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Measuring ecological capital: State of the art, trends, and challenges

Huajun Yu [a], Yutao Wang [a, b, *], Xiao Li [c], Chengdong Wang [a], Mingxing Sun [d], Anshu Du [a]

[a] Fudan Tyndall Center and Shanghai Key Laboratory of Atmospheric Particle Pollution and Prevention (LAP^3), Department of Environmental Science & Engineering, Fudan University, Shanghai, 200438, China
[b] Institute of Eco-Chongming (SIEC), No. 3663 Northern Zhongshan Road, Shanghai, 200062
[c] Center for Industrial Ecology, School of Forestry and Environmental Studies, Yale University, 195 Prospect St, New Haven, CT, 06511, USA
[d] International Ecosystem Management Partnership, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, PR China

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ABSTRACT

It is essential to assess the value of nature, as it provides various benefits for human economic development and well-being. It has been 20 years since two prominent publications came out in valuing nature. New concepts and methods have emerged since then. This study aimed to (1) investigate the relationship between the new proposed concept (ecological capital) and the existing two concepts: natural capital and ecosystem services and (2) examine the research trends of ecological capital accounting publications from 1997 to 2017. Bibliometric analysis was used to reveal the research trends. The results showed that the total number of publications has rapidly increased since 1997 and this growth trend will be maintained in the future. The most productive journal, country, institute, and author were *Ecological Economics*, USA, Chinese Academy of Sciences, and Dr. Verburg, respectively. Ecosystem services and land were the most frequent types of ecological capital. Non-economic evaluation approaches became less of a favorite over time and economic valuation methods were mostly applied in last five years. The integration of different methods has attracted increasing academic attention. The progress, advantages, and limitations of different methods were summarized in this study, including SEEA, ecological footprint, exergy, emergy, LCA, and economic valuation approaches, as well as newly developed modelling approaches. The last part of this study presented three challenges in this academic field – the need to (1) establish a standard framework, (2) consider the transfer/transport of ecological capital, and (3) improve capabilities for decision-making.

1. Introduction

Along with rapid economic development and urbanization, resource shortages (Adamowicz et al., 2016), biodiversity loss (Shepherd et al., 2016), ecological degradation (Ouyang et al., 2016) and other ecological problems have frequently occurred. Human society gradually recognized nature's contribution in supporting the economy and human well-being (Tallis and Lubchenco, 2014; Chan et al., 2016). The value of nature is reflected in two aspects: (1) it provides direct resources, such as food, water, and timber and (2) it delivers indirect services, including carbon sequestration, pollination, recreation, and cultural values (MEA, 2005; Costanza et al., 2017). To sustain human society's development, nature as an important capital or asset must be effectively managed (Barbier, 2014; Polasky et al., 2015). Accounting for its value is the basis for nature's effective management. In 1997, the article – *The value of the world's ecosystem services and natural capital* was published in Nature (Costanza et al., 1997), as well as an edited book (Daily, 1997). These two prominent publications stimulated an explosion of research related to valuing nature (Costanza et al., 2017). For instance, three global initiatives, the Millennium Ecosystem Assessment (MEA) project, the Economics of Ecosystems and Biodiversity (TEEB) project, and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) were successively established to evaluate the values of nature and mainstream them into decision-making at all levels (Costanza et al., 2017).

In the twenty years of development, some new concepts have been proposed, such as ecological capital (Barbier, 2016), ecological

* Corresponding author. Department of Environmental Science and Engineering, Fudan University, 2005 Songhu Road, Yangpu District, Shanghai, 200438, China.
E-mail address: yutaowang@fudan.edu.cn (Y. Wang).

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assets (Galli et al., 2015) and ecosystem assets (Hein et al., 2016). And the accounting techniques have gradually expanded, previously they were limited to the ecological footprint (EF) and some economic valuation approaches, such as avoided cost, travel cost, and hedonic pricing (Costanza et al., 2017). Currently there are many cases of using benefit transfer, emergy, life-cycle assessment (LCA) and dynamic modelling (e.g., InVEST) to assess the value of nature. Costanza et al.(2014) estimated the global changes of values of ecosystem services through benefit transfer. Wang et al. (2019) applied emergy to account for the value of several key ecosystem services in the Yellow River Delta region in China. Liu et al. (2018a, b) developed a conceptual framework to evaluate ecosystem services with LCA. Hoyer and Chang (2014) modeled water related ecosystem services of a river basin, such as water yield and water retention with InVEST software. Many papers have summarized the progress in the field of assessing nature's values. For the relationship of concepts, Smith et al. (2017) synthesized a typology to link natural capital and ecosystem services. Maseyk et al. (2017) introduced a framework to illustrate how natural capital delivers ecosystem services for decision makers. For the development of accounting methods, Pascual et al. (2010) introduced the strengths, limitations and real-world cases of various economic valuation approaches. Richardson et al. (2015) described the role of the benefit transfer technique in facilitating the economic valuation of ecosystem services. Christie et al. (2012) compared the applicability of both economic and non-economic methods in valuing ecosystem services. Emerging methods such as remote sensing (de Araujo Barbosa et al., 2015) and dynamic modelling (Shoyama et al., 2017) have also been reviewed.

However, few studies have explored the relationship between the newly proposed concept (ecological capital) and the existing concepts (natural capital and ecosystem services). Clarifying the differences of these concepts is essential in conducting value assessments of nature. Because the three concepts cover different types of natural resources, the selection of valuation methods needs to be determined according to the specific resource type. Additionally, little research has analyzed the research trends of evaluation approaches from a bibliometric perspective. Bibliometric analysis is a common tool used to investigate the research patterns of a given field (Fu and Ho, 2013; Mao et al., 2015). It has been used in many disciplines, such as green supply chain management (Fahimnia et al., 2015), circular economy (Geissdoerfer et al., 2017), and water footprint research (Zhang et al., 2017).

Therefore, the objectives of this study were to (1) investigate the relationship of the three concepts: natural capital, ecosystem services and ecological capital or assets, and (2) examine the research trends in ecological capital accounting from 1997 to 2017 with bibliometric methods. This paper is as follows: Section 2 investigates the relationship of the three concepts. Section 3 introduces the methodology of this study. Section 4 presents the results of bibliometric analysis. Section 5 summarizes the development of each method. Section 6 presents the identified research challenges and section 7 draws the conclusions.

2. Concepts

Natural capital and ecosystem services concepts are at the core of literature of valuing nature. Their respective definitions and evaluation methods have been well examined, as has been the relationship between them. In last ten years, scientists have proposed some new concepts, such as ecological capital (Barbier, 2016), ecological assets (Galli et al., 2015) and ecosystem assets (Hein et al., 2016). These terms are collectively named as ecological capital in this study. There are overlaps and differences between the two existing concepts and the newly proposed one. This section will briefly introduce the definitions of the three concepts and clarify their relationship, which helps in the choice of appropriate assessment methods.

2.1. Natural capital

The term "natural capital" has a long history in the literature. Its origin and development can be found in (Missemer, 2018) and (DesRoches, 2015). The classical definition of natural capital is a stock able to produce a flow of valuable goods or services into the future, and two groups of natural capital can be differentiated: (1) nonrenewable natural capital, refers to nonrenewable or exhaustible resources, such as fossil fuels and metal ores, and (2) renewable natural capital, including renewable resources (land, water, air, forest, and others) and ecosystems that can provide flows of ecosystem services (Costanza and Daly, 1992). This stock-flow definition was widely accepted by subsequent researchers (Häyhä and Franzese, 2014; Mancini et al., 2017).

