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Bibliometric and visualized analysis of emergy research

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ABSTRACT

A bibliometric approach, along with Citespace software, was used to quantitatively and visually evaluate global scientific research on emergy from 1996 to 2014. 637 publications – in accordance with the search criteria from the Science Citation Index Expanded (SCI-Expanded) and Social Science Citation Index (SSCI) of the Web of Science database – were statistically analyzed. The assessments on document type and language, publication year, authorship, subject categories and journals, countries/territories and institutions, most-frequently cited publications and author keywords were conducted with respect to seven categories. The amount of emergy publications per year has sharply increased in recent years. The most productive author was S. Ulgiati with 50 articles, who was also one of the most frequently cited publication authors. China produced 35.95% of all pertinent publications followed by the USA with 25.59% and Italy with 21.66%. Ecological Modeling, Ecological Engineering and Ecological Indicators were the three most common journals in this field. By synthetically analyzing the keywords, the dominant hot spots of emergy research could be concluded as "energy", "sustainability", "transformity", and "indicators".

1. Introduction

Emergy is one of the sustainability metrics incorporating environmental, social, and economic aspects into a common unit of non-monetary measure. Emergy is a measure of all the direct and indirect energy of the material, services, and information required to make a product or sustain a system (Odum, 1996). Emergy evaluation has become one of the dominant approaches in decision-making to support sustainable development initiatives (Odum, 1996). Based on traditional ecological energetics, systems ecology and ecological economics, emergy analysis was first created by H.T. Odum in the late 1980s (Brown and Ulgiati, 1997). During the early development of the field that was to become emergy research, the term "embodied energy" was used in place of "emergy". After the book "Environmental Accounting: Emergy and Environmental Decision Making", a milestone of emergy research in history, was published by Odum (1996), the word "emergy" began to be widely used in this area. Through transforming various forms of energy into a unified unit, the solar emjoule, sej, emergy analysis uses some rules to calculate indices for the various components of available energy circulating in an ecosystem. Emergy evaluation, which builds a unified platform between natural features and economic structure, provides an environmental accounting and economic evaluation method for ecosystems.

Many researchers have applied emergy to assess eco-economic systems in recent years. Emergy also is widely used to measure energy flow, logistics, information flow and money flow, thus evaluating ecosystem health (Campbell, 2000), managing complex ecological systems and assessing regional sustainable development (Campbell and Garmestani, 2012). Later in the 1990s, the theory was widely applied in agriculture, natural reserves and cities in Italy, Sweden, Australia and China (Lefroy and Rydberg, 2003; Lan and Odum, 1994; Ulgiati et al., 1994). Campbell (2000) believed that driving and organizing the entire ecosystem requires many different forms of energy, and integrity of the ecosystem is one function of the energy signals; namely, large quantities of different forms of energy can increase the stability of ecosystem integrity. In using emergy evaluation, Ulgiati et al. (1994) conducted some research on environmental pressures and the sustainability of agricultural systems in Italy. Ulgiati et al. (1994) also did some comparative evaluations on natural ecosystems such as coastal zones, salt marshes, tropical rain forests, and river basins, and analysis on wastewater and waste material in Texas and Florida. Brown and McClanahan (1996) calculated the economic and environmental emergy value of dams on the Mekong River in Thailand. All of these quantitative studies analyzed the structure and properties

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of regional environmental systems, contributing to regional environmental decision-making. Bakshi (2000) introduced an emergy analysis method for industrial systems, where waste treatment was considered. Ulgiati and Brown (2002) proposed an emergy-based method to quantitatively study the environment's function in absorbing and diluting by-products generated through a process. A new emergy analysis method, which considers waste treatment and reuse, was proposed by Yang et al. (2003). Brown and Buranakarn (2003) evaluated the emergy used in the life cycles of major building materials, as well as the emergy inputs to waste disposal and recycling systems. A new sustainable development index, proposed by Lu et al. (2003), considers not only the ratio of the sum of inputs from the economy and nonrenewable resources to renewable resources but also the level of pollutants. Wang et al. (2006) applied emergy analysis to the systematic evaluation of a combined heat and power plant in an eco-industrial park. Lou et al. (2004) introduced a set of emergy indices to assess the environmental and economic performances, as well as the sustainability of industrial systems in a uniform structure. Feng et al. (2005) proposed joint indices and weighted average indices to compare co-generation systems and individual systems that produce one product. In addition, some researchers have combined emergy with traditional sustainability assessment methods. Zhao et al. (2005) combined emergy with the ecological footprint to form a modified ecological footprint and applied it to analyze the eco-economic system of Gansu province in China. Emergy analysis has also been used to evaluate different aspects of water (Chen et al., 2009, 2011, 2012, 2014; Díaz-Delgado et al., 2014; Kang and Park, 2002), urban systems and renewable energy systems (Chen and Chen, 2011, 2012, 2014; Fang et al., 2015; Yang and Chen, 2014). Researchers from a number of disciplines have used the emergy method to value goods and services originating from natural and human systems (Voora and Thrift, 2010).

Bibliometrics is a statistical analysis of written publications (Mayr and Scharnhorst, 2014). Bibliometric methods are frequently used to provide quantitative analysis of academic literature. Many research fields use bibliometric methods to evaluate the scientific research patterns of authors, journals, countries, and institutes in global trends studies of specific fields (Abramo et al., 2011; Li and Zhao, 2015; Wang et al., 2010). The quantitative information related to spatial distribution of authors and the country/institution collaboration network could also be visually presented in bibliometric study by using some supplementary means (Liu et al., 2011). In recent years, a great number of publications have been published on emergy and related fields. From 1996 until 2014, the Science Citation Index Expanded (SCI-Expanded) and Social Science Citation Index (SSCI) of the Web of Science database collected 637 papers on emergy. Although much attention has been paid to emergy's development, few papers attempted to gather global systematic data and conduct a large-scale review of scientific studies. In that respect, we attempt to use bibliometric methods to quantitatively and visually explore global research trends in emergy-related research. Therefore, our objectives are to reveal underlying patterns in scientific outputs, characteristics of international collaboration, and author distribution on emergy research.

2. Methodology and data sources

The bibliometric method, used in this study, takes advantages of modern technologies in computer engineering, database management, and statistics. Created by Alan Pritchard in 1969, it is a set of methods that quantitatively analyze academic literature and describe distribution patterns within a given topic, field, institute, or country (Pörtner, 2008). According to the online database SCI-Expanded and SSCI of the Web of Science, the bibliometric method can assess development trends or future research orientations using author keywords, title keywords and keywords plus. Ever since statistical analyses in 1990 on Garfield's keywords successfully suggested the future science directions (Barton et al., 1990), bibliometric analysis using keywords to analyze research trends has proved to be effective in recent years (Kam et al., 2007).

