Emergy-based Evaluation of Ecosystem Services: Progress and Perspectives

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Abstract: This review investigates the potential of the emergy analysis (EMA) as a new perspective and approach to the worldwide used ecosystem services (ESs) framework to quantify and analyse the potential benefits people obtain from ecosystems. Based on bibliometric analysis method, the study systematically investigates the latest developments and issues of application of EMA in ESs in conjunction with thematic analysis. The analysis includes an evaluation of its application in nine different types of ESs. The results show that the number of publications and cited frequency in this field grows exponentially. The application of emergy analysis is relatively well established for agriculture, urban, industrial and wetland ecosystems, but the application for forest, grassland, costal, marine and other ecosystems has yet to be advanced. Finally, current limitations and future research directions, including policy and strategy are further discussed. This study found that addressing incomplete data and parameterization, improving the accuracy of emergy accounting for different ecosystems in changing environments, and combining emergy with other methods and policy scenarios remain the long-term directions in the future related studies. These results can pave the way for further use of EMA in ESs research and provide guidance for decision-makers in the future.
Keywords: Ecosystem services, Emergy, Bibliometric analysis, Thematic analysis, Web of science

1. Introduction

Ecosystems are being severely damaged by human activities as a result of urbanization and rapid population growth. To sustain human society’s development, it is necessary to effectively manage nature as an important capital or asset [1,2]. The question of how to account for and assess the value of nature is an important research topic for scientists from all over the world. Already in the year 1970, the Study of Critical Environmental Problems (SCEP) published "Man's Impact on the Global Environment", which first introduced the concept of ecosystem services (ESs). The 1990s saw the rapid development of ESs research [3,4]. In 2001, The Millennium Ecosystem Assessment (MEA) was the first major global project launched by the United Nations to provide a comprehensive and integrated assessment of ecosystems in relation to the links between ESs and human well-being. Since then, the assessment of ESs has received global increasing attention.

ESs are often defined as the benefits that humans derive directly or indirectly from ecosystems [5]. The sustained provision of ESs is the basis for sustainable development of society and nature [3]. Policy makers and stakeholders consider accounting for ESs as an essential tool to inform and support economic and environmental policy [6]. A wealth of study has conducted research on ESs from different disciplinary fields over the past decades, and many studies on the evaluation of ESs are based on material [7,8] and monetary methods [9–11]. Quantitative empirical analysis methods are based on a material quality perspective, including exergy (i.e. useful quantity that stems from the Second Law of Thermodynamics, which is the basis for evaluating fuels and resources, process, device, and system efficiencies, dissipations and their costs), the ecological footprint, life cycle analysis, and material and energy flow analysis, etc. [12–14]. Monetary valuation is the assessment of ESs in terms of economic value, such as willingness to pay, market prices and replacement cost methods. However, these two methods are certain limitations although they have their own advantages. The physical quality approach is based on in situ observations, remote sensing interpretation, model simulations, and survey and statistical analysis to obtain physical quantities related to the supply and consumption of different services at the required spatial and temporal scales [15]. Its assessment results are relatively objective and accurate, but do not facilitate comparisons between different services. The monetary approach can facilitate comparison between different services and socio-economic capital using the same unit, but some service types are difficult to value and are subject to market fluctuations, geographical factors and human preferences, making the assessment highly subjective [16].

The theory and methodology of emergy was developed by H. T. Odum in the 1980s [17] and has been becoming an important tool in the field of environmental accounting. It has been widely used in research areas, such as ESs, ecological assets, ecological carrying capacity and regional sustainability assessment. It uses emergy as a measure, converting all forms of energy into the same unit of comparison: the emergy, providing a common scale for measuring and comparing all forms of energy. Emergy analysis

(EMA) can also unify and quantify ecosystems and economic systems, and plays an important role in the emerging interdisciplinary field of ecological economics, which needs to be enriched by scientific and quantitative research methods. EMA provides a new perspective and approach to ESs analysis, especially, which can strengthen the understanding of ecosystem services flow in linking human and nature, enabling a more in-depth portrayal of service flows, which also allows us to compare different types of energy, resources, products, services flowing or stored in a system in the same energy category unit (solar energy) in the same time. In addition, the EMA assesses the contribution of ecosystems to human society from the perspective of natural ecosystem contributors rather than human preferences and contingencies [18], to some extent bridging the gap between the physical and value quantity approaches in accounting for ESs. As a result, Emergy-based assessment on ESs has evolved rapidly in recent years to encompass a wide range of ecosystems, including agricultural [19,20], industrial [21,22], urban [23,24], and wetland systems [25,26]. Given this, it is necessary to carefully examine the application and problems of EMA of ecosystems over the last decades. However, there are only a few review papers that address the application of the emergy theory to ESs. Nadalini et al. [14] reviewed research on emergy-based methodology of ESs and made a comparison among EMA and other assessment methods. However, research on related topics lacks sufficient breadth and depth, it remains unclear to what extent the evaluation of ESs has been developed on the base of emergy theory. Our paper goes beyond analyses of EMA on different types of ESs providing an overview on current limitations, which might help us better understand research challenges and future directions of this topic.

To fill the gap, this research systematically summarizes the current status of research at the interface between emergy and ESs, strengths, weaknesses and scope of application, and then present limitations and future developments. This work is poised to provide an overall perspective on the related research progress and reveals the limitations in the application of the EMA in different ecosystems, which can pave the way for further use of EMA in ESs research and provide guidance for decision-makers in the future.

This review is organized as follows. Theoretical background of EMA and its general methodology are introduced in section 2. The applied data and methods for bibliometric analysis of publications are described in section 3. Section 4 presents the results of bibliometric analysis, including the basic analysis of publications, cooperation analysis and keywords analysis. The application of emergy on different types of ecosystem services are presented in section 5, whereas section 6 discusses the current limitations, along with recommendations for future studies and conclusions in section 7.

2. Theoretical background and methodology overview

2.1. Theoretical background

The flow and transformation of energy is the basis of any living activity, the flow and storage of energy within an ecosystem follows the laws of thermodynamics. The first law of thermodynamics holds that energy cannot be created or destroyed, but can be transferred from one to another. Further explanation is that the energy flowing into the system is equal to the sum of the variables that store energy within the system and the energy flowing out of the system. The second law of thermodynamics states that the energy transformation process is decreasing and that every transformation of energy is accompanied by a partial dissipation of energy. In addition, the flow of energy within the system is governed by the "maximum power principle", that is, the system needs to be designed and organized in such a way that energy is quickly obtained and fed back in order to obtain more energy and form a dynamic system, thus ensuring the efficient conversion and use of energy within the system [27].

Ecological energetics is considered to be the origin of emergy analysis. It is a science that studies the rules of energy flow, transfer and transformation of ecosystems and complex ecosystems. This research began in the second half of the 19th century [28]. Since then, a wide range of research has been carried out on this subject by describing, accounting for and analysing different vegetation communities and ecosystems, and important concepts such as 'energy metabolism', 'the law of tenths', and 'energy exchange' have been put forward, and a series of energy analysis models have been developed [29-31]. Thereafter, a relatively complete discipline system was initially formed., H.T. Odum has conducted systematic and in-depth research on ecological energetics since the 1950s, proposing a series of new concepts and pioneering theoretical concept, including energy system, energy quality, energy-quality chains, embodied energy and energy conversion rates. This is the first time that the intrinsic relationship between energy flow, information flow and economic flow has been linked together. However, energy analysis can only be applied to the analysis of similar categories of energy (e.g. mechanical kinetic energy, biological energy, etc.). Different categories of energy come from different sources and have fundamental differences in quality and value that cannot be directly added or subtracted and compared, which makes energy analysis difficult. In the late 1980s, Odum further developed a new scientific concept and metric, 'emergy' [17].

Emergy is defined as the total amount of available energy needed directly and indirectly to produce a product or service [32]. Unlike the physical concept of 'energy', which ignores the fundamental differences in the quality and value of energy of different nature and origin, 'emergy' reflects the different sources of various forms of energy and material, and provides a unified yardstick standard for measuring and comparing different energy and ecological flows [33]. Since solar energy is the initial source that drives the flow of matter and energy in natural ecosystem processes and socio-economic activities, it is used as a uniform measure of effective energy and expressed as solar emjoules, abbreviated as sej. [17]. Through the emergy transformity, the energy, resources and products, and even items such as labor and services of different systems can be unified into emergy, and the input and output flows can be directly compared to quantify the economic benefits and environmental impact of a system, and access the overall sustainability of a system [34]. The specific meaning is the amount of emergy contained per unit of energy (J) or substance (g) of a certain category. The higher the emergy transformity, the higher the energy quality of the energy and the higher the rank in the system. The application of emergy theory allows for a more scientific measurement of the true value of resources, the environment and economic activities within an ecosystem and the relationship between them.

