2014.

Progress in Human Geography (34, 2.60%), and *Computers & Geosciences* (26, 1.99%) made the largest contributions. Furthermore, the subject categories of journals are also shown in Table 1. Geography and computer science are the top two subject categories, indicating they exerted a wider influence in the global geo-ontology field.

3.3. Characteristics of collaboration and productivity

In the collected data, 21 papers lacked authors' addresses, and hence 1,288 papers were used to analyze the countries and institutions active in geo-ontology. To explore the spatial distribution of geo-ontology research and its relation to economic development, we created a thematic map of the number of national institutions participating in the research and their papers, the background of which corresponds to each country's GDP in 2014 (Fig. 1). This map clearly shows that 67 countries have been involved in geo-ontology research. The volume of each country's published papers is directly proportional to the number of its institutions. The USA and China are the two countries with the most participating institutions. Meanwhile, Europe has the densest region of geo-ontology research institutions, and the number of its national institutions and papers overlays countries with a GDP that is

Table 2
Fifteen most productive countries in geo-ontology.

Country/Territory	TA	TC	CPA	SCR	h-index	Single-country			Internationally-collaborated			
						SCA (%)	TC	CPA	ICA (%)	TC	CPA	TFC (n)
USA	309	3809	12.49	4.91	28	228(73.79)	2413	10.58	81(26.21)	1396	17.23	China(11)
China	176	310	1.8	7.74	9	150(85.23)	112	0.75	19(10.8)	198	10.42	USA(11)
UK	152	1939	13.01	2.89	24	119(78.29)	1422	11.95	33(21.71)	517	15.67	USA(7)
Germany	105	1297	12.59	3.32	17	78(74.29)	900	11.54	27(25.71)	397	14.7	USA(8)
Canada	59	344	5.34	3.17	10	47(79.66)	216	4.6	12(20.34)	216	8.25	Netherlands(3)
Italy	57	270	4.74	5.56	10	49(85.96)	171	3.49	8(14.04)	99	12.38	USA(2)
France	56	189	2.84	3.14	6	45(80.36)	103	2.29	11(19.64)	86	5.09	USA(4)
Australia	53	497	9.38	1.81	10	36(67.92)	197	5.47	17(32.08)	300	17.65	USA(8)
Spain	41	81	2.03	2.47	4	33(80.49)	52	1.58	8(19.51)	29	3.63	USA(2)
Netherlands	32	204	6.38	2.94	10	14(43.75)	71	5.07	18(56.25)	133	7.39	China(8)
Brazil	30	142	4.73	4.93	4	24(80)	26	1.08	6(20)	116	19.33	USA(3)
India	30	47	1.44	2.56	3	28(93.33)	45	1.61	2(6.67)	2	1	Italy(1)
Mexico	30	30	1	23.33	4	25(83.33)	20	0.8	5(16.67)	10	2	France(2)
South Korea	27	88	3.5	0	4	21(77.78)	70	3.33	6(22.22)	18	2.33	USA(4)
Greece	23	115	5	2.61	6	21(91.3)	83	3.95	2(8.7)	32	16	Germany(2)

TA: total articles; ***CPA:*** average number of citations per article; ***SCR:*** self-citation rate (%);***SCA:***Single-country articles, ***ICA:***internationally collaborated article; ***TFC(n)***:The top collaborator (the number of collaborated articles between two countries)