Citespace software was also used to help with this bibliometric analysis. Invented by C.M. Chen at Drexel University in early 2004, Citespace is a freely available Java application for visualizing and analyzing trends and patterns in scientific literature (Chen, 2004). It is designed as a tool for progressive knowledge domain visualization and already has several optimized editions in the recent years, such as Citespace II and Citespace III. Similar to a camera, Citespace, takes snapshots of a particular field based on a time sequence and links them together, deducing changing process and development trends in this area. The application focuses on finding critical points in the development of a field or domain, especially intellectual turning points and pivotal points (Chen, 2006). Citespace supports structural and temporal analyses of a variety of networks derived from scientific publications, including collaboration networks, author co-citation networks, and document co-citation networks. It also supports networks of hybrid node types. such as terms, institutions, and countries, and hybrid link types. such as co-citation, co-occurrence, and directed citing links (Chen, 2006). The primary source of input data for Citespace is the Web of Science (including full records and references).

Documents included in this study were derived from the SCI-Expanded and SSCI of Web of Science database. This database collected 637 papers with the word "emergy" as a theme (including title keywords, keywords in abstract, author keywords and keywords plus) from 1996 to 2014. The papers were downloaded from the database and analyzed with bibliometric techniques along with Citespace, for the current work.

3. Results and discussion

3.1. Document types and language of publications

Eight document types were identified in a total of 637 publications. Journal articles (572) were the most frequently used document type accounting for exactly 89.80% of the total publications. They were followed by proceeding papers (53; 8.32%), reviews (37; 5.81%), and letters (13; 2.04%), with the remainder of less than 2% including editorial materials (10), corrections (2), a meeting abstract (1) and a reprint (1).

The 637 journal publications were published in three languages, and 99.37% of the articles were published in English in the Web of Science. The non-English publications were published in French (3) and Chinese (1), accounting for less than 1% of the total journal publications. One can see that most of the authors published their documents in English for wider dissemination. The other reason is that the SCI-Expanded and SSCI database mostly collected English journals instead of journals written in other languages.

3.2. Publication year

Because the book "Environmental Accounting: Emergy and Environmental Decision Making" was published in 1996 is a landmark initiating emergy research, we choose this year as the point to begin our study. Actually, the earliest articles directly related to "emergy" were published in 1987 and 1988 when Odum's article titled "Self-Organization, Transformation" was published in Science. The number of all documents published increased from 5 in 1996 to 93 in 2014 and from 5 to 83 articles (shown in Fig. 1).

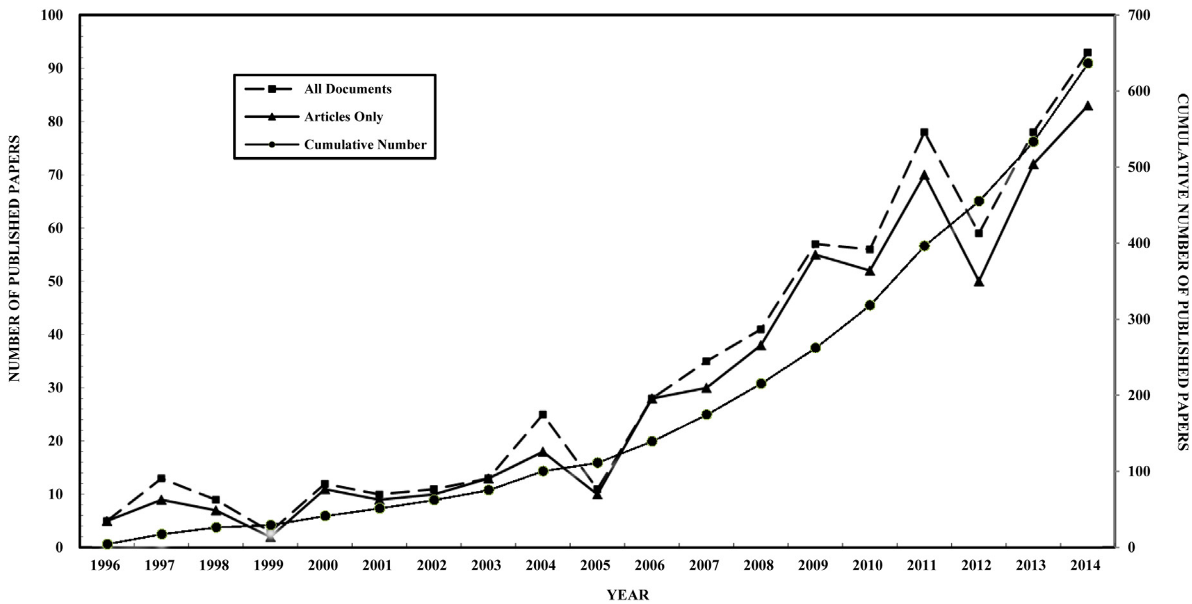

Fig. 1. Number and cumulative number of papers published in each year.

The cumulative number of published papers in each year is also shown in Fig. 1. The difference in the trends between 1996 and 2005 and 2005 and 2014 is significant. A correlation between the number of publications and the publication year was observed, resulting in a linear curve (1996–2005) and a power curve (2005–2014), respectively. The power curve indicates a high growth rate for publications from 2005 to 2014, which may also predict a respective double or triple increase in the number of future articles published in 2016 and 2018 compared with those in 2014, based on the assumption that the growth rate will maintain at the same level found in 2005–2014. In 2004, several important articles were published, such as "Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems" by Brown and Ulgiati (2004) and "Promise and problems of emergy analysis" by Hau and Bakshi (2004), all of whose citation frequency are in the top 10 among 637 publications. Actually 2004 was the year when the memorial issue of Ecological Modelling (Volume 178, Issues 1–2) honoring H.T. Odum was published. This volume alone included 40 papers. These may explain the reason why the cumulative number of publications began to increase in 2004 and after.

3.3. Authorship

According to the database, approximately 300 researchers published documents related to emergy and the average number of authors per paper is 3.45. Consistent with observations in other research fields, a small group of prolific authors contributed to a significant share of emergy research publications. For example, the top 34 authors produced 630 of the total publications. Considering the volume of these published documents rather than their quality, the most productive authors in emergy research were Ulgiati S. with 50 articles, followed by B. Chen with 45 papers, S. Bastianoni with 40, M.T. Brown with 36, and Z.F. Yang with 34. Many of the authors are Odum's direct or short-term students and have studied emergy analysis for many years, such as S. Ulgiati, M.T. Brown, D.E. Campbell and S. Bastianoniare. Chinese authors accounted for a large proportion of the top 10 most productive authors, such as B. Chen, Z.F. Yang, G.Q. Chen, who have also directed many graduate students to have published a number of articles about emergy. Yet G.Q. Chen's research area is mainly cumulative cosmic exergy,

Table 1
The top 17 most productive authors.