2.2. Methodology overview

The flow of ESs from ecosystems to human society is a gradual process, linking the biophysical structure of ecosystems and the socio-economic or cultural benefits of human well-being in the form of a production chain, forming a 'supply-flow-demand' system [35]. Fig. 1 depicts the processes the formation process ESs and the interactions with human society. It presents the structure diagram of the analysis ecosystem, which consists of input module, process module, output module, and consumption module. The input component is the various types of energy input to the system from the outside world (i.e. nature and human society) and is the source of energy for the system to operate, produce and provide services [36]. The process module is the process of interaction between the biosphere and its environment (atmosphere, hydrosphere, cryosphere and lithosphere) through material transport, energy conversion and information transfer processes. The output component refers mainly to the effective energy, logistics or information flows that are exported from the system, i.e. the various services that the ecosystem provides to human society. Human well-being is dependent on ecosystem services, but at the same time, irrational human activities can destroy ecological functions and thus lead to a deficit or even loss of ecosystem services. Thus, the two interact with each other. The consumption module refers to the dissipation of effective energy by consumption and no longer has the ability to do work.

Fig. 1. The concept map of the emergy system diagram.

The flow of energy in an ecosystem is from a high quantity but low quality level (e.g. solar, wind, rain) to a low quantity but high quality level (e.g. biomass, electricity), which ultimately serves human survival activities. Fig. 2 demonstrates the generation and transmission of emergy. The unit of emergy is the emjoules, which represents one kind of energy consumed in transformations. Producers receive different types of matter and energy (i.e., sunlight, wind, rain, fuels, deep heat and human activities), which are converted into another energy flow by interaction. Part of this emergy is exported to serve the ecosystem and provide benefits to human society; the other part should be stored in the system to maintain a virtuous cycle. In this process, a small amount of chemical potential energy is also released. This explains the complete process of input, conversion and output of all types of energy for ESs. The emergy analysis of ecosystems can be generally divided into six steps [33]:

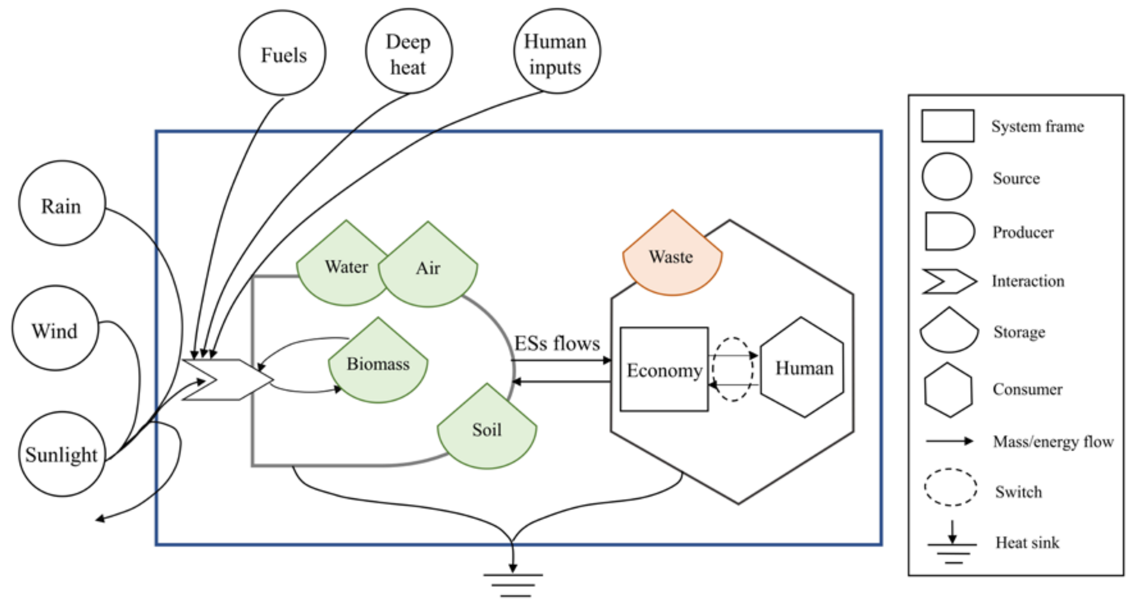


Fig. 2. Emergy system diagram of the ecosystem.

Step 1: Construct a classification system for ESs based on different ecosystem types and identify the types of respective services;
Step 2: Draw an emergy flow diagram based on Odum's "Language of Emergy Systems" legend, summarizing the relationship between the various components of the object of research and the environment, forming an emergy diagram of the system in terms of the main components and their interrelationships, as well as the flow directions of energy, logistics and currency flows;
Step 3: List the main energy sources (inputs) and output items of the system, including local resources, imported non-renewable energy sources, imported goods and labour, and outputs, and then establish a database;
Step 4: Calculate energy flows of each types of resources, expressed in J; the material in g; and economic flows in $;
Step 5: Convert various types of energy and material into emergy units, that is, the amount of various energy materials * corresponding emergy transformity, and calculate the corresponding emergy currency value;
Step 6: combined with indicator analysis, system simulation, etc., comprehensive analysis and application of sustainable development of the system can be carried out to provide scientific basis for formulating system management, control measures and development strategies.

3. Methods and data

Existing research on emergy-based application on ESs was systematically reviewed and analyzed to identify current knowledge gaps and discuss future directions. Fig. 3 illustrates the main review process in this study. Specifically, the first step is to collect data and create a database to identify the number of publications and related information. The second step is data analysis, which includes bibliometric analysis and thematic analysis to illustrate the progress in the application of emergy in ESs through quantitative and qualitative methods, respectively. Finally, gaps in current research and future research directions are discussed.

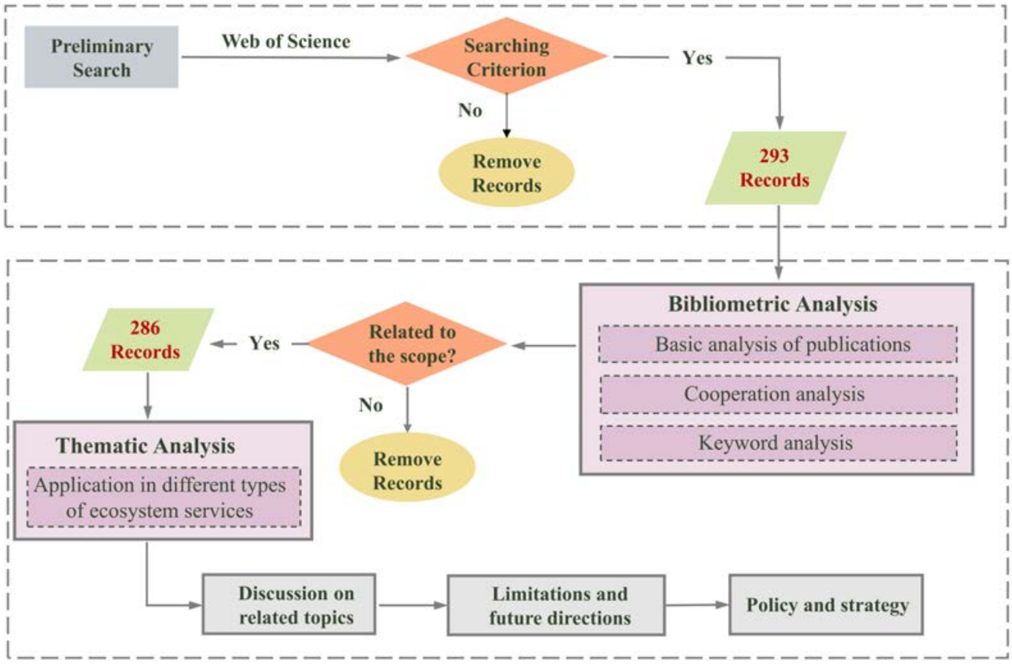


Fig. 3. Process of systematic review.

3.1. Data sources

Web of Science (WoS) was used for searching scientific literature, which covers a large number of publications that are published from 1900 to the present [37,38]. The keywords used for searching the literature in the WoS database were as follows: Topic = “emergy” and “ecosystem services”, and Language = “English”. The searching data period was set between 1995 to 2022, because the boost using emergy analysis in ESs research began in 1995. For the literature search, this study limited the document type to “article” and “review”, while report and conference proceedings are not covered to avoid grey literature and the duplication of collections of similar research. Various information was extracted from these documents to create a database for bibliometric analysis, including title, year of publication, author, affiliation, abstract, keywords, journal source and citation information.

3.2. Bibliometric analysis

Bibliometrics provides a systematic method of quantitative analysis of academic publications [39]. It can visually show the statistical results of academic documents by using bibliometrics tools such as CiteSpace, VOSviewer, Bibliometrix, etc [40]. CiteSpace is a miscellaneous shareware software developed by Chaomei Chen of Drexel University, which is among the well-known and widely used to analyse bibliometric data [39,41]. It is a very useful visual analysis tool in scientific citation analysis, with identifying and displaying new trends and developments in scientific literature [42]. CiteSpace software provides structural and temporal analysis of literature information retrieved from WoS to create various networks, including cooperation networks, author co-citation networks and bibliographic co-citation networks. In addition, it can also provide timeline information on the occurrence of hot keywords. In this study, CiteSpace 6.2 software is used to perform the bibliometric analysis, including basic analysis of publications, cooperation analysis and keywords analysis.