2.2. Ecosystem services

"Ecosystem services" is another core concept that is often mentioned in the literature of valuing nature. Gómez-Baggethun et al. (2010) and Braat and de Groot (2012) summarized its developmental history in economics and other disciplines respectively. The MEA report defined ecosystem services as the benefits humans directly and indirectly acquire from ecosystems, and classified various ecosystem services into four groups: (1) provisioning services, products or goods directly gained from nature, such as food, timber, and biochemical, (2) regulating services, such as air quality regulation, water purification, and erosion control, (3) cultural services are the nonmaterial goods and services attained from nature, including sense of place, recreation and spiritual experience, and (4) supporting or habitat services, which support the operation of all other groups of services (MEA, 2005). Most subsequent studies have adopted this definition and classification, with minor changes in category names and attribution of some individual services (Schröter et al., 2014; Pascual et al., 2017). Some studies proposed other classification system. Wallace (2007) developed a typology classification framework that links human value and ecological structures and processes. Haines-Young and Potschin (2012) and Landers and Nahlik (2013) introduced a paradigm that sorts ecosystem services into supporting and final services. Fisher et al. (2009) suggested a classification scheme under the decision-making context.

2.3. Ecological capital

In addition to the above two concepts, some new terms have been proposed by researchers in the past decade. Barbier (2013, 2016) introduced "ecological capital" and considered that it has three characteristics: (1) depreciation, (2) irreplaceability; and (3) the ability to abruptly collapse. Galli et al. (2015) and Mancini et al. (2017) used the term "ecological assets", defined as "the spatial areas with biotic and abiotic components functioning together". Wang et al. (2011) proposed "natural assets" as the combination of five components: water, land, air, living organisms, and mineral resources. Hein et al. (2016) proposed "ecosystem assets", which include ecosystems capacity and capability to supply ecosystem services, as well as the potential supply of ecosystem services". These phrases, ecological capital, ecological, ecosystem, and natural assets are collectively referred as ecological capital in this study.

2.4. The relationship of the three concepts: natural capital, ecological capital, and ecosystem services

According to their classic definitions, ecosystem services can be understood as the flows of services generated by natural capital (Costanza and Daly, 1992). This idea is widely accepted in current mainstream research (Maseyk et al., 2017; Smith et al., 2017). Some researchers tend to consider ecological capital as the stock part (physical forms) of natural capital (Galli et al., 2015; Mancini et al., 2017), while others view it as including the flow part (ecosystem services) of natural capital, which is equivalent to natural capital (Frazier et al., 2013; Hein et al., 2016). There are also some that consider that non-renewable resources should be excluded (Wang et al., 2011; Barbier, 2013). The disputes are mainly concentrated in two aspects: (1) whether it should contain the flow component and (2) whether it should contain non-renewable resources.

To solve this controversy, we suggest that ecological capital should contain the flow part and exclude non-renewable resources. The relationship of the three concepts is shown in Fig. 1. There are several reasons for proposing such a description. First, it follows the classic definition of "capital" in natural capital, which was defined as a stock that able to generate flows. Second, "ecological" is a derivative of "ecosystem". Non-renewable resources are typically reserved to the lithosphere, which are not included in ecosystem areas in terms of geographical distribution. Finally, this definition distinguishes ecological capital from natural capital, avoiding the use of two phrases expressing the same meaning and splitting relevant resources.

3. Methodology

This section introduces the methods used in this study, as well as the data source and cleaning processes. To predict the trend of research outputs, the Hurst exponent and Mann-Kendall test were used, and the resulting H and Z values reflect the relative tendency of time-series data (Wang et al., 2017). The total available range for the H value is 0–1. An H value that falls between 0.5 and 1 indicates a strong propensity to an increasing trend, meaning that a high value in the series will probably be followed by another high value. A value in the range 0–0.5 indicates the time series is prone to return to the average, meaning high and low values adjacently appear. When H is 0.5, the time series is a completely uncorrelated series. For the Mann-Kendall test, a $Z < 0$ value means that the time series tends to decrease, while $Z > 0$ indicates an increasing trend.

3.1. Bibliometric analysis

Bibliometric analysis, originally introduced by Pritchard, is a collection of mathematical and statistical methods used to analyze written publications (Ellegaard and Wallin, 2015; Ellegaard, 2018).

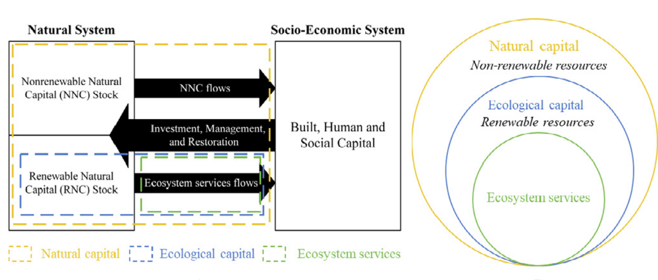

Fig. 1. The relationship of natural capital, ecological capital, and ecosystem services: A – from the stock-flow perspective, adapted from (Costanza et al., 2017) and B – from the renewable and non-renewable resource perspective, adapted from (Liu et al., 2018).

It has become a typical and effective tool for systematic review in a variety of research fields, such as low carbon technologies (Wei et al., 2018), circular economy (Geissdoerfer et al., 2017), green supply chain (Fahimnia et al., 2015), and water footprint (Zhang et al., 2017). Bibliometric analysis helps to reveal the characteristics, structures and patterns of a particular topic, as well as research hotspots and future trends (Ellegaard and Wallin, 2015). A typical bibliometric analysis firstly evaluates the performance of selected publications, including distribution of various journals, countries, institutes, and authors, then investigates research hotspots and predict future research directions with keywords analysis (Mao et al., 2015; Mo et al., 2018). Two common indicators, the impact factor (IF) and h-index were used to evaluate the performance of selected publications (Zhong et al., 2016). The IF of an academic journal is frequently used as a proxy for the relative importance of a journal within its field; journals with higher impact factors are often deemed to be more important than those with lower ones. IF have been calculated yearly starting from 1975 for journals listed in the Journal Citation Reports. The h-index is an indicator that attempts to measure both the productivity (quantity) and citation impact (quality) of the publications of a scientist, an organization or a journal. Specifically, a higher h-index usually means a higher research performance. To facilitate the analysis, Bibexcel (Persson et al., 2009) was used to extract certain information of selected publications, such as author, published year, journal, address, citations, and keywords.

3.2. Social network analysis

Social network analysis (SNA) is the process of investigating social structures through the use of networks and graph theory (McLinden, 2013; Zhong et al., 2016). It characterizes networked structures in terms of nodes and edges. The nodes can be authors, research institutes, universities, and countries, and the edges or links represents their co-occurrences. SNA is an effective way to reflect the relationships among different actors (McLinden, 2013; Mao et al., 2018). Bibexcel was employed to extract relevant data and construct co-occurrence matrices, including author, keywords, address, journal title, citation and other information. The matrices were then treated by Pajek, VOSviewer and Gephi software to produce the co-occurrence network and clusters (Mao et al., 2015; Wang et al., 2017). The resulting graphs visualize the academic collaborations between authors, institutes, and countries.

3.3. Data collection

The following keywords were selected to search publications in the database of the Web of Science Core collection: ("ecosystem services" OR "natural capital" OR "ecological capital" OR "ecological assets") AND ("valuation" OR "assessment" OR "accounting"). The database covers the Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Conference Proceedings Citation Index- Science (CPCI–S), and Conference Proceedings Citation Index- Social Science & Humanities (CPCI-SSH) four key databases. The time interval was set from 1997 to 2017 because this field started to gain mainstream research interests in 1997. A total of 6163 records were found, consisting of 6114 (99.2%) English publications and 49 (0.8%) other language publications. Since English is the dominant academic language, the 6114 English documents were collected for further analysis.