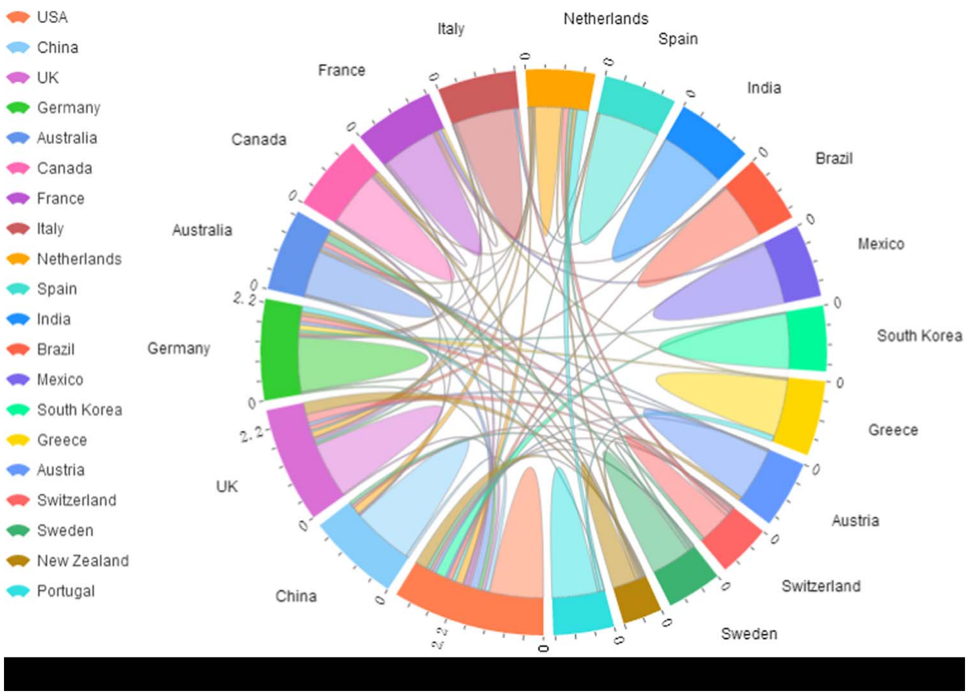

Fig. 2. Chord diagram of the 20 most productive countries.

greater than USD 2000 billion.

Table 2 shows information about the 15 countries with the most published papers. Of these, eight countries are from Europe, three are from Asia, three are from America, and one is from Oceania. The USA is responsible for the most papers (309 articles, 23.61% of the total), with the highest *h-index* values (defined as *h* papers from a country that have been cited at least *h* times). The USA is followed by China (176, 13.45%), the UK (152, 11.61%), Germany (105, 8.21%), and Canada (59, 4.51%). Notably, the USA, the UK, Germany, and Canada are the top five with respect to both volume of papers and frequency of total citations (TC). In addition, their self-citation rates (SCRs) are very low.

With respect to the international cooperation situation, the number of papers independently published by a single country is 1158 (88.46%), and those of publication collaborations number 151 (11.53%), indicating a low level of international cooperation in geo-ontology research. The articles with the most international collaboration are from the USA (Fig. 2), where TC and CPA (the average number of citations per article) both rank first (Table 2). The UK and Germany take second and third place, respectively, with relatively high TCs and CPAs. In contrast, although Brazil, Australia, and Greece do not perform well in terms of volume of publications, as shown in Table 2, the CPAs of their papers with international collaboration are relatively high, which suggests their research level is significantly improved by international collaboration. Fig. 2 is a national production and international collaboration chord diagram for the 20 countries that published the most articles. In Fig. 2, the sectors differ in color and area: a specific color corresponds to a country, whereas its area is proportional to the volume of papers from that country. Moreover, the thickness of links between sectors represents the strength of cooperation among the countries. According to Table 2, The USA was the major cooperative partner of nine other countries, and Fig. 2 visually confirms its predominance in geo-ontology research collaboration. This result shows that the USA is the country with the highest level of international cooperation and it is at the core of geo-ontology research. In addition to the countries in Table 2, countries such as Sweden, Switzerland, and New Zealand have fewer papers published than those in Table 2, but their levels of international cooperation are relatively high.

At the institutional level, 847 institutions altogether have published papers related to geo-ontology research. With respect to paper volume, 572 institutions (67.53%) published only one paper, and 113 published two papers, altogether representing 80.87% of the institutions, indicating their lack of continuity in geo-ontology research. Based on the addresses of the authors' institutions, we obtained the geographical coordinates of institutions using CiteSpace (Chen et al., 2014). We then imported them into ArcGIS to create a heat map of institution distribution. As is shown in Fig. 3, we can clearly see the main spatial clusters of institution distribution, which are in America, Western Europe, and Eastern Asia. In the USA, institutions on the East Coast are more abundant than those in the western regions. In Western Europe, the institutions are mainly located in the UK, France, or Germany. East China, Japan, and Korea are where the Eastern Asian institutions are distributed. Table 3 contains information about the 15 institutions with the largest article volumes. Among these institutions, six are from Europe, three are from the UK, and the other three are from Germany, the Netherlands, and Switzerland. Furthermore, three are from Asia, two are from China, and one is from India. Wuhan University has published 43 papers, making it the institution with the most published articles and independently published articles. It is followed by The University of Munster (32), and Chinese Academy of Sciences (28) have the highest number of articles with institutional cooperation. In addition, Table 3 shows that articles from single institutions were more prevalent than those with inter-institutional collaboration, but the CPAs of papers with inter-institutional collaboration are higher than those of single institution articles.