3.3. Thematic analysis

Thematic analysis is used to analyse each content of all the records identified from the bibliometric statistics. Thematic analysis can be used to identify, classify and analyse themes in detail and is currently applied in a wide variety of qualitative research contexts [43,44]. According to the process of thematic analysis, phase one is familiarisation with data. This step has already been done during the bibliometric process by exporting the relevant publications in WoS. Phase two is generation of initial codes, in which we carefully read 293 papers and deleted the irrelevant records. Seven papers were found that were not relevant to this research and in which the term “emergy” was merely mentioned but did not actually refers to ES. Therefore, 286 publications (i.e., research papers and review papers) were finally selected and encoded here. Phase three is searching for themes, where the codes were sorted into ten distinct themes, all of which were extracted with relevant coding information. Phase four is defining themes, where each theme is defined and named. Phase six is analysis and writing up. This step will be completed in two stages, providing a short description and assessment of each theme on the one hand, and discussing research gaps and future directions on the other.

4. Bibliometric analysis of publications

4.1. Basic analysis of publications

In this chapter, the basic characteristics of retrieved publications in the field of

EMA and ESs research are analyzed. The annual number and cited frequency of publications, the source of the publication, and the most highly cited publications will be considered.

4.1.1. Analysis of annual publications

The change of research topics year by year and the future development trends can be reflected in the number of published papers. Fig. 4 represents the overall number of publications and cited frequency of selected samples from 1995 to 2022, which shows an exponential growth of the number of papers on using emergy analysis for the assessment of ESs. The average annual number of publications during the study period is 10.5. From the perspective of the number of published papers, the academic research in this field from 1995 to 2008 can be considered as its initial stage, with relatively low annual number of publications. From 2006, the number of published papers showed a fluctuating upward trend, and then reached the peak in 2019 (36 papers), with an annual growth rate of 13.3%. Meanwhile, the cited frequency of the research rises from 3 in 1997 to 1348 in 2022, with reaching the peak in 2021 (1392).

Fig. 4. Publication number (PN) and cited frequency (CF) of articles published during 1995–2022.

The type distribution of 293 publications is shown in Fig. 5. Among these publications, just two main publication types are collected, with research articles accounting for 94.5% (n=276), while review articles account for only 5.5% (n=16).

Fig. 5. The distribution of type of publications.

4.1.2. Reference sources

Emergy-related publications had been published in 90 different journals from 1995 to 2022. Table 1 shows the top ten most productive journals in the related field. All these journals can be considered as mainstream in the field of ecosystems, environmental assessment, and sustainable development. Among them, *Journal of Cleaner Production* was the most productive and influential journal, with the highest numbers of publications and impact factor (IF). *Ecological Modelling* published 37 papers in this research field and it ranked the second among all the journals, followed by *Ecological Indicators* (NP=30), *Sustainability* (NP=16) *and Ecosystem Services* (NP=11). Specifically, *Ecological Engineering* was the first journal to publish papers in this field, with the year of 1995. This is mainly because these are all international, interdisciplinary journals that focus on environmental, sustainability research and practice, and aim at describing ecological processes through mathematical models and system analysis.

Table 1

Top ten publication sources.

Rank	Journal	NP	IF	Start year
1	*Journal of Cleaner Production*	47	11.072	2006
2	*Ecological Modelling*	37	3.512	1998
3	*Ecological Indicators*	30	6.263	2007
4	*Sustainability*	16	3.889	2014
5	*Ecosystem Services*	11	6.91	2014
6	*Science of the Total Environment*	11	10.754	2011
7	*Environmental Science and Pollution Research*	9	5.19	2014
8	*Ecological Engineering*	8	4.379	1995
9	*International Journal of Environmental*	6	4.614	2017

	Research and Public Health			
10	*Journal of Environmental Management*	5	8.91	2003

Note: NP: Number of publications; **IF:** Impact factor.

Fig. 6 shows the co-citation network of the cited reference. It is well-marked that the biggest node is *Ecological Modelling,* which revealed that it is the most popular journal in the term of cited numbers with 267 times. In addition, papers in this field have gradually been cited in well-known journals during the recent years, including *Energy*, *Land Use Policy*, *Renewable and Sustainable Energy Reviews*, *Applied Energy*, etc. This indicates that the peer-acceptability of the application of emergy to the valuation of ESs have been increasing over the past years. This also indicates that the research field was gradually coming to the attention of more cross-disciplinary research.

Fig. 6. Distribution of cited journals on application of emergy on ESs during 1995–2022. The size of a circle is in proportion to the number of citations to the journal. The colors of the rings of a circle correspond to the respective year. The flows represent the network of journals that cite each other. The legend on the left indicates the year.

4.1.3. Highly cited publications

Table 2 provides the information of the top ten most cited publications in 1995-2022. As is shown in the Table 2, these papers mainly focused on the emergy theory, the development of emergy methods and the application of emergy. Among these publications, “Embodied energy analysis and emergy analysis: A comparative view” by Brown and Herendeen is the most cited paper so far in the field related to emergy and ecosystems, with a total number of citations (TC) of 385. In addition, we found that the one titled “Effects of River Impoundment on Ecosystem Services of Large Tropical

Rivers: Embodied Energy and Market Value of Artisanal Fisheries" ranked the fourth among all papers. This paper belonged to the field of emergy application in ecosystem evaluation. It is obvious that in recent years, the practical application of emergy and the combination of study cases is gaining more and more attention.

Table 2

Top ten highly cited publications related to ecosystem services and emergy research

Rank	Title	Reference	Country	Source	Type	TC	AC
1	Embodied energy analysis and EMERGY analysis: A comparative view	[45]	USA	*Ecological Economics*	Article	385	14.8
2	Promise and problems of emergy analysis	[46]	Columbus	*Ecological Modelling*	Article	261	14.5
3	A modified method of ecological footprint calculation and its application	[47]	China	*Ecological Modelling*	Article	233	13.7
4	Effects of River Impoundment on Ecosystem Services of Large Tropical Rivers: Embodied Energy and Market Value of Artisanal Fisheries	[48]	USA	*Conservation Biology*	Article	184	14.2
5	Accounting for Ecosystem Services in Life Cycle Assessment, Part I: A Critical Review	[49]	Columbus	*Environmental Science & Technology*	Review	159	13.3
6	Expanding exergy analysis to account for ecosystem products and services	[50]	Columbus	*Environmental Science & Technology*	Article	147	8.2
7	Obscuring Ecosystem Function with Application of the Ecosystem Services Concept	[51]	USA	*Conservation Biology*	Article	120	10
8	Ecosystem Services assessment: A review under an ecological-economic and systems perspective	[52]	Italy	*Ecological Modelling*	Review	118	14.8
9	Industrial and ecological cumulative exergy consumption of the United States via the 1997 input-output benchmark model	[53]	USA	*Energy*	Article	116	7.7
10	The value of the seagrass Posidonia oceanica: A natural capital	[54]	Italy	*Marine Pollution*	Article	112	12.4

assessment	*Bulletin*

Note: TC: Total number of citations; **AC:** Average number of citations.

To further analyze the developing trend of cited publications, this review ranks the top 10 publications by AC. As is shown in Table 3, most of publications with high AC were distributed since 2018. China gradually becomes the most productive country in this field. Some papers with higher average annual citations have lower total citations relative to those published in earlier years, this is due to their later year of publication. Meanwhile, it is obvious that the focus of scientists in recent years has gradually shifted from theory and methodology to practical application and case studies. The results listed in Table 2 and 3 show that half of these highly-cited publications are the result of transnational collaborations, which enhance exchanges among countries, so as to result in high-quality papers.

Table 3

Top 10 publications with the highest average number of citations.

Rank	Title	Reference	Country	Source	Type	TC	AC
1	Analysis of driving forces on wetland Ecosystem Services value change: A case in Northeast China	[55]	China	*Science of the Total Environment*	Article	69	69
2	Resilient urban forms: A macro-scale analysis	[56]	Japan	*Cities*	Article	89	29.7
3	Small-scale urban agriculture results in high yields but requires judicious management of inputs to achieve Sustainability	[57]	Australia	*Proceedings of the National Academy of Sciences*	Article	88	29.3
4	The issue of microplastics in marine ecosystems: A bibliometric network analysis	[58]	Italy	*Marine Pollution Bulletin*	Review	67	22.3
5	Assessing the Sustainability of urban eco-systems through Emergy-based circular economy indicators	[59]	Italy	*Ecological Indicators*	Article	42	21
6	Emergy-based Ecosystem Services valuation and classification management applied to China's grasslands	[60]	China	*Ecosystem Services*	Article	39	19.5
7	Emergy synthesis for aquaculture: A review on its constraints and potentials	[61]	Brazil	*Reviews in Aquaculture*	Review	18	18

8	The eco-efficiency assessment of wastewater treatment plants in the city of Mashhad using emergy and life cycle analyses	[62]	Iran	*Journal of Cleaner Production*	Article	36	18
9	Emergy-based valuation of agriculture Ecosystem Services and dis-services	[63]	China	*Journal of Cleaner Production*	Article	51	17
10	Quantitative analysis of the dynamic changes of ecological security in the provinces of China through emergy-ecological footprint hybrid indicators	[64]	China	*Journal of Cleaner Production*	Article	68	17

Note: TC: Total number of citations; **AC:** Average number of citations.