4. Results

Among the 6114 English publications, articles (80.91%) were the dominant document type, followed by proceeding papers (8.41%), reviews (7.92%), and other types of publications (1.76%). Fig. 2 shows the number of total publications (TP) per year between 1997 and 2017. The TP has rapidly grown, from 6 publications to approximately 1200. The H value was 0.9496, and the Z value was $6.13 > 0$, indicating that the publications of this field will keep growing in the future.

4.1. Journal performance

Table 1 shows the top 20 most productive journals, which accounted for 37.88% of the total publications. *Ecological Economics* was the most productive journal (347) and ranked 1st in the h-index (67), indicating its dominance both in quantity and quality in this field. *Ecosystem Services* as a newly established journal (in 2012) achieved a comprehensive performance, ranked 2nd in publications (341) and 4th in the h-index (30), as well as a high impactor factor (4.395). *Sustainability* had a high quantity of publications (103), but with a relatively low impact factor (2.075) and h-index (12) values. Journals such as *PNAS*, *Journal of Applied Ecology*, and *Landscape and Urban Planning* had a low number of total publication (53, 58, and 81, respectively) yet got high impactor factors (9.504, 5.742, and 4.994, respectively) and h-index values (36, 26, and 29, respectively). The results reflect that diverse indicators are needed to represent a journal's performance.

4.2. Country performance and collaboration

Among the 6114 records, 6092 documents have affiliation information. The 6092 publications were collected for country and institute performance analysis. Results showed that 151 countries/regions contributed to the ecological capital accounting literature. Table 2 lists the top 20 most productive countries. Their publications account for 83.14% of all documents. Among them, 13 countries are from Europe, with a share of 40.91%. The USA (1,919) is the most productive country, as well as in categories of first-author country and publications with and without international collaboration. It also ranked 1st in the h-index (119), indicating USA's dominance in this research area. The following most productive countries are the UK (1,073), Germany (689), and China (662), with a huge gap compared to the USA. The UK and Germany took 2nd and 3rd place in the h-index. In contrast, China merely ranked 13th in h-index, indicating its publications received less academic attention. The reason that China obtained a low h-index could be lack of international collaboration. Table 2 shows that the cooperation ratio of Chinese publications was $C = 35.5\%$, much lower compared to other countries. International collaboration plays an important role in enhancing academic influence. Countries such as

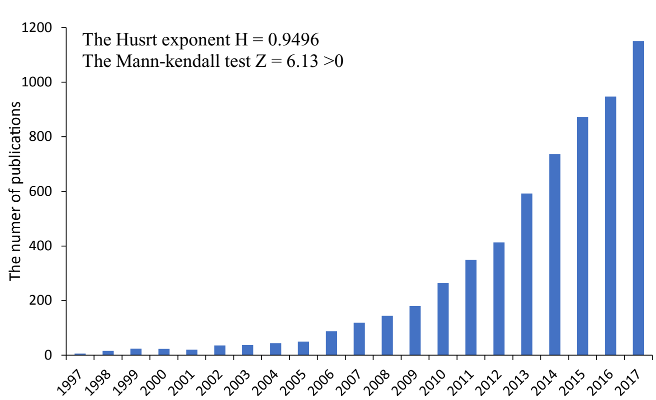

Fig. 2. The performance of ecological capital accounting publications from 1997 to 2017.

Australia and Netherlands with higher levels of international collaboration achieved higher h-index values.

Fig. 3 presents the academic collaboration relationship among the 25 most productive countries. The Louvain method was applied in Pajek software to make a cluster analysis. Two clusters were identified, and the color of the nodes indicates which cluster it belongs to. The size of the nodes represents the number of a country's publications with international collaboration. The width of the edges refers to the frequency of collaboration between two countries. The USA occupies the core of the network and has the most cooperative publications. The connection between USA and UK is the strongest, with 233 publications. Canada, Australia and China are also closely linked to the USA, with 150, 129, and 120 co-authored publications, respectively. The UK is the most active country of the blue cluster, it had 144, 136, and 111 cooperative publications with Germany, Netherlands, and France, respectively. The blue cluster mainly consisted of European countries, indicating distance could be an important factor affecting international cooperation.

4.3. Institute performance and collaboration

Table 3 shows the top 15 most productive institutes and their performance. Seven institutes are in the USA, reflecting USA's leading position in this academic field. The Swedish University of Agricultural Sciences (SLU) is the only research organization not from the top 5 productive countries. The Chinese Academy of Sciences (CAS) is the most productive academic institute, with a total of 250 publications, as well as in first author publications and publications with and without cooperation. However, its h-index (31) ranked 10th. Another Chinese research institute, Beijing Normal University, had a similar performance to CAS. It ranked 5th in number of publications yet 47th in the h-index. The results indicated that their publications attracted fewer academic interests. The following most productive academic institutes are Wageningen University & Research, Helmholtz Centre for Environmental Research (UFZ), and Stanford University. All of them achieved high h-index performances, with a value of 53, 38, and 47, respectively.

Fig. 4 shows the academic collaboration network among the 20 most productive institutes. These institutes were divided into 3 clusters by the Louvain method in Pajek. The size of the nodes refers to the number of publications with collaboration, and the width of the lines refers to the frequency of collaboration between two institutes. Research organizations from the same continent are clustered together, red for North America, blue for Europe, and green for China. The CAS is the most active institute with 201 cooperative documents. Beijing Normal University is CAS's closest partner. They have published 20 documents together. Wageningen University & Research is the second most active research organization, it has a close connection with UFZ (16), Vrije University Amsterdam (13), and SLU (13). Stanford University – University of Minnesota and University of Cambridge – University of East Anglia are the most cooperative pairs, with 25 co-authored publications.

4.4. Author performance and collaboration

More than 20,000 authors have published research in this field. Fig. 5 presents the performance of authors who have published more than 20 research papers, a total of 18 authors. These authors are from 12 different countries, indicating this topic has attracted extensive interests from various nations. The grey dashed line helps to understand these authors' performance. The closer the author to the line, the better performance the author has achieved in both quality and quantity. Dr. Lavorel, Dr. Pascual, Dr. Chan, and Dr. Haase

Table 1
The top 20 most productive journals and their performance during 1997–2017.

Journal title	TP	% (R)	IF-2017	h-index (R)
Ecological Economics	347	5.68 (1)	3.895	67 (1)
Ecosystem Services	341	5.58 (2)	4.395	30 (4)
Ecological Indicators	231	3.78 (3)	3.983	40 (2)
Journal of Environmental Management	126	2.06 (4)	4.005	27 (7)
Ecology and Society	123	2.01 (5)	3.256	29 (5)
Land Use Policy	116	1.90 (6)	3.194	24 (13)
PLOS One	115	1.88 (7)	2.766	25 (10)
Science of the Total Environment	113	1.85 (8)	4.61	23 (14)
Sustainability	103	1.68 (9)	2.075	12 (43)
Environmental Science & Policy	88	1.44 (10)	3.826	25 (10)
Landscape and Urban Planning	81	1.32 (11)	4.994	29 (5)
Ecological Modelling	72	1.18 (12)	2.507	21 (18)
Agriculture Ecosystems & Environment	66	1.08 (13)	3.541	25 (10)
Environmental Management	65	1.06 (14)	2.177	18 (24)
Biological Conservation	58	0.95 (15)	4.66	27 (7)
Journal of Applied Ecology	58	0.95 (15)	5.742	26 (9)
Landscape Ecology	56	0.92 (17)	3.833	21 (18)
PNAS[a]	53	0.87 (18)	9.504	36 (3)
Ocean & Coastal Management	53	0.87 (18)	2.276	15 (33)
Regional Environmental Change	51	0.83 (20)	2.872	14 (35)

TP: total publication; % (R): the ratio and rank of the publications; IF-2017: the impactor factor of the journal in 2017; h-index (R): h-index and its rank; a: *PNAS – Proceedings of the National Academy of Sciences of the United States of America.*

Table 2
The top 20 most productive countries during 1997–2017.