4. Discussion

In this section, we discuss the research hotspots, key documents, current problems, and the direction of development using a combination of keywords, term words, and references.

Keywords provide important information regarding research status and development trends (Zhang et al., 2010). Term words were extracted from a comprehensive analysis of the title and abstract of the paper using CiteSpace (Chen et al., 2014). There is a pairwise relationship between citing and cited articles. The clustering and critical analysis of reference co-citations can disclose the knowledge

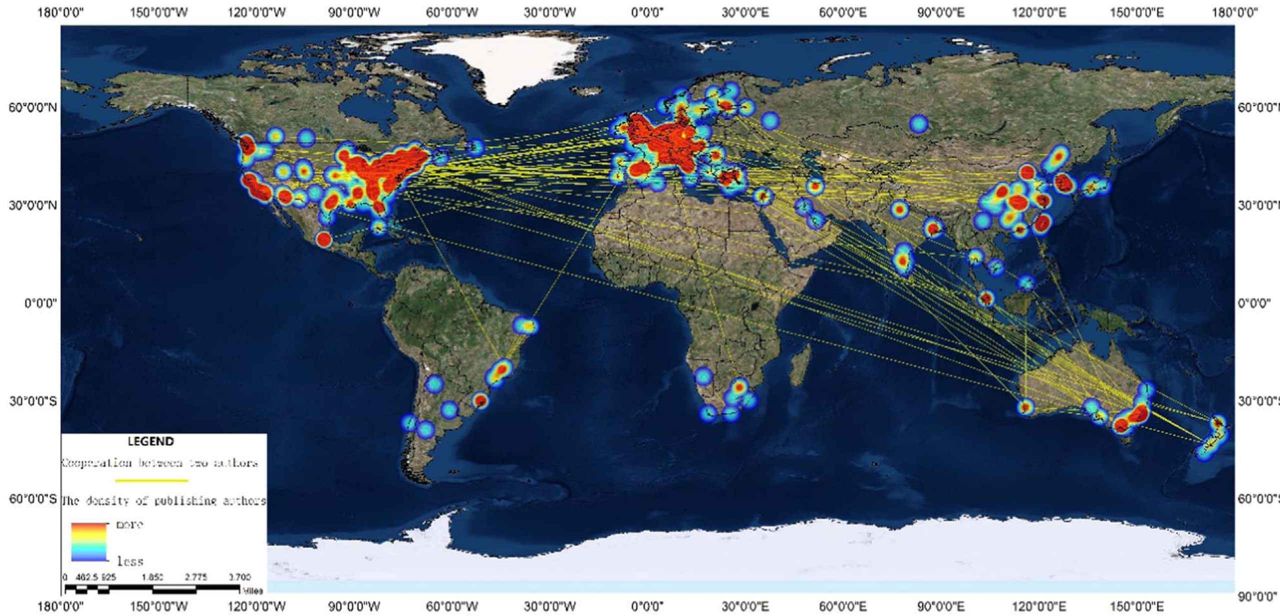

Fig. 3. Heat map of the spatial distribution of institutions.

structure of a field as well as the evolution of research fronts and its key documents (Chen et al., 2014).

With the exception of "ontology," which is a search word in this study, the three most frequently used keywords were "GIS," "Semantic Web," and "space" (Table 4). That is to say, the topics of geographic information systems (GIS), the Semantic Web, and space attracted the greatest attention in geo-ontology related research. Meanwhile, "model," "principle," and "interoperability" were the three fastest growing keywords.