Name	Total publication
S. Ulgiati	50
B. Chen	45
S. Bastianoni	40
M.T. Brown	36
Z.F. Yang	34
G.Q. Chen	31
D.E. Campbell	25
N. Marchettini	21
H.F. Lu	19
Y. Zhang	17
B.F. Giannetti	17
C.M.V.B. Almeida	17
F.M. Pulselli	17
E. Ortega	16
L.X. Zhang	16
G.Y. Liu	16
E. Orteg	16

which is calculated in a different way comparing with emergy. Additionally, the 17 most productive authors whose name appears on more than 15 papers in SCI-Expanded and SSCI database are listed in Table 1, which can offer highly individualized scientific research information to other researchers.

A collaboration pattern for the productive authors was analyzed with Citespace, and the collaboration map is presented in Fig. 2. The size of circles represents the amount of publications, and the distance between two circles is inversely proportional to the collaboration between individual authors, i.e., shorter distances suggest more collaboration. It can be noticed that many authors tended to cooperate with a small group of collaborators, generating several major clusters of authors, each of which usually have two or more core authors. Among all the authors, M.T. Brown, N. Marchettini, S. Bastianoni and S. Ulgiati, who are the top productive authors, conduct the top 4 most cooperative positions. Author productivity analysis could be biased because two or more authors may have the same initial name, or authors may use different names in their publications (e.g., names changed due to marriage). So an "international identity number (IIN)", which is offered to an individual when he/she first publishes in an ISI-listed journal, is exigently needed. It

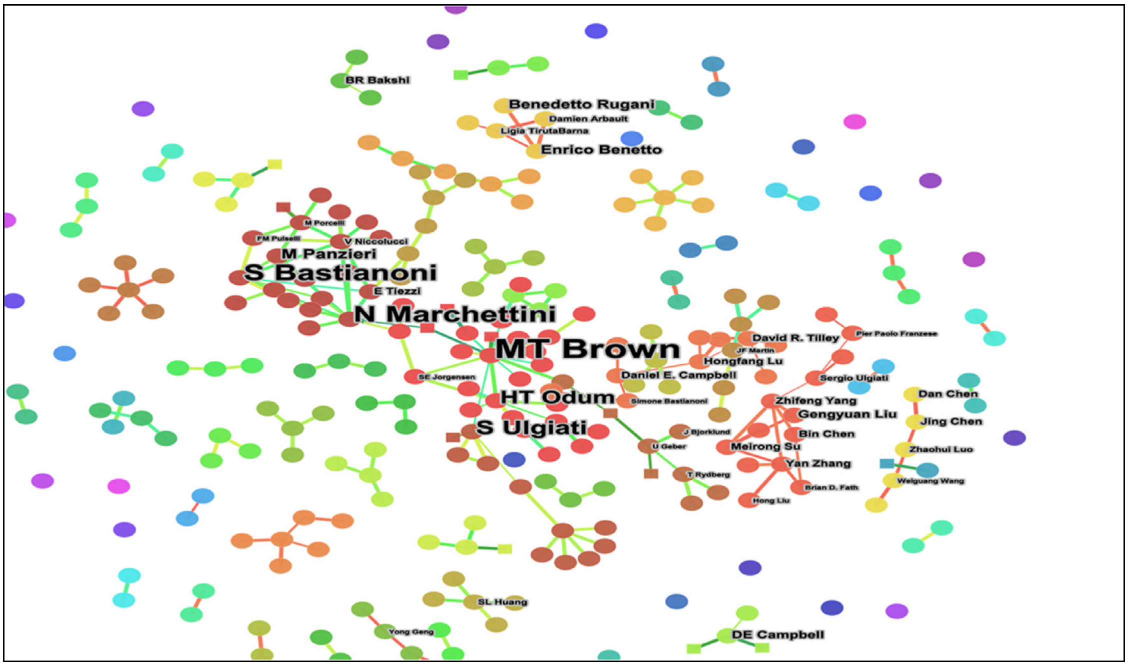

Fig. 2. Combined mapping and clustering of productive authors.

is certain that assigning and tracing IIN offers a method that would more appropriately assess authorship (Sun et al., 2011).

3.4. Subject categories and journals

Based on the classification of subject categories in the Web of Science database, the output data of publications on emergy were distributed among more than 45 subject categories. Environmental Sciences (308; 48.35% of all publications) was the most common category; followed by the categories of Ecology (228; 35.75%), Environmental Engineering (131; 20.57%), Energy Fuels (97; 15.23%), Environmental Studies (58; 9.11%), Biodiversity Conservation (43; 6.75%), Thermodynamics (27; 4.24%), Applied Mathematics (24; 3.77%), Mechanics (22; 3.45%), and Interdisciplinary Mathematics (21; 3.30%), many of which are related to the environment, ecosystems or energy. The trend of papers published in the top 3 categories – Environmental Sciences, Ecology and Environmental Engineering has been generally increasing in recent years (Fig. 3).

The 637 papers are published in more than 100 journals. Ecological Modeling ranks first in the number of publications (118, 18.52%), followed by Ecological Engineering (53, 8.32%), and Ecological Indicators (35, 5.49%). It can be observed that most of these journals are correlated to ecologists. A comparison of growth trend among the top three productive journals with a total publication of more than 35 papers is presented in Fig. 4. Articles in Ecological Modeling generally increased, especially in 2011 and 2014, with a high Impact Factor (IF) of 2.326 in 2014. Based on the IF, it ranked 24th in the subject category compared with the other 99 journals. All of this can provide important submission information for new researchers.

3.5. Countries/territories and institutions

The contribution provided by different countries/territories was estimated by focusing on the location of the affiliation of at least one author of the published papers. Of 58 published countries or territories, the People's Republic of China ranked first in the number of publications (229, 35.95%), followed by the USA (163, 25.59%), and Italy (138, 21.66%). The top 10 most productive countries for total publications are shown in Table 2. It can be concluded that scientific researchers and institutions in China, the USA and Italy have already paid great attention to emergy research and published a great number of related papers in recent years. However, there are many other emergy publications in the USA and other countries, which were not included in this study because they are not covered in the SCI-Expanded and SSCI of Web of Science database. For instance, the Proceedings from the Biennial Emergy Research Conferences (1999–2014) have included many papers. The website of Emergy Systems by the Center for Environmental Policy in University of Florida also listed different kinds of emergy publications, available online at http://www.cep.ees.ufl.edu/emergy/publications/index.shtml. Yet the published volume in one country could not objectively indicate the academic research level on emergy in this country. Other indices could be used to judge, such as the average citation rate and h-index.