Country	TP	% (R)	FP% (R)	SP% (R)	CP%(R)	C%	h-index (R)
USA	1919	31.39 (1)	22.19 (1)	16.8 (1)	14.62 (1)	46.6	119 (1)
UK	1073	17.55 (2)	9.42 (3)	6.2 (3)	11.33 (2)	64.6	89 (2)
Germany	689	11.27 (3)	5.82 (4)	3.6 (4)	7.65 (3)	67.9	72 (3)
China	662	10.83 (4)	9.57 (2)	7.0 (2)	3.84 (10)	35.5	45 (13)
Australia	511	8.36 (5)	5.36 (5)	3.1 (5)	5.27 (5)	63.0	63 (5)
Netherlands	446	7.29 (6)	2.75 (10)	1.6 (10)	5.66 (4)	77.6	67 (4)
Italy	440	7.20 (7)	4.22 (6)	2.8 (6)	4.37 (8)	60.7	47 (10)
France	422	6.90 (8)	3.83 (8)	1.8 (7)	5.14 (6)	74.4	53 (8)
Spain	405	6.62 (9)	3.97 (7)	1.7 (9)	4.94 (7)	74.6	58 (6)
Canada	355	5.81 (10)	3.04 (9)	1.8 (7)	4.04 (9)	69.6	54 (7)
Sweden	295	4.82 (11)	2.00 (11)	1.3 (11)	3.53 (11)	73.2	53 (8)
Switzerland	263	4.30 (12)	1.83 (12)	0.8 (13)	3.48 (12)	81.0	46 (11)
South Africa	188	3.07 (13)	1.77 (13)	1.2 (12)	1.88 (15)	61.2	46 (11)
Denmark	164	2.68 (14)	1.42 (14)	0.4 (23)	2.31 (13)	86.0	35 (14)
Belgium	150	2.45 (15)	1.34 (16)	0.7 (18)	1.80 (16)	73.3	32 (16)
Finland	146	2.39 (16)	1.23 (17)	0.8 (15)	1.62 (18)	67.8	34 (15)
Brazil	146	2.39 (16)	1.42 (14)	0.8 (14)	1.59 (19)	66.4	31 (18)
Austria	144	2.36 (18)	0.93 (21)	0.4 (23)	1.98 (14)	84.0	32 (16)
Portugal	125	2.04 (19)	0.83 (22)	0.6 (20)	1.41 (20)	68.8	25 (24)
New Zealand	113	1.85 (20)	0.98 (19)	0.7 (17)	1.11 (23)	60.2	30 (19)

TP: total publication; %(R): the ratio and rank of the publications; FP% (R): the ratio and rank of first author publications; SP% (R): the ratio and rank of publications without international collaboration; CP% (R): the ratio and rank of publications with international collaboration; C%: the ratio of international collaborative publications of a country; h-index (R): h-index and its rank.

have a better performance. If the author is under the dashed line, it means his/her publications received less citations.

Fig. 6 shows the collaboration network of authors who have published more than 14 articles. A total of 45 authors were selected. They were classified into 6 clusters through the Louvain method, and the color of the nodes refers to which cluster it belongs to. The size of the circles refers to the cooperative number of publications. The width of the links represents the frequency of cooperation between two researchers. The purple cluster represents a group of authors focusing on land related ecosystem services and land use modelling. Researchers belonging to the orange cluster are interested in biodiversity, conservation and ecosystem services, and they show a stronger connection compared to other clusters. Scholars with a blue color have a background of ecological economics, such as Dr. Costanza and Dr. de Groot, and they focus on economic valuation approaches in valuing nature. The light green scientists are interested in using Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) models to evaluate ecosystem services. For example, Dr. Daily is the major contributor of InVEST models. The dark green cluster represents two Chinese scholars, Dr. Fu and Dr. Lu. Land resource and land related ecosystem services are their main research interests. The pink cluster shows scientists developing Artificial Intelligence for Ecosystem Services (ARIES) and Social Values for Ecosystem Services (SoLVES) models.

4.5. Keywords analysis

Keywords reflect the research focus of a paper and help to identify the research trends of an area. All the keywords from the 6114 documents were extracted and pre-treated. For example, “economic valuation” represents “economic analysis”, “economic assessment”, and “monetary valuation”. There are 65 keywords

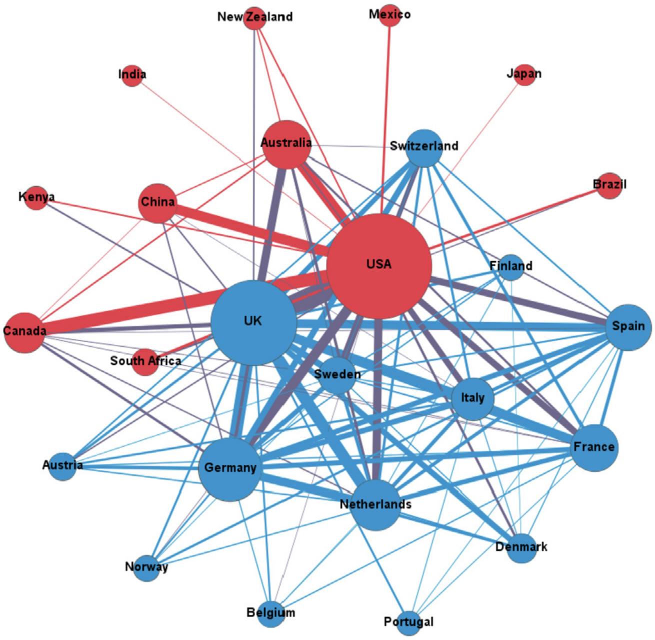

Fig. 3. The collaboration network of the 25 most productive countries during 1997–2017.

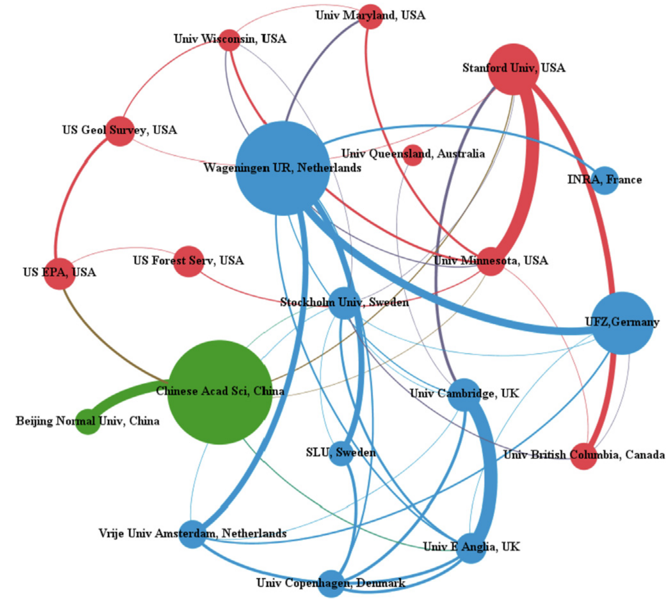

Fig. 4. The academic collaboration network of the 20 most productive institutes during 1997–2017.

Table 3
The top 15 most productive institutes during 1997–2017.