4.2. Cooperation analysis

Cooperation analysis has been widely used in various fields where a social network is visualized from a statistical and mathematical perspective [65]. In this section, the cooperation of country's scientific and technological achievements from distribution of publications and social network is analyzed.

4.2.1. Country/region distribution of publications

Fig. 7 shows the country/region distribution of publications from 1995 to 2022, covering a total of 43 countries. Among them, China has the most publications (162 papers), followed by Italy (82 papers), USA (65 papers), Brazil (31 papers), and Luxembourg (9 papers).

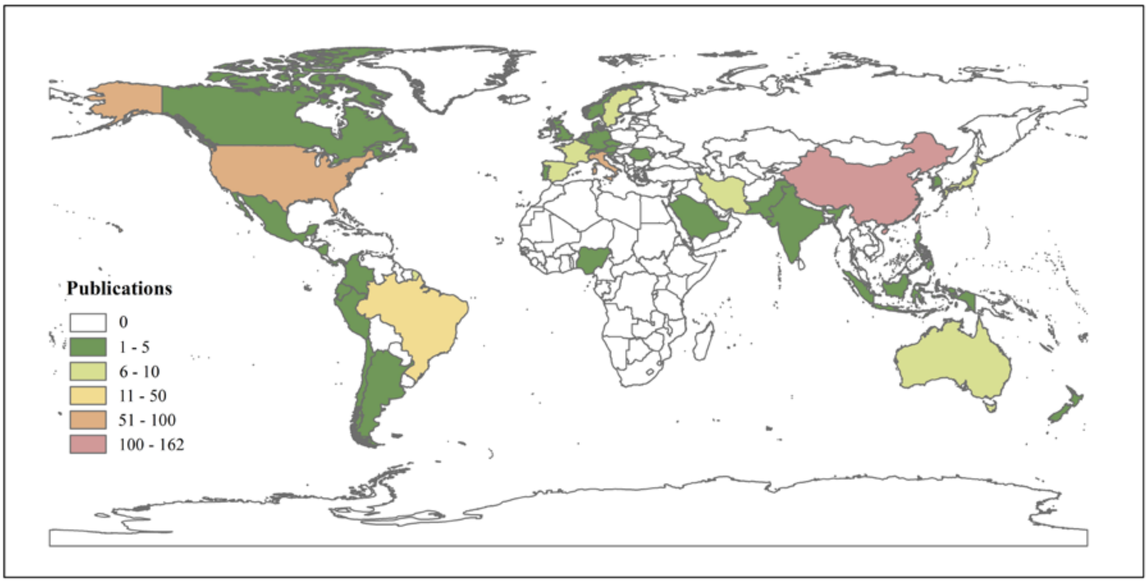


Fig. 7. The country/region distribution of publications.

4.2.2. Countries/regions network

Countries/regions network can represent the production distribution and partnerships among countries/regions [66]. Fig. 8 shows the evolution of emergy-based analysis of ESs at a national scale and their international cooperation network. The cooperative network consists of 43 nodes and 81 links, which indicates that 43 countries have contributed to the field of the using emergy in ESs. Betweenness centrality is an important component of the cooperative network, representing the strength of a node in the entire network [67]. In Fig. 8, nodes with a betweenness centrality greater than 0.1 are marked by purple rings, indicating that the node has strong collaborative relationship with other nodes. During the study period, the USA has the highest degree of centrality (Centr = 0.63), followed by China (Centr = 0.58), Brazil (Centr = 0.4), Italy (Centr = 0.29), and Spain (Centr = 0.1). This shows that these countries are important hubs for scientific cooperation in the field of emergy and ESs. At the same time, this research found that it is not the case that the higher the publication numbers, the stronger the cooperation. For example, China is the most productive country in this field, but the centrality of the USA is higher than that of China. From the viewpoint of time sequence, the research related to emergy was originated from USA due to the creation of the emergy theory by Odum et al. [17]. Then, the emergy was introduced into Italy firstly by Bastianoni [68], further developing and improving the emergy evaluation method. It was in 2001 that emergy was introduced to Sweden and China. Subsequently, countries successively began to conduct the emergy in ESs. Among them, China is developing the fastest. Additionally, results show that there is close international cooperation among countries/regions, especially among the top three most productive countries (i.e., China, Italy, and USA).

Fig. 8. The cooperation network of countries/territories during 1995-2022. The size of a

circle is in proportion to the number of publications of the country. The purple rings of a circle represent the high degree of centrality of a country. The flows represent the network of countries/ territories. The legend on the left represents the year.

4.3. Keyword analysis

The keywords usually reflect the author's research purpose and interest in a research field. To gain an insight into the important research topics in the field of EMA and ESs, this section analyses the evolution of keywords, constructs co-occurrence, and performs burst detection of keywords.

4.3.1. High frequency keywords in different periods

Table 4 expresses the top 10 keywords used in the publications of emergy and ecosystems in four periods, with providing the frequency of these. The most used keyword is 'ecosystem services' in both the second period (2006–2015) and the third period (2016–2022), even in the whole period (1995-2022). In recent years, the frequency of the keywords 'sustainability' and 'emergy analysis' have been increased. Since 2016, the keywords 'China', 'life cycle assessment', 'management' are appeared frequently. As a result, the keywords 'ecosystem services', 'sustainability', 'emergy analysis' appeared most frequently throughout the research period.

Table 4

Top 10 keywords used in emergy and ecosystems in four periods.

1995-2005		2006-2015		2016-2022		1995-2022	
Keywords	Freq	Keywords	Freq	Keywords	Freq	Keywords	Freq
sustainability	5	ecosystem services	50	ecosystem services	107	ecosystem services	160
ecosystem services	3	sustainability	32	emergy analysis	50	sustainability	81
design	2	systems	24	sustainability	44	emergy analysis	69
goods	2	energy	23	systems	34	systems	59
services	2	emergy analysis	17	energy	33	energy	58
embodied energy	2	valuation	16	emergy	30	emergy	43
indicators	2	emergy evaluation	14	china	26	emergy evaluation	36
carrying capacity	2	index	14	emergy evaluation	23	china	29
cost	2	emergy	13	life cycle assessment	18	valuation	26

exergy analysis	2	exergy	13	management	18	life cycle assessment	26

Note: Freq: Frequency of keyword used in a given time period.

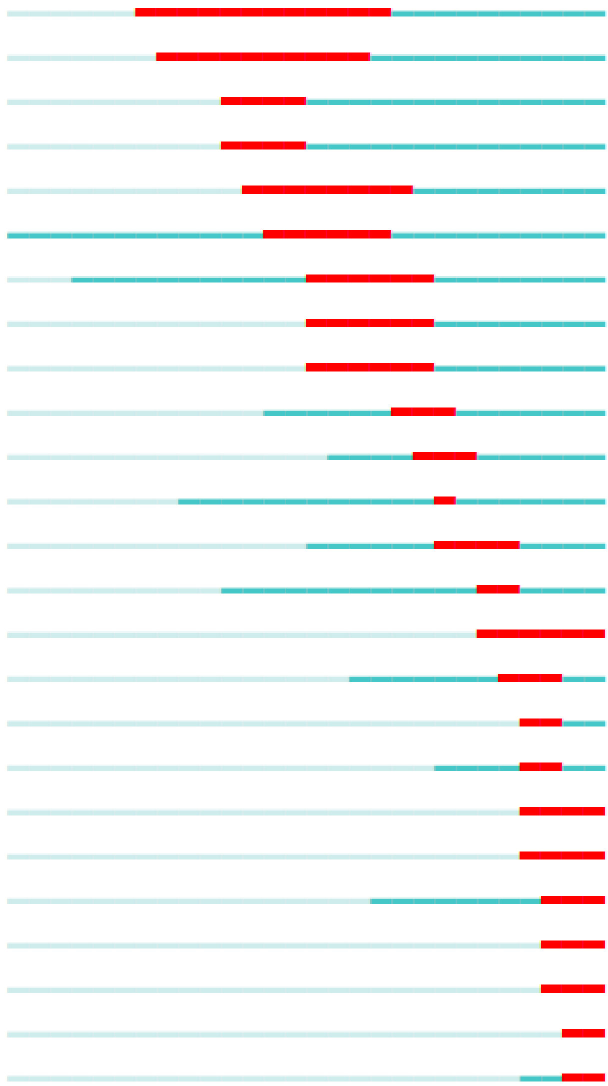
4.3.2. Keywords burst detection analysis

Identifying the keywords that have surged in a certain period and using burst detection analysis to observe rapidly growing research topics can help understand the changes in research themes in recent years [66]. “Burst” is a term widely used in short period to identify the emerging and fading themes. The usage of each term could be considered as similar to a person's life circle that develops through the birth, growth, fade and death stages [69].