GIS is a vital component of geographic information science. Introducing geo-ontology into GIS research significantly helps to remove the limits of geographic information communication and knowledge discovery caused by the multi-source, multi-scale, isomerism and heterogeneous characteristics of spatial data (Hillen and Hofle, 2015; Lukinbeal and Monk, 2015). Hence, on one hand, in a single geo-information system, geo-ontology can not only regulate the storage and management of spatial data, but also can greatly improve the precision of spatial query and analysis. On the other hand, apart from improving the level of information reuse and semantic interoperability among different systems, geo-ontology also assists the integration of several geo-information systems into a single, more powerful geo-information system. With the development of network technology, the establishment of intelligent discovery and query in GIS using geo-ontology has become a popular research topic (Huang et al., 2005; Lukinbeal and Monk, 2015). The "Semantic Web" has remained a popular research topic over the last 16 years. Keywords like "Semantic Web" and "interoperability" appear many times (see Table 4). Meanwhile, term words like "semantic-information", "semantic-similarity", "user-interface , "semantic-integration" have relatively high burst values (see Table 5), which indicates that research related to the Semantic Web occupies an important position in geo-ontology research. At the same time, the results reveal several research directions of the Semantic Web such as semantic information, semantic similarity, semantic integration, and how to construct the Semantic Web using ontology to achieve semantic communication between the user and computer (Butt et al., 2011; Reitsma et al., 2009). The keyword "space" maintained relative stability. "Geospatial-ontologies," "spatial-reasoning," and "spatial-relations" showed relatively high burst values according to Table 5. Spatial relations are an important topic in the study of geoscience. Representing and reasoning about spatial relations from the viewpoint

Table 3
Fifteen most productive institutions in geo-ontology.

Institute	TA (%)	TC	CPA	Single-institute			Inter-institutional collaborated		
				SI (%)	TC	CPA	CI (%)	TC	CPA
Wuhan Univ, China	43(2.53)	137	3.19	35(81.4)	26	0.74	8(18.6)	111	13.88
Univ Munster, Germany	35(2.06)	479	13.69	29(82.86)	421	14.52	6(17.14)	58	9.67
Chinese Acad Sci, China	28(1.65)	42	1.5	14(50)	11	0.7	14(50)	31	2.21
SUNY Buffalo, USA	25(1.47)	457	18.28	16(64)	272	17	9(36)	185	20.56
Penn State Univ, USA	23(1.35)	377	16.39	12(52.17)	180	15	11(47.83)	197	17.91
George Mason Univ, USA	20(1.18)	191	9.55	13(65)	55	4.23	7(35)	136	19.43
Univ Calif Santa Barbara, USA	20(1.18)	173	8.65	10(50)	126	12.6	10(50)	47	4.7
Cardiff Univ, UK	19(1.12)	117	6.16	13(68.42)	50	3.85	6(31.58)	67	11.17
Univ Manchester, UK	19(1.12)	316	16.63	7(36.84)	129	18.43	12(63.16)	187	15.58
Univ Leeds, UK	16(0.94)	232	14.5	12(75)	112	9.33	4(25)	120	30
Delft Univ Technol, Netherlands	14(0.82)	108	7.71	4(28.57)	19	4.75	10(71.43)	89	8.9
Univ Zurich, Switzerland	14(0.82)	118	8.43	6(42.86)	16	2.67	8(57.14)	102	12.75
Indian Inst Technol, India	13(0.77)	22	1.69	12(92.31)	13	1.08	1(7.69)	9	9
Univ Wisconsin, USA	13(0.77)	235	18.08	6(46.15)	103	17.17	7(53.85)	132	18.86
Univ Arizona, USA	12(0.71)	492	41	5(41.67)	430	86	7(58.33)	62	8.86

TA: total articles; ***CPA:*** citations per articles; ***SI:*** single-institution articles; ***CI:*** inter-institutionally collaborated articles;

Table 4
Temporal evolution of the fifteen most frequently used keywords.

Keywords	FR (%)	R	1999–2002		2003–2006		2007–2010		2011–2014	
			FR	R	FR	R	FR	R	FR	R
Ontology	577(9.27)	1	8	1	100	1	238	1	231	1
GIS	138(2.22)	2	3	4	25	2	63	2	47	5
Semantic Web↑	121(1.94)	3	3	4	20	3	35	4	63	2
Space	110(1.77)	4	4	2	15	5	32	6	59	3
Geography	107(1.72)	5	4	2	10	11	38	3	55	4
System	90(1.45)	6	0	–	16	4	33	5	41	6
Model↑	71(1.14)	7	1	21	14	6	24	11	32	8
Management↑	65(1.04)	8	2	7	9	13	17	18	37	7
Principle↑	64(1.03)	9	0	–	9	13	32	6	23	11
Interoperability↑	62(1)	10	1	21	12	7	29	8	20	16
OWL	57(0.92)	11	1	21	4	29	25	9	27	10
Semantic↑	57(0.92)	11	2	7	5	24	20	14	30	9
Knowledge	53(0.85)	13	2	7	6	18	24	11	21	15
Web↑	52(0.84)	14	1	21	11	9	18	16	22	12
Science	51(0.82)	15	1	21	10	11	25	9	15	24

FR: Frequency of occurrences; ***R***: rank

Table 5
Twenty-five burst term words in geo-ontology.