Institute	TP (R)	FP % (R)	SP% (R)	CP% (R)	C%	h-index (R)
Chinese Acad Sci, China	250 (1)	2.58 (1)	0.80 (1)	3.29 (1)	80.40	31 (10)
Wageningen UR, Netherlands	210 (2)	1.21 (2)	0.43 (2)	3.01 (2)	87.62	53 (1)
UFZ[a], Germany	153 (3)	1.06 (3)	0.31 (5)	2.19 (3)	87.58	38 (4)
Stanford Univ, USA	126 (4)	0.79 (6)	0.16 (18)	1.90 (4)	92.06	47 (2)
US EPA, USA	108 (5)	0.95 (4)	0.39 (3)	1.37 (7)	77.78	25 (21)
Beijing Normal Univ, China	97 (6)	0.90 (5)	0.38 (4)	1.21 (16)	76.29	19 (47)
Univ Cambridge, USA	95 (7)	0.44 (22)	0.15 (25)	1.41 (5)	90.53	38 (4)
Stockholm Univ, USA	94 (8)	0.54 (12)	0.15 (25)	1.39 (6)	90.43	36 (6)
Univ E Anglia, UK	92 (9)	0.51 (15)	0.16 (18)	1.34 (9)	89.13	41 (3)
Vrije Univ Amsterdam, Netherlands	92 (9)	0.69 (8)	0.23 (8)	1.28 (12)	84.78	36 (6)
US Forest Serv, USA	92 (9)	0.57 (10)	0.15 (25)	1.36 (8)	90.22	27 (18)
US Geol Survey, USA	91 (12)	0.70 (7)	0.16 (18)	1.32 (10)	89.01	29 (13)
Univ Minnesota, USA	89 (12)	0.46 (19)	0.16 (18)	1.29 (11)	88.76	36 (6)
Swedish Univ Agr Sci, Sweden	87 (14)	0.51 (15)	0.23 (8)	1.19 (17)	83.91	23 (28)
Univ British Columbia, Canada	86 (15)	0.54 (12)	0.16 (18)	1.24 (15)	88.37	30 (12)

TP: total publication and its rank; FP% (R): the ratio and rank of first author publications; SP% (R): the ratio and rank of publications without collaboration; CP% (R): the ratio and rank of publications with collaboration; C%: the ratio of collaboration publications of an institute; h-index (R): h-index and its rank; [a] UFZ: Helmholtz Centre for Environmental Research.

that appeared more than 100 times. Three categories of keywords, research location, type of resources, and methods, were then collected to analyze research trends. As shown in Fig. 7, there are about 1400 keywords referring to research locations, among which 28.9% are European countries. The rest are the USA (22.8%), China (14.3%), Australia (6.1%), UK (5.0%), and other countries.

There were 7182 keywords focusing on types of resources, a quarter of which were ecosystem services. The following were land (22.3%), biomass or biodiversity (16.3%), forest (15.2%), water (11.5%), and others. Fig. 8 represents the time variation (five-year interval) of research focus in types of resources. The frequency of each resource had an upward trend. In terms of ratio, most resources fluctuated with time. Only land showed an increasing trend, and the share of ecosystem services and water decreased over time. Method-related keywords analysis is presented in next section.

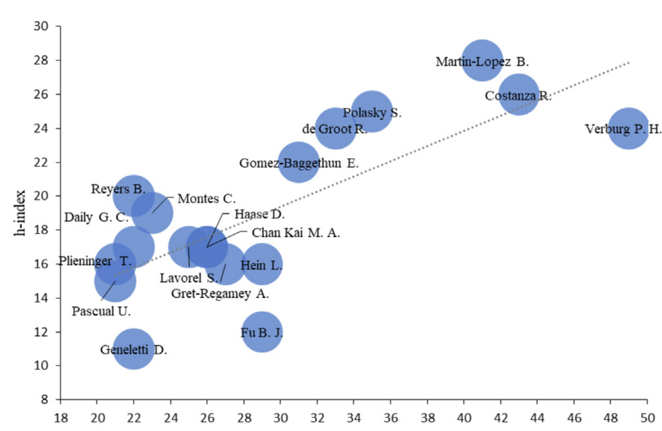

Fig. 5. The performance of the top 18 productive authors during 1997–2017.

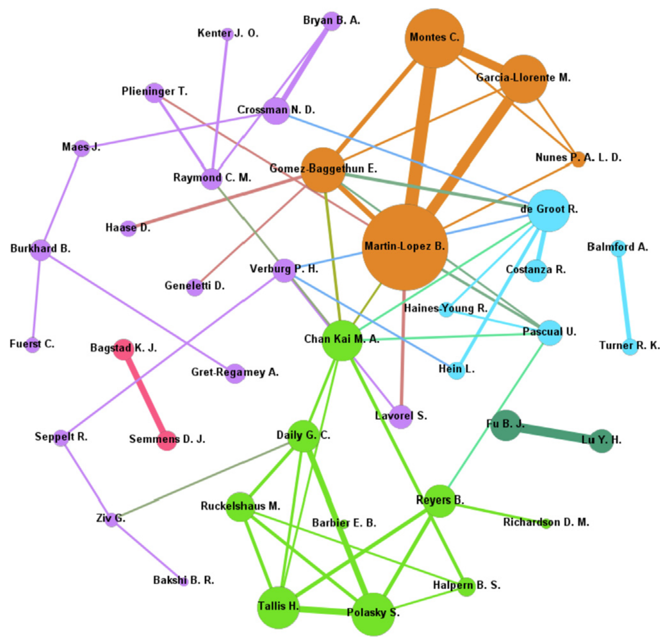

Fig. 6. The collaboration network of authors (TP > 14) during 1997–2017.

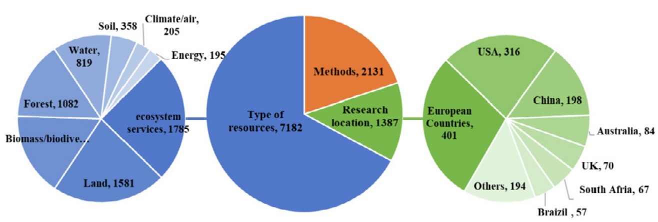

Fig. 7. The distribution of research focus during 1997–2017.

5. Measuring ecological capital: state of the art and trends

Ecological capital contains two components: renewable natural capital stock and ecosystem services. Each part has a variety of frameworks and methods, and the value of ecological capital can be expressed in physical and monetary terms. This section presents the trend of commonly used methods, and summaries the developments of each, including integrated Environmental and Economic Accounting (SEEA), EF, exergy, emergy, and LCA for natural capital accounting, and biophysical and monetary value evaluation approaches for ecosystem services.

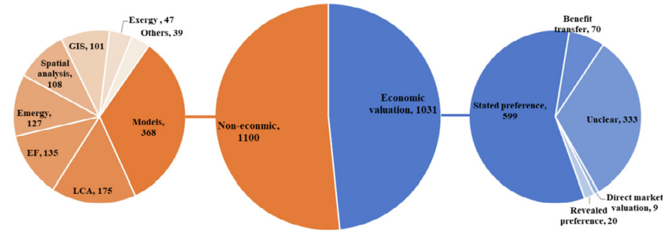

Fig. 9. The application of various methods during 1997–2017.

5.1. Trends

There were approximately 2131 method-related keywords, and their distribution is showed in Fig. 9. Economic and non-economic approaches each accounted for about 50%. The stated preference method was the most popular approach of economic valuation approaches, with 599 occurrences. The contingent valuation method (CVM) and choice experiment were the two most applied stated preference methods, with 292 and 117 occurrences, respectively. In terms of non-economic or biophysical evaluation methods, model-related methods occurred 368 times, including InVEST, SoLVES, and ARIES. LCA took the second position, accounting for 15.9%. The following methods were EF (12.3%), emergy (11.5%), spatial analysis (9.8%), GIS (9.2%), exergy (4.3%), and others.