Table 2
The top 10 most productive countries/territories.

Country/territory	Total publication
People's Republic of China	229
USA	163
Italy	138
Brazil	45
France	20
Taiwan	18
Sweden	17
Denmark	15
Spain	14
Luxembourg	14

Moreover, the number of papers in the published literature from the top 3 most productive countries in each year is shown in Fig. 5. Obviously, it can be observed that China became the country with the largest amount of emergy research since 2008. This rapid increase might be attributed to the large-scale initiatives on basic research in China, such as the "211 Project","973 Plan" and "985 Project" initiated in 1995, 1997 and 1998, respectively (Ma et al., 2006). Plentiful and substantial achievements of emergy research in China owe much to many productive scientists, such as B. Chen, Z.F. Yang and S.F. Lan, M.C. Yan, P. Qin and H.F. Lu. As Odum's

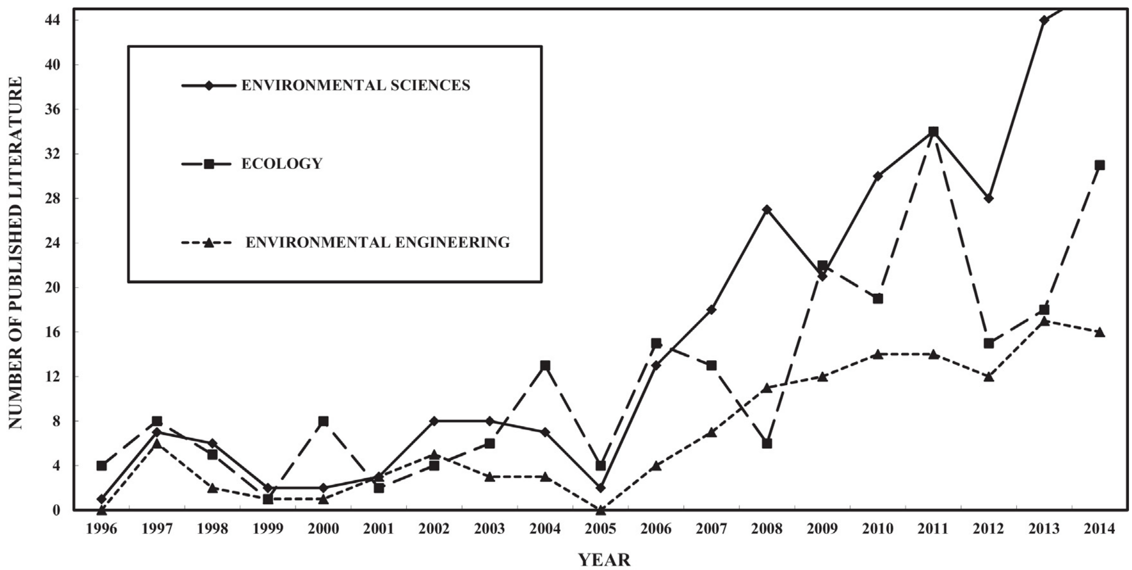

Fig. 3. Comparison of total publications among top three subject categories.

students, S.F. Lan and M.C. Yan were the first scientists introducing emergy to China; while P. Qin and H.F. Lu made a great contribution to the first Chinese translation of Odum's work. These scholars are mostly from several scientific institutions or universities, such as Chinese Academy of Sciences and Beijing Normal University.

The collaboration pattern for the productive countries or territories was analyzed with Citespace (Fig. 6). It can be noticed that several countries or territories tended to cooperate with a small group of collaborators, generating some major clusters of countries or territories, each of which usually have one or two core countries or territories (except the USA, which has more than 9 countries or territories as collaborators). As the most productive country, China also has many collaborators, but this relationship is relatively much weaker than those of the USA and Italy. It is universally known that exchanges and cooperation in scientific research are important. Although China is already the most productive country, more international cooperation and exchanges are needed.

The contribution of different institutions was estimated by the affiliation of at least one author of the published article per institution. Of 80 published institutes, the University of Siena in Italy ranked first in the number of publications (79, 12.40%), followed by Beijing Normal University in China (71, 11.15%) and the Chinese Academy of Sciences (55, 8.63%). The aftermentioned result coincides with the most productive top 3 countries and the most productive top 10 authors. Moreover, the University of Florida, which is the source and cradle of emergy research, takes the 4th and 5th places, respectively. The top 10 most productive institutions for total publications are shown in Table 3.

A collaboration pattern for the productive institutes was analyzed with Citespace (Fig. 7). It can be noticed that several institutes tended to cooperate with a small group of collaborators, generating several major clusters of institutes, each of which usually have one or more core institutes, such as the University of Siena in Italy, the University of Florida in the USA, the United States Environmental

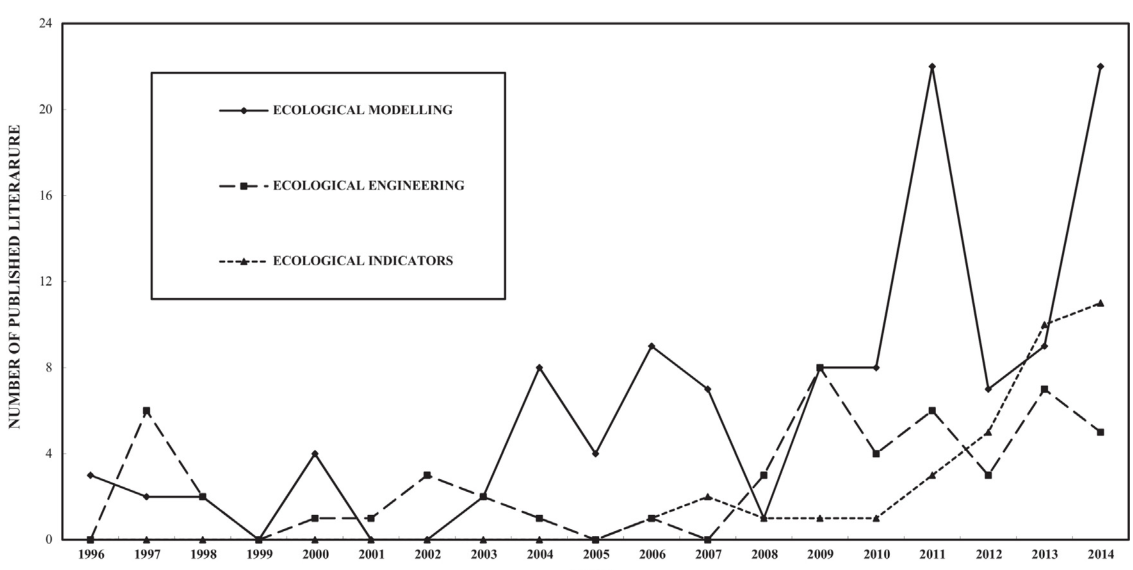

Fig. 4. The number of publications of the three most productive journals.