Burst	Centrality	Term Words
8.06	0	model-based
7.18	0	decision-making
6.07	0	remote-sensing
5.64	0.01	semantic-information
5.43	0	semantic-similarity
4.98	0	knowledge-management
4.46	0	geospatial-ontologies
4.38	0	decision-support
4.04	0	user-interface
3.92	0	geographical-information
3.82	0	service-based
3.82	0	information-services
3.8	0.06	data-mining
3.73	0	sensor-web
3.41	0.01	spatial-reasoning
3.36	0.03	semantic-integration
3.34	0	digital-libraries
3.31	0	geo-spatial
3.31	0	geographic-domain
3.29	0.01	geographic-ontologies
3.29	0	spatial-relations
3.14	0	volunteered-geographic-information
3.14	0	resource-discovery
3.14	0	knowledge-discovery
3.00	0	data-infrastructures

of geo-ontology and regulating the spatial relationships expressed in different applications will contribute to the integration and sharing of different information or systems describing spatial relations (Bittner et al., 2009; Li et al., 2015). In addition, "model" continues to be frequently used method in geo-ontology. Presently, the model of geo-ontology does not comprehensively reflect the topological, orientation, hierarchical, and semantic relations between geographical objects, and this requires further study (Wang et al., 2011; Zhu et al., 2015).

To explore the relations among the references of papers on geo-ontology research as well as their evolution, this research performs a network clustering analysis based on the co-citation of references and visualizes it using CiteSpace (Chen et al., 2014). In Fig. 4, we divide the time from 1999 to 2014 into four periods and the top-20 references with the highest frequency in each period are selected for analysis. The resulting network clustering map based on co-citations is made up of 28 nodes and 44 links. The color of the node center represents the earliest date this reference appeared. The ring enclosing the node shows the history of this reference's appearance, and its color corresponds to that of its time partition. Moreover, the width is proportional to the volume of citing papers published during this period. Nodes with a red–purple halo have relatively high betweenness centrality. Centrality is used to characterize the intermediary function of the node in the field and its degree of influence. In general, if the centrality of a node exceeds 0.1, this indicates the strong intermediary properties of the node, large amount of research based on this node, and its strong influence (Chen et al., 2014). Furthermore, a link between nodes indicates a co-citation relationship between the two references. The width of the link is directly proportional to number of co-citations of the two references, and its color corresponds to the color of the time when two references were first co-cited. In Fig. 4, the citing articles of cluster #1 are concentrated on research such as semantic similarity, knowledge representation, and matching. The citing articles of cluster #2 are mainly about geospatial-related research. The citing articles of cluster #3 focus on theoretical research. The citing articles of cluster #4 mainly focus on computer–human issues. Finally, the citing articles of cluster #5 are mostly about the cognition of geographic elements and objects. Clusters #2, #3, and #5 are the largest clusters, and they are closely linked.

In Fig. 4, Fonseca et al. (2002) has the highest centrality and strong co-citation relationship with Smith and Mark (2001) and Kuhn (2001) in cluster#4. Gruber (1993)has the highest number of citations and a strong co-citation relationship with Guarino (1998), as do Studer et al. (1998) and Gruber (1995). Among the references, Fonseca et al. (2002) (Node information please see Table 6) pays more attention to semantic-based geographic information sharing and interoperation and geographic information retrieval. Smith and Mark (2001) (see Table 6) studies the general understanding of basic geographic concepts and refers to research results on naive and folk geography, then extracts a geo-ontology, providing an experience and experiments basis for the establishment of a geo-ontology that is aimed at a better understanding of the structure of the geographical world and a more rational conceptual model for the development of GIS. Kuhn (2001) (see Table 6) introduced a method for deriving ontology in the field of geography from natural language texts describing human activities. Guarino (1998) (see Table 6) compares ontology and general concepts, and he considers ontology as a logical theory to explain the meaning of formal terms. Gruber (1993) (see Table 6) believes that ontology is an explicit specification of conceptualization. Gruber (1995) (see Table 6) extended the research of Gruber (1993) and found that ontology is a formal and clear norm of shared conceptualization. Studer et al. (1998) (see Table 6) believes that ontology is a shared, conceptual, explicit, and formal specification. Although these articles belong to three topics of different clusters, they are all related to ontology theory. In