Fig. 10 reflects the frequency of occurrence and the corresponding ratio of method-related keywords with time. From the ratio perspective, EF was the most popular approach, yet its percentage gradually decreased and currently is almost the least used one. Economic valuation approaches remained a dominant method and their proportion has gradually increased. Presently, it is the favorite approach. The ratio of models and LCA both increased over time and are the 2nd and 3rd used methods in last five years. The share of emergy and exergy had a decreasing trend. Spatial analysis first appeared in 2008 and its ratio has been increasing since then. Another space-related method, GIS has a similar trend. There are growing numbers of studies applying GIS or spatial analysis in measuring ecological capital. de Araujo Barbosa et al. (2015) and Shoyama et al. (2017) summarized the remote sense and modelling approaches and practical cases.

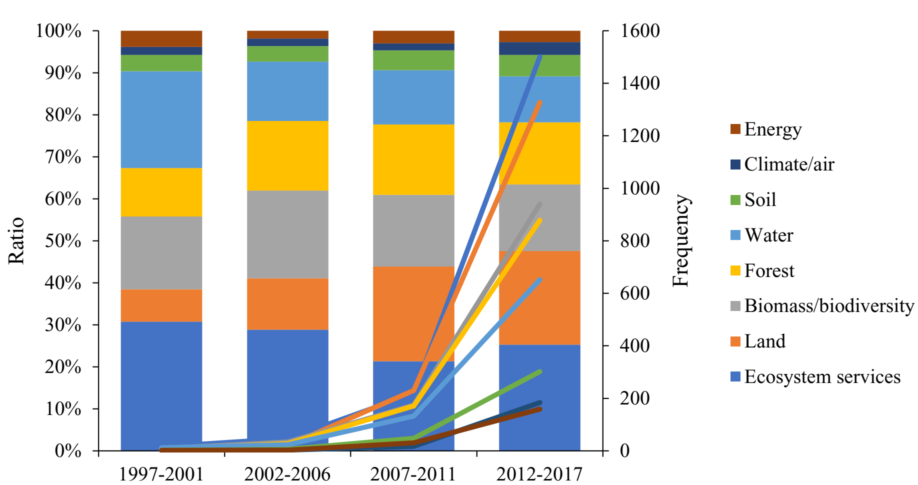

Fig. 8. The time variation of focused types of resources during 1997–2017.

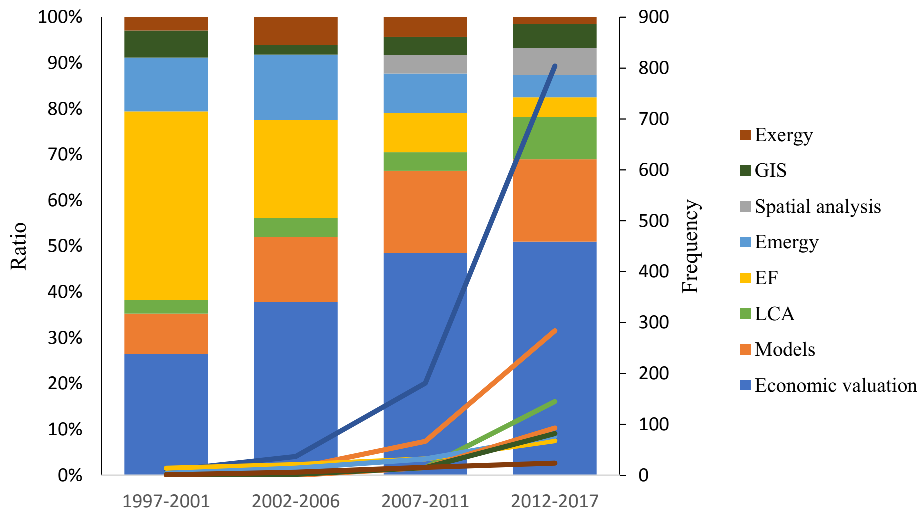

Fig. 10. The time variation of method-related keywords during 1997–2017.

Ecological capital encompasses diverse resources and services, and each of them has a relatively appropriate accounting approach. To evaluate the true value of ecological capital, different methods are needed, and the combined use of methods has become a trend. Reza et al. (2014) explored the possibility of integrating emergy into LCA and calculated the impacts of paved roads on ecosystems. Wang et al. (2019) assessed several key ecosystem services in China through the incorporation of modelling, GIS, and emergy. Fig. 11 represents the combination of various approaches based on their co-occurrence. The size of the nodes refers to the total number of co-occurrence of one method, and the width of the edges indicates their frequency of co-occurrence. These techniques are divided into two clusters by Gephi. The blue cluster represents methods that are usually applied to evaluate natural capital, while the green cluster stands for ecosystem valuation approaches. Models are the most favored approach for integration. InVEST models typically involve GIS inputs and spatial analysis (Goldstein et al., 2012; Arkema et al., 2015). ARIES and SoLVES models often utilize GIS to show the spatial distribution of economic valuation results (Sherrouse et al., 2014; Villa et al., 2014). Emergy, exergy and EF use coefficients to transform into each other, and their values can be treated as inputs into LCA (Zhang et al., 2010b; Raugei et al., 2014). Consequently, these approaches are often combined.

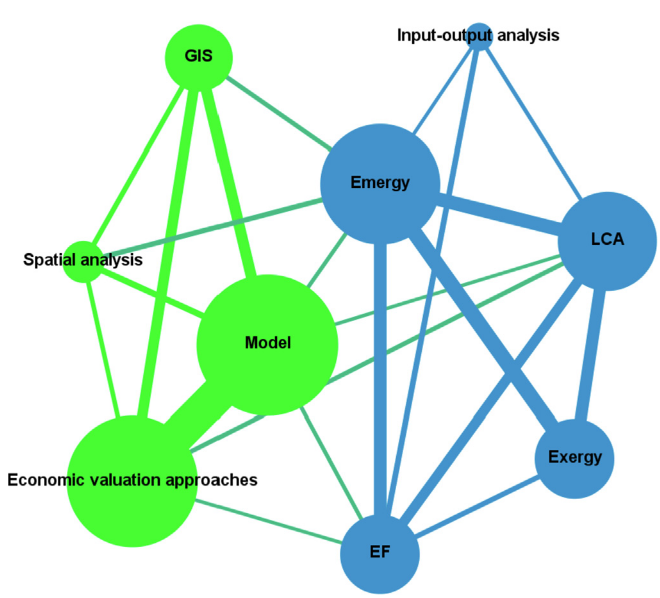

Fig. 11. The co-occurrence of different methods during 1997–2017.

5.2. Natural capital accounting

Natural capital consists of two parts, the stock and flow components. This subsection introduces the common methods used to evaluate the stock part. Ecosystem services valuation approaches are presented in next subsection. The focus of this paper is on ecological capital, so accounting approaches for renewable resources are mainly discussed.

5.2.1. Integrated Environmental and Economic Accounting (SEEA)

The SEEA is a framework for accounting for national natural resources. Natural resources play an essential role in a country's economic development, and thus their stock and flow changes should be documented (Obst et al., 2016). The first handbook of SEEA was released in 1993. It was continuously revised since then, and the latest manual was published in 2012 (Bartelmus, 2014; UN, 2014a). Many nations such as Australia (Obst and Vardon, 2014), Netherlands (Remme et al., 2015) have adopted SEEA framework. The SEEA framework has also been applied to account for specific types of sources, such as water (Borrego-Marín et al., 2016; Pedro-Monzonís et al., 2016) and soil (Robinson et al., 2014). As a satellite account to the System of National Accounts (SNA), SEEA connects the economic system with the environment. However, it is not clear how specific types of natural resources circulate in the socio-economic system. Some researchers constructed input-output database to analyze resource metabolism in society (Wood et al., 2015; Stadler et al., 2018).