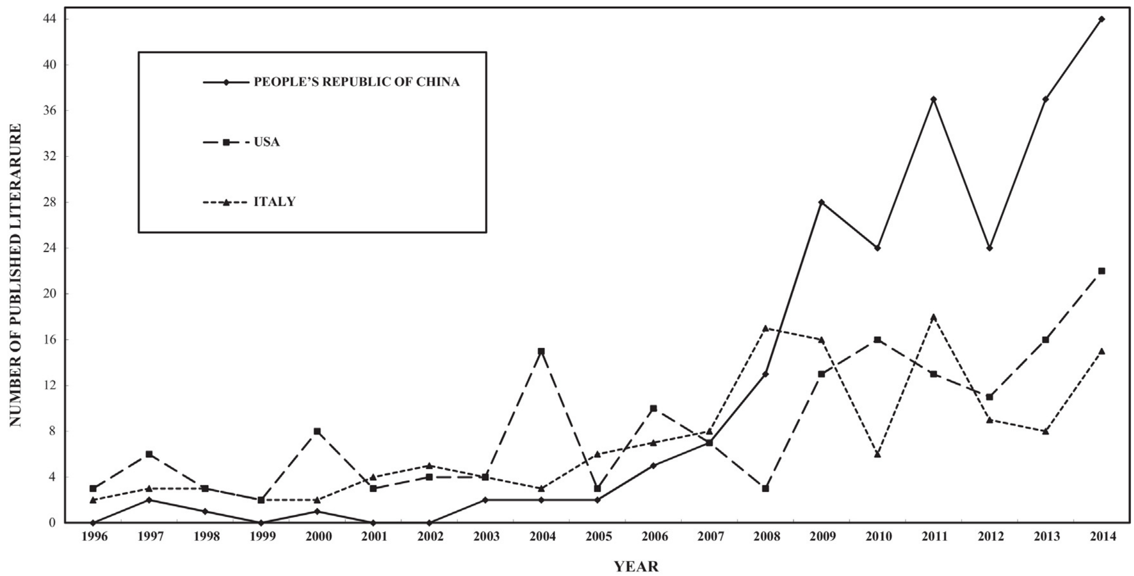

Fig. 5. The number of publications of the three most productive journals.

Table 3
The top 10 most productive institutes.

Institutes	Total publication
University of Siena	79
Beijing Normal University	71
Chinese Academy of Sciences	55
University of Florida	52
Peking University	50
United States Environmental Protection Agency	40
Parthenope University Naples	35
University System of Maryland	19
Ohio State University	18
Universidade Estadual de Campinas	17

Protection Agency in the USA, the Chinese Academy of Sciences and Beijing Normal University in China.

3.6. *The most frequently cited publications*

Although much literature has been published, a relatively small number of individuals accounts for a large proportion of these articles. The 10 most frequently cited articles have been cited more than 1400 times from their initial publication year until December 31st, 2014. These papers were primarily published in Ecological Economics and Ecological Modeling. The most frequently cited article was "Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation", published in 1997 in Ecological Engineering (IF = 3.041, 2014) by Brown and Ulgiati (1997), and cited 216 times

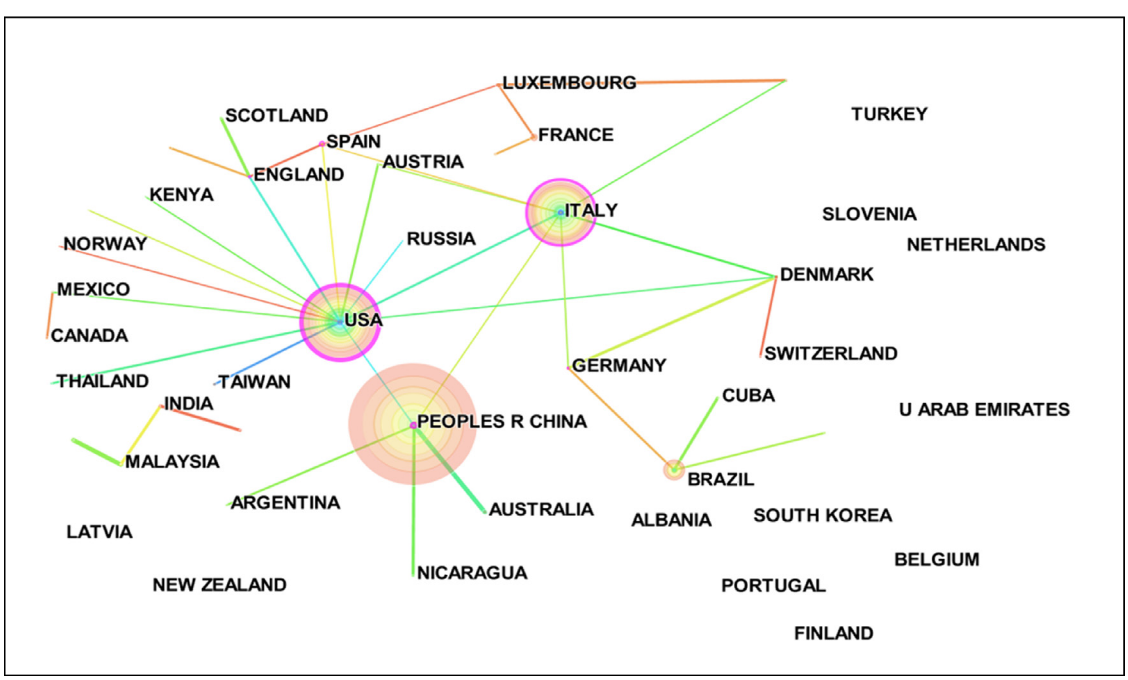

Fig. 6. Combined mapping and clustering of productive countries/territories.