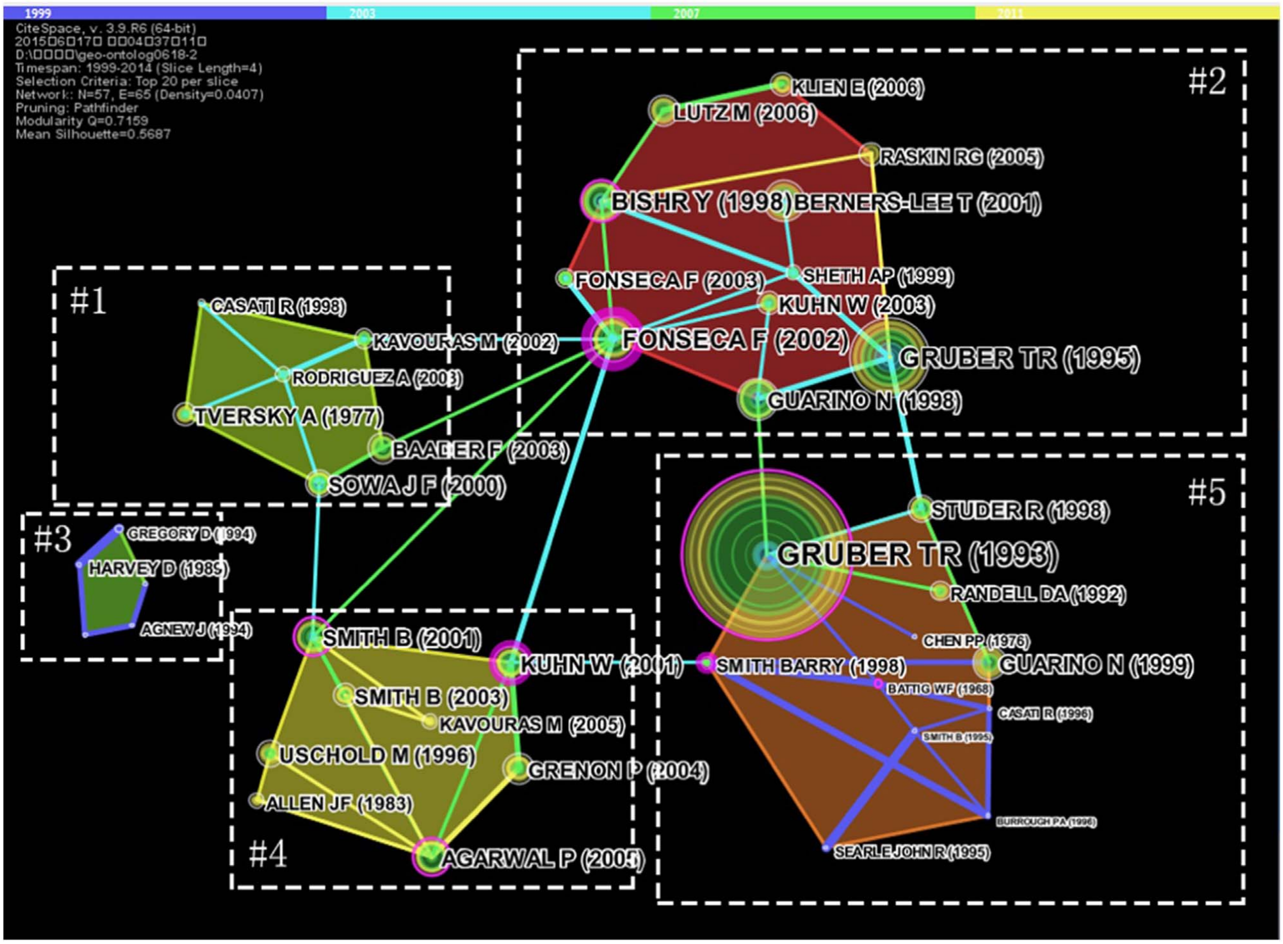

Fig. 4. Cluster network of document co-citations for 57 documents and 65 links.

Table 6
Key point cited references in geo-ontology.