One problem with the old SEEA framework is that it separately accounts for different resources. Each type of resources is expressed in its physical value, such as hectares for land resource (Bartelmus, 2014). The revised version incorporated economic valuation methods, so that all categories of resources can be converted into and summed up in monetary value, which helps to facilitate the inclusion of assessment results in decision-making (Galos et al., 2015; Vardon et al., 2016). Another limitation of SEEA is that the indirect value of nature such as climate regulation, water purification and pollination services (Obst et al., 2016) were neglected in the framework. These indirect benefits provide significant support for social and economic development. The SEEA Experimental Ecosystem Accounting (SEEA-EEA) was developed for the valuation of non-market values of nature in 2014 (UN, 2014b). Lai et al. (2018) adopted the SEEA-EEA framework and quantified water-related services in Finland. La Notte et al. (2017) conducted a case study of assessing the value of the nitrogen retention service for Europe.

5.2.2. Ecological footprint

The EF is a method proposed in 1990s to measure the land demand of human activities against the supply of the earth (Wackernagel and Rees, 1997; Wackernagel et al., 2018b). If the demand exceeds supply, the targeted region is subjected to an ecological deficit (Collins et al., 2018). After more than 20 years of development, the EF has been gradually improved and widely used in different geographic scales (Wackernagel et al., 2018a). The Global Footprint Network (GFN) established the national footprint accounting (NFA) framework and publishes national footprint results at intervals. According to their latest research, the footprint of humanity greatly surpassed the capacity of earth, with an additional 0.7 earth needed for the future (Lin et al., 2018). EF has become a favorite tool to assess the ecological supply and demand at different geographic scales. Galli et al. (2017) applied input-output models to assess the food sector's ecological footprint of 15 Mediterranean countries. Rugani et al. (2014) accounted for the change of ecological capital in Luxembourg from 1995 to 2009 through hybrid input-output models. Baabou et al. (2017) used a top-down EF approach and estimated the ecological footprint of 19 Mediterranean cities.

Some aspects of the EF have been often criticized. On one hand, the equivalence factor used in the conventional EF ignores the multiple uses of land (Galli et al., 2016). Venetoulis and Talberth (2008) proposed calculating the equivalent factor based on net primary productivity (NPP), which considers land occupation of other species. On the other hand, apart from land and carbon sequestration services, it does not take into account other resources and services. Some scholars have proposed the water footprint (Fang and Heijungs, 2015; Fang et al., 2016) and material footprint (Wiedmann et al., 2015) to evaluate other kinds of resources. Mancini et al. (2018) examined the potential of using the EF to value ecosystem services and compared the results against economic approaches. In addition, Niccolucci et al. (2009) presented a three-dimensional ecological footprint (^{3D}EF), which can better express the deficit between the human demand and supply of earth. Cases that utilized the applied the ^{3D}EF model can be found in (Fang et al., 2018; Yang and Hu, 2018).

5.2.3. Exergy analysis

Exergy is generally understood as the available energy that can be used (Zhang et al., 2010b). In principle all kinds of resources can be transformed into exergy. One advantage of exergy is presenting the value of various resources with one metric (Zhang et al., 2010b; Zhong et al., 2016). Exergy analysis can help to improve the efficiency of a process. It is typically used to assess the inputs of non-renewable resources, such as metal ores, fossil fuels and others. Valero et al. (2018) applied exergy to assess the degradation of mineral resources. Some researchers suggest considering ecological resources and processes in exergy analysis, such as ecological cumulative exergy consumption (Ukidwe and Bakshi, 2007) and eco-exergy (Jørgensen, 2010; Zhang et al., 2010a). These methods are quite similar to emergy analysis (Zhang et al., 2010b; Lu et al., 2015), which is illustrated in the next section.

5.2.4. Emergy analysis

Emergy analysis was proposed in the 1990s by the prominent ecologist H.T. Odum (Odum et al., 2000; Chen et al., 2016). Emergy theory views the earth as a system and its primary energy source is solar energy. All kinds of resources and ecological processes are formed and driven by solar energy (Zhang et al., 2010b; Chen et al., 2016). Accordingly, all goods and services can be converted into solar energy equivalents based on the solar energy they consume. The conversion factor is defined as transformity and determined by the total solar energy absorbed by the earth. The annual total solar energy is the baseline, whose assessment is at the core of emergy theory (Brown et al., 2016). Scholars in the emergy community have continuously updated the baseline. The latest result is presented in (Brown et al., 2016; Campbell, 2016).

Compared to other methods, emergy has three advantages. First, various forms of materials can be expressed by one unit – solar emjoules (sej). Many studies have applied emergy to assess the total value of different types of resources. Vassallo et al. (2017) estimated the value of marine ecosystems. Wang et al. (2016) assessed the natural capital change in the Yellow River Delta region in China by the integration of GIS and emergy. Mellino et al. (2015) mapped the spatial distribution of the key natural capital in the Campania region, as well as man-made assets. Secondly, emergy value can be converted into monetary terms through the emergy-to-dollar coefficient (Campbell and Tilley, 2014a). Monetary value is generally easier to be understood for by decision makers. Finally, emergy is appropriate to evaluate some ecosystem services, including provisioning, supporting, and regulating services (Coscieme et al., 2014). Wang et al. (2019) accounted for the value of several key ecosystem services in the Yellow River Delta region in China, such as soil retention, water provision and carbon sequestration. Other applications of emergy for ecosystem services evaluation can be found in, forest ecosystem services (Campbell and Tilley, 2014b), water and carbon ecosystem services (Watanabe and Ortega, 2014), and flood control (Chang and Huang, 2015). Nevertheless, cultural services cannot be valued through emergy.

5.2.5. Life-cycle assessment

LCA is a common tool for decision-making, which accounts for the environmental impact of a product or service throughout its life-cycle (ISO, 2006). LCA has two limitations in assessing natural capital. On one hand, conventional LCA primarily considers the consumption of abiotic resources, such as fossil fuel, metal and non-metal minerals, and impacts on human (Dewulf et al., 2015; Schaubroeck and Rugani, 2017). Improvements have been made to assess the consumption of renewable resources and ecosystem services, as well as impacts on other species and the natural environment (Chaplin-Kramer et al., 2017). Müller-Wenk and Brandão (2010) developed a framework to calculate the land-use impact on climate regulation services through LCA. Koellner et al. (2013) established the LCA guidelines to assess the land-use impact on biodiversity and ecosystem services. Other methods to account for ecosystem services with LCA can be found in: water-related services (Saad et al., 2013) and soil erosion service (Quinteiro et al., 2014). Liu et al. (2018a, b) developed a conceptual framework to evaluate a variety of ecosystem services with LCA. Pizzirani et al. (2014) even explored the possibility of assessing cultural values with LCA. Nevertheless, most of these studies are at a preliminary stage, and more efforts are needed to incorporate renewable resources and ecosystem services into LCA.

5.3. Ecosystem services valuation

"Ecosystem services" is the flow component of ecological capital. Since ecological capital is renewable, it is difficult to directly account for its value. Researchers typically evaluate the value of its flow part as a proxy of ecological capital. This section reviews ecosystem services assessment approaches, including biophysical and monetary approaches.

5.3.1. Biophysical value evaluation approaches

Ecosystem services are produced and maintained by ecological structures and processes (MEA, 2005; Costanza et al., 2017). Some services can be measured through simulation models of corresponding ecological processes. InVEST is a software that integrates many ecosystem service models and has been widely applied (Goldstein et al., 2012; Guerry et al., 2015). Fu et al. (2014) evaluated the ecosystem services provided by hydropower plants in the Zagunao River Basin. Arkema et al. (2015) estimated the value of ecosystem services provided by marine ecosystems in Belize. Hoyer and Chang (2014) modeled water related ecosystem services of a river basin, such as water yield and water retention. Grafius et al. (2016) accounted for several land related ecosystem services in urban areas with carbon storage, soil retention and pollination models. Shoyama et al. (2017) summarized cases that used modelling approaches in the Asia region.