Table 5

Top 25 keywords with the strongest citation bursts.

Keywords	Strength	Begin	End	1995-2022
energy analysis	3.93	2001	2012	
embodied energy	3.17	2002	2011	
ratios	3.22	2005	2008	
evaluate	2.57	2005	2008	
index	4.83	2006	2013	
emergy synthesis	2.31	2007	2012	
exergy	5	2009	2014	
constructed wetland	2.5	2009	2014	
classification	2.28	2009	2014	
valuation	4.47	2013	2015	
framework	3.15	2014	2016	
energy	3.68	2015	2015	
emergy evaluation	3	2015	2018	
transformity	2.83	2017	2018	
marine protected areas	2.55	2017	2022	
land use	3.18	2018	2020	
sustainability assessment	3.49	2019	2020	
impact	2.8	2019	2020	
protected areas	2.33	2019	2022	
eco exergy	2.33	2019	2022	
china	3.25	2020	2022	
flows	2.41	2020	2022	



region	2.39	2020	2022
geobiosphere	3.07	2021	2022
system	2.77	2021	2022

Note: Strength: represent the weight of a burst word between its length; **Begin, End:** start and end time of keyword bursts. The red lines indicate the duration of the keyword bursts, blue lines represent the entire study period.

Based on constructing the keyword co-occurrence network for the collected publications, we detected 293 burst keywords. The top 25 bursting keywords are listed in Table 5. The beginning of a blue line depicts when an article is published. The beginning of a red segment marks the beginning of a period of burst, whereas the end of the red segment marks the end of the burst period [70]. Where no end date is noted, the keyword is defined as still active. The term strength represents the weight of a burst word between its lengths; therefore, a higher value could be a result of using longer period, higher frequency, or both [71]. The strongest bursting keyword is ‘exergy’ with 4.83 strength, followed by ‘index’ and ‘valuation’.

Since 2016, there are more than 10 bursting words, which indicate the application of emergy in the ecosystems gradually develops in different directions. Among bursting keywords in the third period, the strength of the keyword ‘sustainability assessment’ is the strongest, which began in 2019. Based on the frequently occurred keywords listed in Table 4 and the bursting keywords listed in Table 5, we conclude that the research topics of recent publications mainly focus on the methods, models, emergy applications in different ecosystems and case studies. We found that it is the mainstream trend of academic research to apply these theories and models to solve, optimize and make decisions on practical problems.

4.3.3. Co-occurrence and timeline view analysis

Co-word cluster analysis can obtain the evolution relationship of research literature and present the evolution process of keywords, which can help scholars identify research frontiers and distinguish the research development trends [42]. The co-word analysis assumes that keywords which frequently occur together are connected thematically [72]. This review analyse the cluster views, and timeline views provided by CiteSpace. In the process, the key points and the dynamics of the research front were identified.

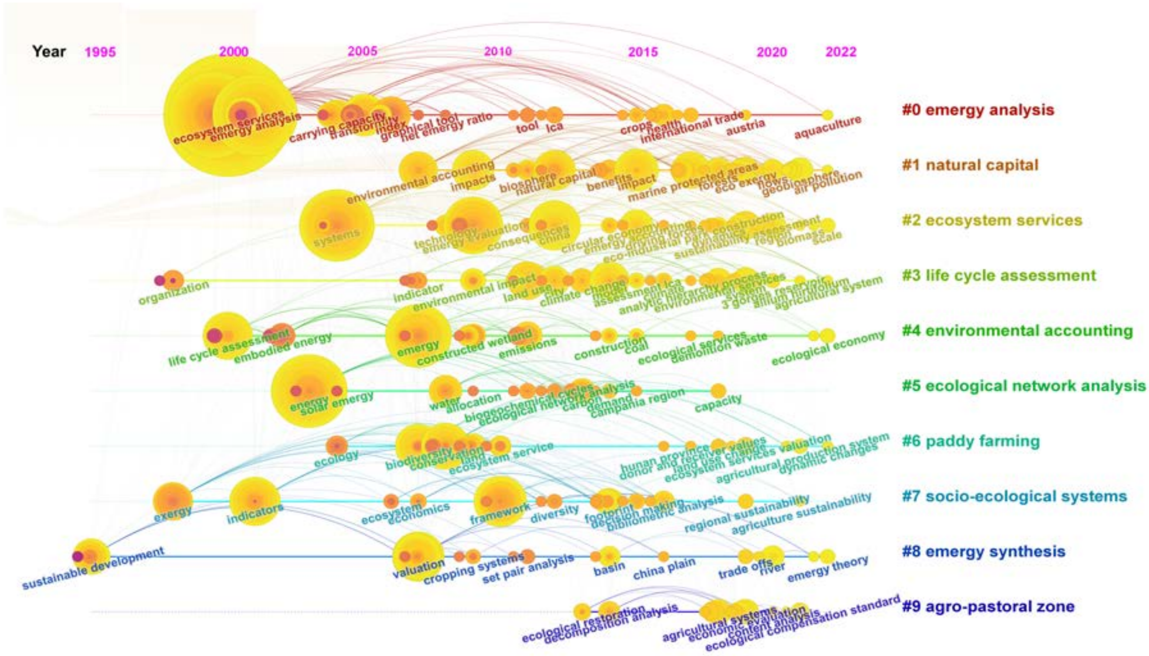


Fig. 9. Co-occurrence network of keywords. The colors represent different cluster networks. The tag signed by the "# + number + phrase" represents the cluster number and name. The node size indicates the frequency of keywords. The numbers in the upper part of the figure represent time periods.

Fig. 9 shows the co-word clustering results. CiteSpace tools are used to divide the relevant research literature into 10 categories according to keywords. Each node in the figure represents a keyword whose position depends on the year in which it first appeared. The size of the node represents the frequency of co-occurrence of this keyword from the year of its appearance to the present. The timeline view generated in this work consists of 10 clusters: clustering #0 and clustering #8 are related to the concept and methods of emergy; clustering #2 is related to the emergy application in ESs; clustering #1, #3, #4, #5 are related to methods, including other methods used in ecosystem evaluation and a comparison between various methods with emergy; #6, #7, #9 are related to evaluation of different categories of ecosystems.

5. Application of emergy for the analysis of different types of ESs

In this part, this research reviewed the initially collected 293 papers and deleted the irrelevant records. Seven papers were found that were not relevant to t research and in which the term "emergy" was merely mentioned but did not actually refer to ES, which just mentioned the term emergy but did not actually apply to ESs. Therefore, 286 publications (i.e., research papers and review papers) were finally selected for content analysis here. This study mainly analyzed the application of emergy analysis for the evaluation of different ESs.

Fig. 10. Research topics of selected publications during 1995–2022. PN represents the numbers of publications; CF represents the frequency of citation.

Fig. 10a divides the total 286 publications into ten topic categories. According to the publications related to emergy and ecosystems, there are nine ecosystems, including wetland ecosystem (lake, river basin), agro-ecosystem (orchard, aquaculture, crop production), coastal ecosystem (including island), marine ecosystem (seagrass, marine phytoplankton), urban ecosystem, industrial ecosystem (hydropower, dam, wastewater), regional ecosystem (administrative district or natural terrain). In addition, this study found that there is a category of publication that do not belong to any ecosystem, which focus more on the discussion of theories and methods. Hence, this research divided these publications into the category “methodology/concept”. Fig. 10b represents the publication numbers and cited frequency of the research categories of ecosystems. This study also analyzed the application of emergy in different ecosystems. In terms of the publication numbers, wetland ecosystem is the most popular field of interest, followed by agro-ecosystem and urban ecosystem. While from the perspective of cited frequency, urban and industrial ecosystems have attracted more attention from the paper authors. Agro and wetland ecosystems follow closely behind. Only a small proportion of publications focus on grassland, forest, coastal or marine ecosystems. Based on the results of this analysis, studes on value accounting and sustainable assessment of different ecosystems based on emergy have been the hot topic in the 21st century.

5.1. Agro-ecosystems

The application of emergy theory to agro-ecosystems was first proposed by Cuadra et al. [73]. In his study, the production, processing, and export of coffee were analysed for the first time to assess the impact of traded products to the environment. Since then, many scientists have applied the emergy theory to the valuation of agro-ecosystems.

Current research in this area covers crop cultivation and fertilization [74,75], gardening [73], animal husbandry and its dairy products [76–78], transgenic production [79], commercial fisheries and aquaculture systems [80], urban aquaponics farms [81]. Due to the complexity of agro-ecosystems, which involve multiple ecosystems, some studies have combined agro-ecosystems with other ecosystems, which include for example the assessment of coastal systems and fisheries [80], agricultural watersheds [82], and urban agriculture [83,57]. Some of the studies are devoted to coordinating the contradictions between landscapes with specific characteristics and agricultural development, such as agriculture in karst regions [84] and agriculture in reservoir areas [85], with a view on resolving the conflicts caused by limited land. These studies focus on production intensification and attempts to increase productivity, enhance ESs and reduce environmental damage due to economic development [86].