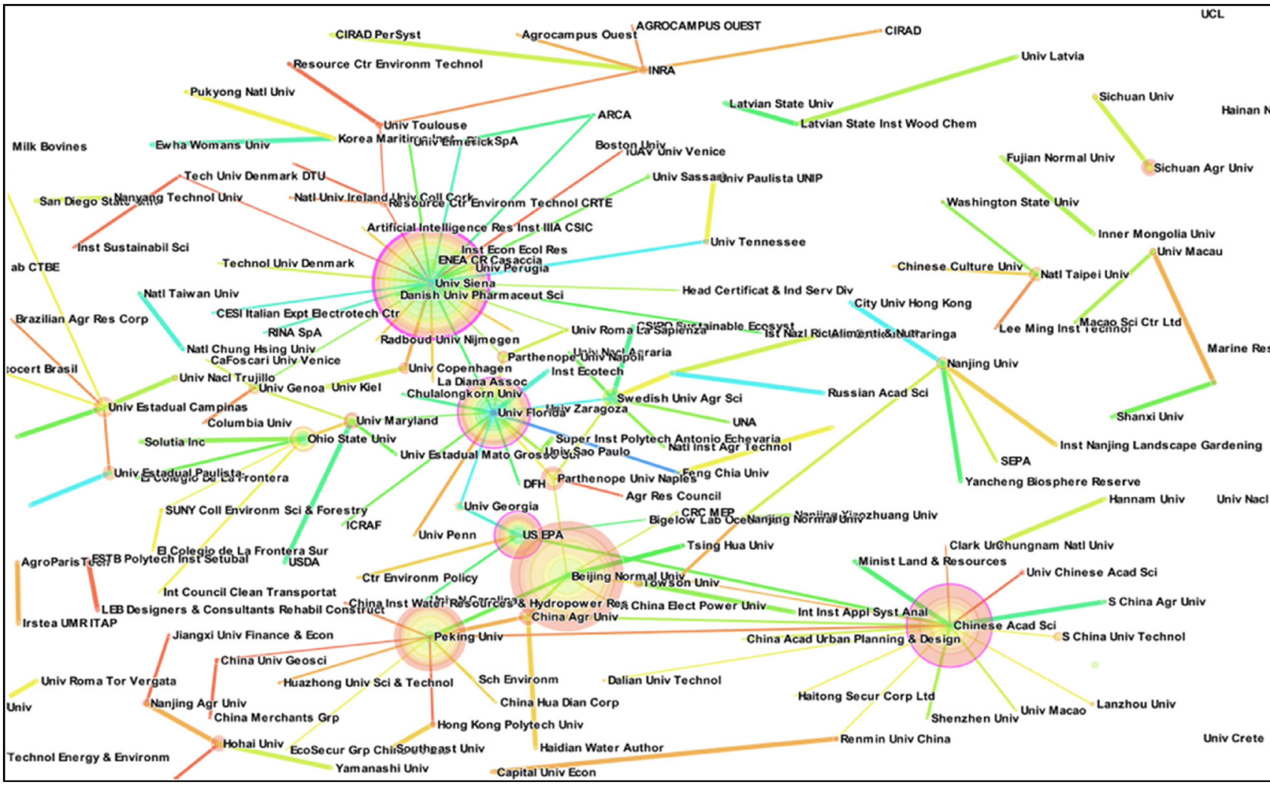

Fig. 7. Combined mapping and clustering of productive institutes.

Table 4
The top 10 most frequently cited publications.

Title	Publication year	Cited frequency	Journal	Author
Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation	1997	216	Ecological Engineering	M.T. Brown, S. Ulgiati
Biodiesel as alternative fuel: experimental analysis and energetic evaluations[a]	2004	199	Energy	C. Carraretto, A. Macor, A. Mirandola, A. Stoppato, S. Tonon
Categorizing tools for sustainability assessment[a]	2007	173	Ecological economics	B. Ness, E. Urbel-Piirsalu, S. Anderberg, L. Olsson
Embodied energy analysis and EMERGY analysis: a comparative view	1996	166	Ecological Economics	M.T. Brown, R.A. Herendeen
Review of the foundations of network environ analysis	1999	149	Ecosystems	B.D. Fath, B.C. Patten
Monitoring patterns of sustainability in natural and man-made ecosystems[a]	1998	136	Ecological Modelling	S. Ulgiati, M.T. Brown
Complementarity of ecological goal functions[a]	2001	125	Journal of Theoretical Biology	B.D. Fath, B.C. Patten, J.S. Choi
Aggregation and the role of energy in the economy[a]	2000	119	Ecological Economics	C.J. Cleveland, R.K. Kaufman, D.I. Stern
Promise and problems of emergy analysis	2004	110	Ecological Modelling	J.L. Hau, B.R. Bakshi
Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems	2004	107	Ecological Modelling	M.T. Brown, S. Ulgiati

[a] These articles only mention emergy, but are not particularly important to those currently publishing in the emergy literature.

in SCI-Expanded and SSCI database. In this article, they puts forward a basic analytic procedure for evaluating sustainability using emery analysis, which has provided ideas and methods for other researchers (Brown & Ulgiati, 1997). The other 9 publications that were the most frequently cited in the field of emergy research are shown in Table 4 (Brown and Ulgiati, 2004; Carraretto et al., 2004; Fath and Patten, 1999; Fath et al., 2001; Hau and Bakshi, 2004; Ness et al., 2007). However, not all of the 10 publications are closely about emergy. Some of them may just mention emergy, but are not particularly important to the currently publishing in emergy literature, such as "Categorizing tools for sustainability assessment" (Cleveland et al., 2000). Moreover, other publications outsides the Web of Science database are influential in emergy research and have also been frequently cited, such as many project reports of USEPA, the proceedings of the biennial emergy research conferences, emergy evaluation folios and encyclopedia.

In addition, the number of citations for each country is also an important index considering the scientific influence of one country in emergy research. Among the top 3 most productive countries, the average citation of each paper of the USA is 28.32, Italy 25.42 and China 13.81. Moreover, the h-index of the USA is 36, Italy 33 and China 30. The above data show that the papers from the USA and