There are some limitations with modelling approaches. First, the relationship between some services and corresponding processes remains unclear (Costanza et al., 2017). These models need to be optimized. Efforts have been made in model optimization, such as the soil retention model (Hamel et al., 2015). A second shortcoming is that it requires large ecological data inputs, such as water, soil, air and geological information. These inputs require considerable field research, which is typically expensive and even difficult for some regions. Therefore, some studies use default values as substitutions. Third, cultural values cannot be measured through InVEST. Models such as SoLVES (Sherrouse et al., 2014) and ARIES (Villa et al., 2014) were developed to assess some cultural services. Nevertheless, the raw data inputs of the two models are obtained through economic methods.

5.3.2. Economic valuation approaches

Economic or monetary valuation approaches refer to a series of methods that values ecosystem services through economic means (Häyhä and Franzese, 2014; Costanza et al., 2017). It is the primary technique in ecosystem services evaluation. According to market settings, monetary valuation methods can be classified into three groups: (1) direct market valuation methods, (2) revealed preference approaches, and (3) stated preference approaches (TEEB, 2010; Costanza et al., 2017). Each category can be further divided, and precise classification can be found in (MEA, 2005; TEEB, 2010). There are so many types of ecosystem services, and each of them has relatively appropriate approaches (Díaz et al., 2015; Pascual et al., 2017). In general, provisioning services are better to use direct market valuation methods, while cultural services are commonly assessed with revealed or stated reference approaches (Häyhä and Franzese, 2014; Kenter et al., 2015).

Monetary methods have two strengths. First, the result is presented in monetary term, which can be better understood by decision makers (Costanza et al., 2017). However, some scholars hold a different view and argue that economic value is not objective and cannot reflect the true value of nature, because these methods heavily rely on human preferences (Schröter et al., 2014). The dependence on human preferences can in fact be viewed as an advantage, because this is how the cultural services are valued (Kenter et al., 2015). For example, Van Berkel and Verburg (2014) estimated the cultural value of an agricultural landscape through the willingness to pay (WTP) exercise. Castro et al. (2014) applied CVM to assess the value of several landscape interests in Spain and compared the results with biophysical valuation in order to investigate the disparity between the supply and demand of ecosystem services. Questionnaires are an expensive approach in terms of cost and time. Some researchers suggested adapting empirical valuation results from one place or time to another. This technique is defined as benefit transfer and has been broadly adopted. For example, the global value of ecosystem services was estimated through benefit transfer (Costanza et al., 2014). Frélichová et al. (2014) constructed a database that includes 190 values of ecosystem services and used the benefit transfer technique to estimate the ecosystem services value in Czech Republic. Chaikumbung et al. (2016) synthesized more than 1400 wetland ecosystem services valuation cases and calculated the benefit transfer function for wetland. Rchiardson et al. (2015) and Costanza et al. (2010) summarized each method's applicability in using benefit transfer.

6. Challenges

Ecological capital provides vital support for human development. Accounting for changes of its value helps achieve effective management of ecological capital. After 20 years' development, many achievements have been obtained, yet there are still some challenges that need to be overcome for further progress (Guerry et al., 2015; Costanza et al., 2017). This section presents the three primary challenges in ecological capital accounting.

The first barrier is to establish a standard framework for ecological capital accounting (Díaz et al., 2015; Pascual et al., 2017). The authors of this paper define ecological capital as the combination of renewable natural capital stock and ecosystem services. Both fields have various methods, and each approach has its own advantages and limitations in assessing specific types of ecological capital (Kenter et al., 2015). For example, different kinds of resources or services can be expressed in one metric with EF, emergy and exergy. Non-economic approaches including SEEA, EF, emergy, exergy, LCA and InVEST, are not appropriate to assess the cultural and social values of nature (Zhang et al., 2010a,b; Christie et al., 2012). To facilitate decision-making, monetary valuation approaches are more appropriate as their results are presented in monetary terms (Costanza et al., 2017). However, the objective of economic approaches is controversial as most of them rely on human preferences (Schröter et al., 2014). In practice, which method to choose depends on the targeted types of ecological capital. A standard framework can help to decide the most appropriate approach, as well as facilitate comparison of different cases (Costanza et al., 2017; Pascual et al., 2017).

Another challenge is the need to consider the transfer or transport of ecological capital in an open and complex system. Currently most studies assess ecological capital without considerations of its movement. Many types of renewable resources, such as food and water, are transported to different locations through trade. These kinds of ecological capital usually associated with industrial products, can be referred as virtual ecological capital. When assessing a territory's ecological capital, it is insufficient to only consider its native ecological capital. Import and export flows should be considered as well. Input-output analysis is a potential tool to investigate this issue (Wood et al., 2015; Stadler et al., 2018). Furthermore, most ecosystem services have spatial limitations in delivering benefits. It is important to explore their serviceshed.

The last challenge is how to better incorporate ecological capital assessment into the decision-making process (Schaefer et al., 2015; Schultz et al., 2015). From the supply side, ecological capital is produced and maintained by ecosystems, and an increase of one desired service can result in a decrease of other desired ones. The trade-offs among various resources and ecosystem services should be scrutinized (Howe et al., 2014; Lu et al., 2014). From the demand side, people value nature in different aspects. For example, some people cherish the conservation value of natural land, while local farmers prefer to convert them into agricultural land for production. Opinions of various stakeholders shall be included in relevant policy-making (Mouchet et al., 2014). In addition, the relationship between supply and demand of ecological capital should be further investigated (Bagstad et al., 2014).

7. Conclusion

In 1997, two prominent publications stimulated an explosion of research interests in valuing nature. In the 20 years of development, some new concepts such as ecological capital emerged. The authors of this study suggest defining ecological capital as the integration of renewable natural resources (renewable natural capital stock) and ecosystem services. This definition clarifies its conceptual relationship with the two existing concepts: natural capital and ecosystem services.

Various methods have been applied in valuing nature. This study used bibliometric methods to analyze the research trends. The results showed that the total publications have rapidly grown, from 6 publications in 1997 to 1151 in 2017. The most productive journal, country, institute, and author were *Ecological Economics*, USA, CAS, and Dr. Verburg respectively. Chinese research organizations and scholars had a relatively poor performance in h-index. Lack of international cooperation is a possible reason. Keywords analysis showed that the most concerned types of ecological capital were ecosystem services and land resources. In terms of assessment methods, the share of non-economic approaches has decreased over time. EF was the favorite method in the early stages, yet it has become less and less popular. Economic valuation approaches have remained as a dominant approach and have become the most applied ones in last five years. Some new techniques have emerged, such as dynamic modelling: InVEST, ARIES, and SoLVES. The integration of GIS technology helps to visualize the spatial distribution of ecological capital. The combined use of several methods has gained increasing academic attention, which can overcome the limitations of using single approach.

Despite so many achievements, there are three main challenges that need to be overcome for further development. The first barrier is the need to establish a standard framework. Each approach has its own advantages and limitations in assessing specific types of ecological capital. A standard framework can help to decide the most appropriate approach. A second challenge is the need to consider the transfer of ecological capital between different regions. Multi-regional input-output tables (MRIO) is a potential method for investigating the transportation of ecological capital. Finally, to better support decision-making, the following three issues need be further examined: the trade-offs among various kinds of ecological capital, preferences of different people, and the disparity between the supply and demand of ecological capital.

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