In recent years, food security [87], resource recycling and sustainable agriculture research [20,88] have started to become hot topics in the field. In the face of diverse agricultural management and technologies, there is an urgent need for a suitable integrated evaluation method based on multidimensional indicators [89], to address complex issues such as agroforestry systems [90] and agro-livestock [91]. For the field of agro-ecosystems, the papers have mainly used case studies to model the system based on the Odum Energy System Language, and some studies have used scenario setting to identify the functional positioning of the components of circular agricultural systems to provide a basis for rational allocation of environmental resources [20,88,92]. In addition, the integration of agricultural systems with carbon emissions is a major research priority [75,93], offering opportunities for greenhouse gas emission reduction and sustainable intensification of agricultural systems through the restructuring of agriculture.

Methodologically, the construction of an agricultural life-cycle theory based on emergy is currently a hot topic [94,88]. Some studies also compare different methods (EMA, economic cost and return estimation, ecological footprint and life cycle assessment) to explore their economic feasibility, ecological carrying capacity and sustainability assessment [95,89].

The structure of agro-ecosystems is largely influenced by consumers and regional policies [96], therefore, it is necessary to consider and simulate the assessment of agro-ecosystems under different scenarios. Differences in scenarios may lead to changes in energy inputs, ecosystems and their subsystem structure [97]. Emergy-based scenario analysis allows for more accurate comparisons and analysis of differences in ESs values under different policy scenarios, and explore better agricultural governance models.

5.2. Wetland ecosystems

Wetlands are characterized by rich biodiversity and biomass, representing important parts of global terrestrial ecosystems [98]. In 2005, the application of emergy in wetland ecosystem assessment began to enter people's field of vision [99]. Since then, a great deal of research in this area has been carried out. Currently, it is mainly concerned with wetland fish farming [99], urbanizing watershed [25], urban wetland parks [26], biological invasions by exotic species [100], and freshwater lakes [101,102]. Some papers have focused on wetland ecosystems in different temperature zones, such as subtropical wetlands [25], tropical wetlands [48], temperate wetlands [103] and plateau wetlands [104]. Assessing their impact on wetland systems for specific functions is also part of the research in this area. Hoeinghaus et al. [48] studied the important ESs provided by river storage in large tropical rivers. Li et al. [105] systematically assessed the impact of freshwater release on wetland ESs. Due to the certain negative impacts of human activities on wetlands, wetland construction, restoration and conservation are urgent [106]. Some works have begun to assess the extent of pollution of wetland systems by land use change and urban/community development [107,108].

In wetland system assessments, we observe an increased use of combinations of methods. Such combinations include an integrated evaluation of emergy and eco-exergy [109], emergy accounting and life cycle assessment , emergy accounting and ecological footprint [98], emergy combined with the InVEST model [110], emergy combined with Logarithmic Mean Divisia Index decomposition analysis (LMDI) [55], and a joint application of ecological indicators [100]. The combination of emergy and various other methods weighs the various service functions of the wetland system, thus guiding environmental flows decisions and informing management decisions [111]. In recent years, the analysis of the contribution of drivers to wetland ESs [55,101] and the development of eco-compensation standard using emergy theory [112–114] have been hot topics and trends of research in this field.

5.3. Urban ecosystems

Urban areas are complex ecosystems consisting of natural, social and economic components whose development comes at the cost of environmental degradation and ecological stress [115]. Urban ecosystems were the first to introduce emergy theory and apply it to case studies compared to other systems. Huang et al. [116] used emergy synthesis to evaluate the benefits of an ecological engineering on the environmental quality and sustainable development of the metropolitan region. Early studies aimed to focus on urban regulation and spatial optimization. In addition, the construction of a framework for evaluating urban ecosystem health indicators to assess urban ecosystem health was a hot topic until the 2010s [117,118].

Due to land use changes and continued urban expansion caused by global environmental change, some scientists started to focus on peri-urban ESs [119]. As the research progressed, the focus changed from the health evaluation of individual cities to the integrated health evaluation of urban agglomerations [120,121]. In the earlier period, studies were conducted on urban agglomerations in a single year and focused mainly on the spatial differentiation of urban ecosystems in order to better understand regional variability [122,123]. In this process, circular economy [124], resource metabolism [125] has also emerged, which is essential to alleviate the pressure on regional resources and improve environmental quality. In recent years, studies have begun to focus on changes in urban resources over time series [126], as well as on historical evaluations and future projections of urban ecological safety and sustainable development [64,127].

Due to the complexity of urban systems, they are also closely integrated internally with other ecosystems. Thus, urban wetlands [110], mountainous urbans [128], urban parks [123], and urban agriculture [57] are also popular topics of research. The complexity of the urbans has also resulted in a diversity of research content and scope. Some papers have studied the functions and services of urban systems, including municipal solid waste management [129], urban waste-energy self-circulation [130], urban tourism [131], and urban infrastructure [132,133]. In addition, there are studies of ecosystems in different types of urbans, such as: resource-based cities dependent on energy resources for development [134], megacities [135], coastal cities [110], and watershed cities [102,136]. Similar to other systems, the methodological research on urban ecosystems is mostly a combination and modeling of multiple methods [137,138,64].

5.4. Industrial ecosystems

Before 2010s, the research field was dominated by attempts to incorporate emergy theory into industrial systems, led by the American academic Bhavik and his colleagues. Bhavik was the first to use thermodynamics to joint analyze industry and ecosystems, considering both ecological inputs and the effects of industrial emissions. During this decade, the development of emergy in industrial systems has been dominated by the use and development of thermodynamics to evaluate industrial systems [46,53]). After 2010s, the use of emergy in industry became widespread. These include dam construction [139,140], electricity production [141], industrial symbiosis assessment [21,142], industrial clusters [143], environmental building design [144,145], renewable resource flows [146], bioenergy systems [147], hydropower construction [148]. Of these, wastewater treatment [149–151] and the joint construction of reservoirs and their environmental sustainability [152,153] are two of the major research hotspots in the field.

In addition, over-exploitation and depletion of resources in old industrial areas is a growing problem, and most of them are experiencing decline and ecosystem degradation, issues that are of concern to academia and local governments. Therefore, some studies assess the energy flows of material input-output in old industrial areas and the current state of industrial area systems and reconstruction networks in order to provide relevant recommendations for policy makers [154,155]. International trade patterns can be seen as ways to redistribute natural resources and manufactured products, by means of convergence and divergence pathways. With the promotion of international trade, some scientists focused on the driving forces affecting the balance of export and import resources [156], as well as assessing international trade from an environmental perspective [157].

The application of emergy in industrial systems focuses on the application of the emergy synthesis method. These include model development [147,149], life cycle assessment (Buonocore et al., 2015), synergic use of geographic tools and emergy [146], indicator devising [151], ecological cumulative exergy consumption (ECEC) analysis [158]. In recent years, the focus of attention in this area has been mainly on sustainable development of light manufacturing [159,160,85], waste utilization [161,162], and eco-compensation [163,164].

5.5. Grassland ecosystems

The application of EMA to the assessment of grassland ecosystems is relatively new. In 2012, Dong et al. [165] conducted a study on natural pastures and applied emergy theory to grassland systems for the first time. As the greenhouse effect continued to intensify due to the dramatic increase in carbon emissions, some studies laid a focus on grassland carbon stocks and carbon cycling [166]. Yang et al. [60] assessed the value of ESs in China's grasslands based on emergy and proposed emergy-based index of classification management of grassland, providing a systematic approach to biophysical accounting and sustainable development of grassland ecosystems. The latest research is an assessment of cultivated grassland with a view to the rational allocation and scientific management of cultivated grasslands on desert margins [167]. Overall, there is a lack of research on grassland ecosystems based on emergy theory.

5.6. Forest ecosystems

Forest ecosystems are characterized by their wide distribution and large biomass. Their stability and balance not only play an invaluable role in maintaining global energy flows and material cycles, but also provide a variety of direct and indirect products for human life and economic development. In 2003, Tilley and Swank [168] introduced emergy synthesis to the environmental assessment of temperate forests. However, research on forest ecosystems and emergy has been stagnant for a long time. It was only in 2012 that research resumed on the application of EMA in forest ecosystems again [169]. Up to now, research on forest systems has been divided into two broad categories: accounting for the biophysical value of forest ESs [170,171]; and calculating the life cycle of wood resources, which includes both natural and planted forests [172,173]. Overall, there is also a paucity of research on forest ecosystem assessment based on emergy theory. Integrating the economic value of ESs into the integrated assessment of the emergy of forest systems, as well as focusing on the contribution of forests to carbon sequestration and the value of the aesthetic and cultural services that they provide to humans, are poised to sustainable management of forest ecosystem.