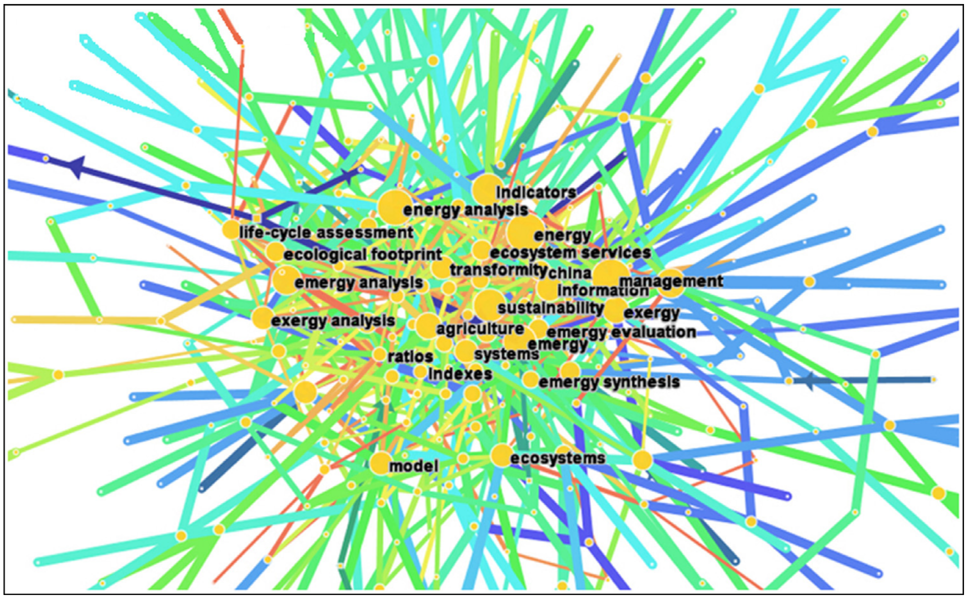

Fig. 8. Combined mapping and clustering of keywords.

Italy have more citations than from China and have more scientific value, though China has more papers published each year.

3.7. Author keywords

Author keywords are the words used to reveal the internal structure of an author's reasoning. Author keywords supply the main information in articles and thus research trends can be obtained by analyzing these keywords (Min et al., 2010). Based on the distribution of words in an author keyword analysis, emergy research issues could be roughly found using statistically analysis.

All the author keywords in the 637 publications were ranked according to the frequency of their use. "Energy" was the most frequently used word because that the development of the concept of emergy by H.T. Odum is based on traditional energy analysis. Sustainability has also become an issue of increasing environmental concern. Emergy analysis can provide analytic procedures and techniques for measuring ecosystem sustainability. The keyword "sustainability" ranked 2nd in author keywords. Transformity and indicators are the controlling factors for emergy research. Therefore, "transformity" and "indicators" have also received more attention in recent years, which can be deduced from the author keywords analysis (ranked 3rd and 4th, respectively). In addition, the author keyword "exergy" ranked 5th. The relationship pattern for the keywords analyzed with Citespace (Fig. 8). Two or more related keywords can by and large describe the focus of one article.

4. Conclusions

Due to serious environmental problems as well as the reliance of society on finite resources, the emergy analysis method is an important tool to evaluate environmental sustainability. Hence understanding the developing process and trends in emergy analysis becomes a common goal for related researchers, institutes and journals. Based on 637 publications in the SCI-Expanded and SSCI of the Web of Science database, significant points about emergy research points were obtained using the bibliometric and visualized analyses, providing a systematic overview of emergy research from 1996 to 2014.

Eight document types relating to emergy research were found in a total of 637 publications and almost all of them are published in English. The reason is that the SCI-Expanded and SSCI database mostly collects papers from English language journals rather than papers published in journals written in other languages. Each year the number of publications has grown significantly, especially during the period of 2005–2014. From the present trend, it can be predicted that the number of related publications in this study will continue to growth rapidly. The top 5 most productive authors in emergy research were S. Ulgiati with 50 articles, B. Chen with 45 articles, S. Bastianoni with 40, M.T. Brown with 36 and Z.F. Yang with 34, according to the data in SCI-Expanded and SSCI database. There is no doubt that many other scientists, without abundant papers published, have made major contributions to emergy research. The literature was published in more than 100 journals in 45 subject categories from 58 countries/territories. The People's Republic of China, the USA, and Italy were ranked as the top three countries for total publications on emergy research. However, according to the citation rate of each paper and the h-index, the emergy publications from the USA and Italy might have more scientific value than those from China, through China is the most productive country. The top 3 most productive journals were Ecological Modeling, Ecological Engineering and Ecological Indicators, which are all well-known and authoritative ecological journals. A keyword analysis offered interesting insights into the dynamics of this field. This study showed that emergy research mainly focuses on "energy", "sustainability", "transformity" and "indicators", which have been the hottest topics from 1996 to 2014 and will continue to be the key issues in emergy research in the near future. This finding suggests that the basic theory of emergy analysis and the evaluation of environmental sustainability have been recognized as the leading research hotspots.

Acknowledgments

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References

Abramo, G., D'Angelo, C.A., Viel, F., 2011. The field-standardized average impact of national research systems compared to world average: the case of Italy. Scientometrics 88 (2), 599–615.

Bakshi, B.R., 2000. A thermodynamic framework for ecologically conscious process systems engineering. Comput. Chem. Eng. 24 (2), 1767–1773.

Barton, Norman W., Furbish, F.S., Murray, G.J., Garfield, M., Brady, R.O., 1990. Therapeutic response to intravenous infusions of glucocerebrosidase in a patient with Gaucher disease. Proc. Natl. Acad. Sci. U.S.A. 87 (5), 1913–1916.

Brown, M.T., McClanahan, T.R., 1996. Emergy analysis perspectives of Thailand and Mekong River dam proposals. Ecol. Modell. 91 (1), 105–130.

Brown, M.T., Ulgiati, S., 2004. Energy quality, emergy, and transformity: HT Odum's contributions to quantifying and understanding systems. Ecol. Modell. 178 (1), 201–213.

Brown, M.T., Buranakarn, V., 2003. Emergy indices and ratios for sustainable material cycles and recycle options. Resour. Conserv. Recycl. 38 (1), 1–22.

Brown, M.T., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. 9 (1), 51–69.

Campbell, D.E., 2000. Using energy systems theory to define, measure, and interpret ecological integrity and ecosystem health. Ecosyst. Health 6 (3), 181–204.

Campbell, D.E., Garmestani, A.S., 2012. An energy systems view of sustainability: emergy evaluation of the San Luis Basin, Colorado. J. Environ. Manage. 95 (1), 72–97.

Carraretto, C., Macor, A., Mirandola, A., Stoppato, A., Tonon, S., 2004. Biodiesel as alternative fuel: experimental analysis and energetic evaluations. Energy 29 (12), 2195–2211.

Chen, C., 2004. Searching for intellectual turning points: progressive knowledge domain visualization. Proc. Natl. Acad. Sci. U.S.A. 101 (Suppl. 1), 5303–5310.

Chen, C., 2006. CiteSpace II: detecting and visualizing emerging trends and transient patterns in scientific literature. J. Am. Soc. Inform. Sci. Technol. 57 (3), 359–377.

Chen, D., Chen, J., Luo, Z., 2012. Communications on emergy indices of regional water ecological-economic system. Ecol. Eng. 46, 116–117.