Centrality	Frequency	Nodes in Fig. 4	Title	ClusterID
0.42	49	Fonseca F (2002)	Semantic granularity in ontology-driven geographic information systems	2
0.25	34	Kuhn W (2001)	Ontologies in support of activities in geographical space	4
0.2	135	Gruber TR (1993)	A translation approach to portable ontology specifications	5
0.13	22	Guarino N (1998)	Formal ontology and information systems	2
0.13	32	Smith B (2001)	Geographical categories: an ontological investigation	4
0.12	66	Gruber TR (1995):	Toward principles for the design of ontologies used for knowledge sharing	2
0.07	27	Studer R (1998)	Knowledge engineering: principles and methods	5

conclusion, the geographical space research, computer-human interaction, and ontology cognition are three main research areas, and they are closely linked with each other. Ontology provides theoretical support for those fields. Geo-ontology is a branch of ontology research that can describe the geographical area of the objective world as a set of concepts and relations between concepts, and it can be used to solve the issue of the geographic space existing in research and application of geographic entity semantic inconsistency and opacity (Miao et al., 2014; Yang et al., 2015). First, we use geo-ontology to describe geographical spatial entities as a set of concepts and relations between concepts, and then we can realize the semantic communication between humans and computers through human-computer interaction modeling.

Despite the progress in theory and application of geo-ontology, a geo-ontology that involves a number of theories, techniques, and methods of research requires long-term study. At present, there are still many problems to be solved, such as the semantic mismatch among the producers of ontology data (or between the producers and users of this data) which is caused by ontology dynamics and error propagation in interdisciplinary and cross-linguistic data discovery and reuse. (Kuai et al., 2016; Ma and Fox, 2013; Ma et al., 2014, 2010). In the future, geo-ontology should be able to provide users with more intelligent geographic information services through the Semantic Web platform (Čeh et al., 2013; Yang et al., 2015). Hence, a geo-ontology that follows the Semantic Web specification and also can be reused needs to be constructed. Effective language that is easy for a computer to understand and process is key to the construction of the Semantic Web (Miao et al., 2014). Currently, the OWL ontology language, which is widely used to express spatial aspects, still has defects. Hence, developing new modeling primitives based on OWL to express spatial attributes such as spatial locations, spatial shapes, and spatial relations is a key topic in geo-ontology research (Miao et al., 2014). Given the continuous evolution of geo-ontology, finding new methods to automatically or semi-automatically rework data in the Semantic Web is going to be a focus of future research (Ma and Fox, 2013; Ma et al., 2014). Finally, to address the complex topological, directional, and hierarchical relationships of geographical spatial objects, especially the specific processing, description, and expression of topological and directional relations, we need carry out further thorough research and improve the current geo-ontology (Čeh et al., 2013; Li et al., 2015).

5. Conclusion

The analyses in this paper are all based on the 1309 geo-ontology-related articles collected from the WOS from 1999 to 2014. The article is the main document type of current geo-ontology research. Most papers have been published in the *International Journal of Geographical Information Science*, *Progress in Human Geography*, and *Computers & Geosciences*.

The number of institutions and spatial distribution of article numbers were visualized. The results show that the number of institutions is proportional to the number of published papers; moreover, this data corresponds with regions with a GDP of over USD 2000 billion. The USA has the largest numbers of published papers, single-country published papers, and international collaborations, followed by China and the UK. A chord diagram analysis of the 20 most productive countries suggested that the USA was in a core position in global geo-ontology research. The research heat map of institution region distribution shows that the USA, Western Europe, and Eastern Asia are regions with the highest interest in geo-ontology research. Wuhan University has contributed the most papers, followed by the University of Munster and Chinese Academy of Sciences. In addition, articles from international and inter-institutional cooperation have a higher average cited rate.

A popularity analysis shows that “GIS,” “Semantic Web,” “space,” and “model” are the most popular research topics of 1999–2014. More importantly, the core technologies of geo-ontology, Semantic Web related research (interoperability) and research in geo-ontology applications (GIS and Web) all continue to increase. Further, “semantic granularity in ontology-driven geographic information systems”, “Ontologies in support of activities in geographical space”, “A translation approach to portable ontology specifications” are important references. Geographical space research, computer-human interaction, and ontology cognition are the three main research areas of geo-ontology. At present, the semantic mismatch among the producers of ontology data (or between the producers and users this data) and error propagation in interdisciplinary and cross-linguistic data discovery and reuse remain to be solved. In the future, geo-ontology should follow the Semantic Web specifications so that it can be reused, which calls for new geo-ontology modeling primitives based on OWL and new methods to automatically or semi-automatically rework data in the Semantic Web. The explicit processing and description of topological relations and directional relations between geographical entities still requires further study.

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