5.7. Coastal ecosystems

The coastal zone is a complex geographic unit linking marine and terrestrial systems, and is an area with the most superior resource and environmental conditions, which is closely related to human survival and development. Lu et al. [175] were the first to apply emergy theory to coastal ecosystems. Recently, the research topics of the coastal ecosystems are relatively diverse, including assessment of freshwater releases [105], assessment of economic forestry [176], fisheries management [177], costal wetland reserve [178,179], uninhabited islands [180], benthic ecosystems [181,182]. As the coastal zone contains islands, this type of system is mostly closely integrated with other ecosystems, forming an assessment of integrated ecosystems [183].

The development of coastal cities is also a hot topic of research in this field. Coastal cities have experienced rapid waves of industrialization and urbanization and resulted in serious ecological and environmental problems. Assessing urbanization and its associated tourism impacts on coastal ESs is increasingly attracting academic attention [184,185]. Liu et al. [186] established a non-monetary ESs valuation framework for classifying and evaluating marine ESs. The valuation of coastal ESs in various coastal countries from the perspective of ecosystem contributors provides some reference for decision making. However, due to the difficulty of acquiring marine spatial data, current emergy-based studies have not spatial-explicitly investigated world’s coastal ESs, this knowledge gap should be addressed in the future.

5.8. Marine ecosystems

Marine ecosystems are among the most productive environments [187] . Degradation of global marine ecosystems and loss of ESs have been caused by increased pressure on coastal areas from human activities and the conflicting relationship between economic growth and ecosystem health [188]. In contrast, the application of emergy theory for assessing marine ecosystems is relatively late compared to other systems [54]. Up to now, the relevant content has mainly focused on the study of seagrasses [54] and phytoplankton [189]. Most studies have constructed biophysical and trophodynamic environmental accounting models for marine protected areas based on emergy, mainly by assessing habitats, to value the natural capital of marine protected areas [190,191] (Franzese et al., 2017;). At the same time, some papers have studied the trajectory of changes in ecosystem values, highlighting the importance of long-term monitoring of environmental management and protection of natural capital [192]. Assessing the unevenness of the degree of development of marine ecosystem service values has also been a hot topic in recent years, which is crucial for the future development of the oceans [192,193]. However, the open nature of marine ecosystems leads to particular complexity in characterizing the trophic dynamics of benthic habitats and assessing the environmental flows that support the generation of natural capital stocks [191]. Therefore, the combined biophysical and economic-monetary valuation of natural capital stocks within marine areas remains to be explored in the future, requiring a systematic interdisciplinary approach. In addition, the impacts of natural disasters, such as tsunamis, saltwater intrusion, coastal land subsidence and marine oil spills, on marine ecosystem assessments should also be considered.

5.9. Other ecosystems

This study has categorized papers that are could not be assigned to specific ecosystems. Therefore, a category was introduced “other ecosystems” for these studies. This category includes papers on sustainability assessments for different regions, ranging from large to small and, including assessments of the world [194], countries [195,196], provinces/states [197], and geomorphological areas [198,199]. These studies, from the perspective of natural capital, aim to resolve human-land conflicts and maintain regional ecological security, and are closely integrated with policy development with a view to achieving sustainability of ecosystem services [198,200,201].

In summary, current studies cover ecosystems such as cultivated land, forests, grasslands, wetlands, urban and industrial mining, coastal and marine areas, while there is still a gap in the field of using emergy for the assessment of ESs such as deserts, tundra, and the cryosphere. Desert ecosystems provide important ecological services in terms of climate regulation, hydrological regulation, soil retention, biodiversity, and provide the basic material basis for the survival and development of people living in desert areas [202]. Cryosphere ecosystems also provide water supply, hydrological regulation and habitat support for people and animals in extensive arid and cold areas of the world [203]. Therefore, the use of emergy theory to evaluate such terrestrial ecosystems is also a priority for future research.

6. Limitations and future directions

Based on the joint bibliometric and thematic analysis of retrieved publications, this chapter further discusses the limitations and future directions in the research field of emergy and ESs.

6.1. Strengthen research on the coupling of supply and demand for different ESs based on emergy

Accurate measurement of the spatial characteristics and spatial matching of ecosystem service supply and demand is the scientific basis for regional ecosystem management and restoration [204]. Existing use of emergy theory to assess ESs has mostly focused on the supply side of the service, while research on demand and the relationship between supply and demand is fragmented and scarce. Therefore, in the future, there is a need to study the process of spatial and temporal changes in emergy based on emergy system dynamics models, and to enrich and improve research on demand and systemic, multidimensional supply and demand relationships by combining human demand for ESs and the characteristics of the economic and social activities that arise. However, it is still a major challenge to accurately determine the emergy input and output for a system, especially the value of the emergy transformative rate for the various energy and material flows, which is influenced by the level of production and efficiency. Therefore, when assessing ESs based on emergy theory, more local characteristics need to be considered and integrated to determine the emergy conversion rate scientifically and rationally.

Many ecosystems are not limited to a single country, such as marine ecosystems, glacier ecosystems, wetland ecosystems, etc. This means that not only the people of that country benefit from the ecosystem, but also provide services that benefit other countries as well [186]. Open questions in this regard are how to integrate the planning and policies of different countries for the same system, coordinate the interests between countries, and achieve policy integration needs to be further taken into consideration? However, recent studies have shown that insufficient stakeholder commitment, procedural complexity, lack of cross-border harmonization of rules, and weak interest among managing authorities are common problems currently existing in cross-border ecosystem coordination [205, 206]. Therefore, future in-depth exploration around tele-coupling between different systems should be conducted.

6.2. Conducting spatially and temporally explicit assessments of emergy-based ESs

Global warming has already and will increasingly lead to changes in the structure and function of ecosystems, with profound implications for nature and human systems. . Therefore, studying and predicting the ecological impacts of global warming and the response of ecosystems to it is a critical issue for future research in this field. At present, there are only few studies that use emergy to study the effects of climate change on ecosystems [207]. In addition, many ESs are delivered at landscape scales [208,209], e.g., urban wetland systems, urban-agricultural ecosystems, and coastal-agricultural ecosystems. Thus, these services are influenced not only by localized processes, but also by landscape-level processes occurring in heterogeneous spaces [210,211]. Different ecosystems interact and restrict each other, making the structure and function of the composite ecosystem more complex. In addition, the interactions between various ESs within the same system are currently unclear [212]. Therefore, in the broader context of climate change, the quantification of ESs through landscape-level processes based on emergy is an area that needs to be explored. This requires assessing ESs processes that occur simultaneously at multiple scales and in landscapes with different structures [213]. On this basis, the emergy interactions within and between coupled systems are evaluated and analyzed. Through a comprehensive analysis of the degree of sustainable development of coupled systems, a deeper understanding of the mechanisms of change in ESs can be provided, so as to explore a better governance model that coordinates the development of human economic and social systems and natural ecological systems.

6.3. Strengthen and coordinate in-situ and remote sensing observations and to improve emergy-based ESs models

The current ESs assessment still has limitations due to incomplete data and parameters in some parts of the assessment process, which lead to the fact that some services are not accounted for. Therefore, scientists are still facing the problem of insufficient data, which hinders a more complete assessment of ecosystem services in future related studies. In addition, current research lacks an understanding of key ecological processes. EMA for ESs are mostly static, few studies have focused on the dynamic processes within and between stocks and flows. Interactions between system processes are characterized by a certain lag, so long-term monitoring is essential for us to assess changes in ecosystem diversity and ESs. Therefore, future studies need to integrate and strengthen in situ monitoring, remote sensing observations, model simulations, and socio-economic statistics to provide solid data base for emergy-based analysis of different types of ESs.

In addition, due to emergy theory estimates ESs values based on the energy of input process, values estimated using only emergy accounting methods still have limitations with respect to changes on the receiver side [167]. Therefore, emergy synthesis may be an important tool for assessing the sustainability of ecosystems. To date, publications focused on comparing EMA with energy analysis [45], integrating thermodynamics[68], combining emergy with ecological footprints [214], improving energy vale assessments using life cycle theory [215], constructing energy value indicator systems [216], using GIS to visualise energy value assessment results [217,218], and constructing a non-monetary ecosystem service function framework based on emergy and integrated monetary methods [219] The combination of emergy with other methods remains the long-term directions in the future related studies, also the integration of geoprocessing tools with emergy is also a trend in ESs research, such as geographic information systems (GIS), remote sensing (RS) and global positioning systems (GPS), to facilitate better identification and assessment of spatial and temporal changes in different types of ESs.

6.4. Develop emergy-based management system of ESs

Integrating ESs into the decision-making process is important to achieve regional sustainable development. Regional ESs are influenced by the natural environment, human activities and policy development. Therefore, consideration could be given to including multi-scenario models in future assessments and simulating ecosystem assessments under different scenario models. Scenario analysis can improve the scope and validity of assessment results by comparing different management options and providing useful insights to decision makers responsible for ensuring sustainable management of regional systems and energy security of local communities [220]. IPBES aims to achieve long-term human well-being and sustainable development by strengthening the impact of science policy on biodiversity and ESs [221]. This study proposes to create an emergy-based platform for ESs analysis and management of ESs, and to develop an ecological risk diagnosis and early warning system.