Chen, D., Chen, J., Luo, Z., Lv, Z., 2009. Emergy evaluation of the natural value of water resources in Chinese rivers. Environ. Manage. 44 (2), 288–297.

Chen, D., Luo, Z., Webber, M., Chen, J., Wang, W., 2014. Emergy evaluation of the contribution of irrigation water, and its utilization, in three agricultural systems in China. Front. Earth Sci. 8 (3), 325–337.

Chen, D., Webber, M., Chen, J., Luo, Z., 2011. Emergy evaluation perspectives of an irrigation improvement project proposal in China. Ecol. Econ. 70 (11), 2154–2162.

Chen, S., Chen, B., 2011. Assessing inter-city ecological and economic relations: an emergy-based conceptual model. Front. Earth Sci. 5 (1), 97–102.

Chen, S., Chen, B., 2012. Sustainability and future alternatives of biogas-linked agrosystem (BLAS) in China: an emergy synthesis. Renew. Sustain. Energy Rev. 16 (6), 3948–3959.

Chen, S., Chen, B., 2014. Energy efficiency and sustainability of complex biogas systems: a 3-level emergetic evaluation. Appl. Energy 115, 151–163.

Cleveland, C.J., Kaufmann, R.K., Stern, D.I., 2000. Aggregation and the role of energy in the economy. Ecol. Econ. 32 (2), 301–317.

Díaz-Delgado, C., Fonseca, C.R., Esteller, M.V., Guerra-Cobián, V.H., Fall, C., 2014. The establishment of integrated water resources management based on emergy accounting. Ecol. Eng. 63, 72–87.

Fang, D., Chen, S., Chen, B., 2015. Emergy analysis for the upper Mekong river intercepted by the Manwan hydropower construction. Renew. Sustain. Energy Rev. 51, 899–909.

Fath, B.D., Patten, B.C., 1999. Review of the foundations of network environ analysis. Ecosystems 2 (2), 167–179.

Fath, B.D., Patten, B.C., Choi, J.S., 2001. Complementarity of ecological goal functions. J. Theor. Biol. 208 (4), 493–506.

Feng, X., Min, S.-l., Dai, Y.-l., Liu, Y.-z., 2005. Emergy analysis of industrial multi-product systems. Chin. J. Process Eng. 5 (3), 317.

Hau, J.L., Bakshi, B.R., 2004. Promise and problems of emergy analysis. Ecol. Modell. 178 (1), 215–225.

Kam, M.K.M., Leung, S.-F., Zee, B., Chau, R.M.C., Suen, J.J.S., Mo, F., Brian, K.H., 2007. Prospective randomized study of intensity-modulated radiotherapy on salivary gland function in early-stage nasopharyngeal carcinoma patients. J. Clin. Oncol. 25 (31), 4873–4879.

Kang, D., Park, S.S., 2002. Emergy evaluation perspectives of a multipurpose dam proposal in Korea. J. Environ. Manage. 66 (3), 293–306.

Lefroy, E., Rydberg, T., 2003. Emergy evaluation of three cropping systems in southwestern Australia. Ecol. Modell. 161 (3), 195–211.

Li, W., Zhao, Y., 2015. Bibliometric analysis of global environmental assessment research in a 20-year period. Environ. Impact Assess. Rev. 50, 158–166.

Liu, X., Zhang, L., Hong, S., 2011. Global biodiversity research during 1900–2009: a bibliometric analysis. Biodivers. Conserv. 20 (4), 807–826.

Lou, H.H., Kulkarni, M.A., Singh, A., Huang, Y.L., 2004. A game theory based approach for emergy analysis of industrial ecosystem under uncertainty. Clean Technol. Environ. Policy 6 (3), 156–161.

Lu, H., Lan, S.-f., Li, L., Peng, S.-l., 2003. New emergy indices for sustainable development. J. Environ. Sci. 15 (4), 562–569.

Ma, Y.C., Zuo, L., Chen, J.-H., Luo, Q., Yu, X.-Q., Li, Y., Huang, W., 2006. Modified glomerular filtration rate estimating equation for Chinese patients with chronic kidney disease. J. Am. Soc. Nephrol. 17 (10), 2937–2944.

Mayr, P., Scharnhorst, A., 2014. Scientometrics and information retrieval: weak-links revitalized. Scientometrics, 1–7.

Min, K., Zhang, Z., Wright, J., Ma, Y., 2010. Decomposing background topics from keywords by principal component pursuit. In: Paper presented at the Proceedings of the 19th ACM International Conference on Information and Knowledge Management.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecol. Econ. 60 (3), 498–508.

Odum, H.T., 1996. Environmental Accounting: EMERGY and Environmental Decision Making.

Pörtner, H.-O., 2008. Ecosystem effects of ocean acidification in times of ocean warming: a physiologists view. Mar. Ecol. Prog. Ser. 373, 203–217.

Lan, S., Odum, H.T., 1994. Emergy synthesis of the environmental resource basis and economy of China. Ecol. Sci. 13, 63–74.

Sun, J., Ni, J., Ho, Y.-S., 2011. Scientometric analysis of coastal eutrophication research during the period of 1993 to 2008. Environ. Dev. Sustain. 13 (2), 353–366.

Ulgiati, S., Odum, H.T., Bastianoni, S., 1994. Emergy use, environmental loading and sustainability an emergy analysis of Italy. Ecol. Modell. 73 (3), 215–268.

Ulgiati, S., Brown, M.T., 2002. Quantifying the environmental support for dilution and abatement of process emissions: the case of electricity production. J. Cleaner Prod. 10 (4), 335–348.

Voora, V., Thrift, C., 2010. Using Emergy to Value Ecosystem Goods and Services. International Institute for Sustainable Development, Winnipeg, Canada.

Wang, L., Ni, W., Li, Z., 2006. Emergy evaluation of combined heat and power plant eco-industrial park (CHP plant EIP). Resour. Conserv. Recycl. 48 (1), 56–70.

Wang, M.-H., Yu, T.-C., Ho, Y.-S., 2010. A bibliometric analysis of the performance of Water Research. Scientometrics 84 (3), 813–820.

Yang, H., Li, Y., Shen, J., Hu, S., 2003. Evaluating waste treatment, recycle and reuse in industrial system: an application of the emergy approach. Ecol. Modell. 160 (1), 13–21.

Yang, J., Chen, B., 2014. Emergy analysis of a biogas-linked agricultural system in rural China – a case study in Gongcheng Yao Autonomous County. Appl. Energy 118, 173–182.

Zhao, S., Li, Z., Li, W., 2005. A modified method of ecological footprint calculation and its application. Ecol. Modell. 185 (1), 65–75.