7. Conclusion

This study systematically reviewed the current progress and problems of the emergy-based evaluation of ESs based on a joint use of the bibliometric and thematic content analysis methods. It analyzed some basic characteristics of retrieved publications in terms of publications, cooperation, and keywords, recognized the global research focus, and forecast future research directions. Results show that the topic of EMA application in ecosystems has received much attention, with an exponential growth trend in the publication number and cited frequency of selected samples. The most important contributors with regard to using emery analysis for ecosystem services assessments (i.e. China, Italy, and the United States) have close academic collaborations. *Journal of Cleaner Production*, *Ecological Modelling*, *Ecological Indicators* are the most productive and influential journals. After that, the keywords “evolution analysis”, “burst detection analysis”, and “co-occurrence analysis” are conducted. The results show that the keywords ‘ecosystem services’, ‘sustainability’, ‘emergy analysis’ appeared most frequently throughout the research period. In recent years, especially since 2016, the keywords ‘China’, ‘life cycle assessment’, ‘management’ are appeared frequently. In addition, the research topics of recent publications mainly focus on the methods, models, emergy applications for different ecosystems and case studies.

This work further analyzed the EMA application in ESs. We have found that the extent to which EMA are used varies across different ecosystems. The application of emergy is relatively well established for the assessment of agro-ecosystems, urban ecosystems, industrial ecosystems and wetland ecosystems, but the application for assessments of forest ecosystems, grassland ecosystems, costal ecosystems, marine ecosystems and others has yet to be advanced. Although the application of EMA in ESs assessments has made great progress in current decade, there are still some limitations in this research field. The incomplete data and parameters are currently major challenges for academics to face. Furthermore, due to the limitations of current emergy methods, emergy synthesis is still the trend in the future research. There is still a gap in the field in the use of emergy to assess ESs in special landscapes such as deserts, tundra, and cryosphere, which needs to extend the exploration of other terrestrial ecosystems in the future.

The emergy-based assessment of ESs contributes to a better understanding of the generation and formation of ESs, which is expected to represent the flow of ESs more objectively and accurately. This approach can be also used as an appropriate tool for the development and improvement of ecosystem management and related public policy to assist decision-makers in balancing synergistic inter-systems and achieving sustainable development.

Although bibliometric-based assessment is an effective method for summarizing and sorting out the literature, it still has its limitations [222]. Because bibliometric analysis is quantitative by nature, bibliometric qualitative assertions can be relatively subjective, and the relationship between quantitative and qualitative results is often unclear [223]. In this study, thematic analysis is combined on the basis of quantitative analysis, overcoming the limitations of bibliometric methods to a certain extent. However, using only documents from WoS for the analysis may also lead to an incomplete collection of documents. Therefore, this study has certain limitations.

Nevertheless, this study provides a holistic and objective picture of publications of emergy-based application in ESs and future research directions. In summary, this review study is intended to serve as a guide and reference for scientists, stakeholders and policy makers interested in emergy-based evaluation of ESs.

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Author Contributions

Can Zhang: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Bo Su:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Funding. **Michael Beckmann:** Methodology, Writing – review & editing. **Martin Volk:** Conceptualization, Writing – review & editing.

Declaration of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Reference

[1] Barbier EB. Economics: Account for depreciation of natural capital. Nature 2014; 515(7525):32–3.

[2] Polasky S, Bryant B, Hawthorne P, Johnson J, Keeler B, Pennington D. Inclusive wealth as a metric of sustainable development. Annu Rev Environ Resour 2015; 40:445–66.

[3] Daily GC, editor. Nature's services: societal dependence on natural ecosystems. Island press; 1997.

[4] Costanza R, d'Arge R, De Groot R, Farber S, Grasso M, Hannon B, et al. The value of the world's ecosystem services and natural capital. Nature 1997;387(6630):253–60.

[5] Díaz S, Demissew S, Carabias J, Joly C, Lonsdale M, Ash N, et al. The IPBES Conceptual Framework—connecting nature and people. Curr Opin Environ Sustain 2015;14:1–6.

[6] Müller F, Burkhard B. The indicator side of ecosystem services. Ecosyst Serv 2012;1(1):26–30.

[7] VanderWilde CP, Newell JP. Ecosystem services and life cycle assessment: A bibliometric review. Resour Conserv Recycl 2021;169,105461.

[8] Vanham D, Leip A, Galli A, Kastner T, Bruckner M, Uwizeye A, et al. Environmental footprint family to address local to planetary sustainability and deliver on the SDGs. Sci Total Environ 2019; 693,133642.

[9] Bunse L, Rendon O, Luque S. What can deliberative approaches bring to the monetary valuation of ecosystem services? A

literature review. Ecosyst Serv 2015;14:88–97.

[10] Schmidt K, Sachse R, Walz A. Current role of social benefits in ecosystem service assessments. Landsc Urban Plan 2016;149:49–64.

[11] Mehvar S, Filatova T, Dastgheib A, De Ruyter van Steveninck E, Ranasinghe R. Quantifying economic value of coastal ecosystem services: a review. J Mar Sci Eng 2018; 6(1), 5.

[12] Wall G. Exergy: a useful concept. Chalmers Tekniska Hogskola; 1986.

[13] Pan HS, Li Y, Chen ZH. A review and perspectives on the methods for evaluation of forest ecosystem service values. Journal of Arid Land Resources and Environment 2018;32(6):72–8. (Chinese)

[14] Nadalini AC, Kalid RD, Torres EA. Emergy as a tool to evaluate ecosystem services: A systematic review of the literature. Sustainability 2021;13(13):7102.

[15] Ying X, Wu TH. Su B, Zhu XF, Xiao Y. Discussion on the evaluation method of cryosphere services. J Gloclol Geocryol 2019; 41(5):1271–1280. (Chinese)

[16] Alcamo J. Ecosystems and human well-being: a framework for assessment. Island Press; 2003.

[17] Odum HT. Self-organization, transformity, and information. Science 1988,242(4882):1132–1139.

[18] Liu G Y. A review of a non-monetary valuation of ecosystem services. Acta Ecologica Sinica2018; 38(4), 1487–1499.

[19] Wang XL, Li ZJ, Long P, Yan LL, Gao WS, Chen YQ, et al. Sustainability evaluation of recycling in agricultural systems by emergy accounting. Resour Conserv Recycl 2017;117:114–24.

[20] Xu Z, Fan W, Dong X, Wang XC, Liu Y, Xue H, et al. Analysis of the functional orientation of agricultural systems from the perspective of resource circulation. J Clean Prod 2020;258:120642.

[21] Geng Y, Liu ZX, Xue B, Dong HJ, Fujita T, Chiu A. Emergy-based assessment on industrial symbiosis: a case of Shenyang Economic and Technological Development Zone. Environ Sci Pollut Res 2014;21:13572–87.

[22] Zhao G, Zhang H, Zhang GJ, Guo LM. Morphology and coupling of environmental boundaries in an iron and steel industrial system for modelling metabolic behaviours of mass and energy. J Clean Prod 2015;100:247–61.

[23] Liu GY, Yang ZF, Chen B, Ulgiati S. Emergy-based dynamic mechanisms of urban development, resource consumption and environmental impacts. Ecol Model 2014;271:90–102.

[24] Yang DW, Kao WTM, Zhang GQ, Zhang NY. Evaluating spatiotemporal differences and sustainability of Xiamen urban metabolism using emergy synthesis. Ecol Model 2014;272:40–8.

[25] Tilley DR, Swank WT. EMERGY-based environmental systems assessment of a multi-purpose temperate mixed-forest watershed of the southern Appalachian Mountains, USA. J Environ Manage 2003;69(3):213–227.

[26] Duan N, Liu XD, Dai J, Lin C, Xia XH, Gao RY, et al.Evaluating the environmental impacts of an urban wetland park based on emergy accounting and life cycle assessment: A case study in Beijing. Ecol Modell 2011;222(2):351–359.

[27] Odum HT, Odum EC. Energy Basis for Man and Nature. McGraw-Hill, New York, 1981.

[28] Forbes SA. The lake as a microcosm. 1887;537–550.

[29] Newcombe K, Kalma JD, Asto Boyden S V. Ecology in relation to urban population structure. The Structure of Human Populations Oxford: Clarendon Press; 1972.

[30] Boyden SV. Ecology in relation to urban population structure. The Structure of Human Populations. Oxford: Clarendon Press; 1972.

[31] Zucchetto J. Energy-economic theory and mathematical models for combining the systems of man and nature, case study: The urban region of Miami, Florida. Ecol Model 1975; 1(4): 241–268.

[32] Odum HT. Environmental accounting: emergy and environmental decision making, New York: John Wiley & Sons;.1996.

[33] Lan SF, Qin P, Lu HF. Emergy Analysis on the Eco-economics System. Guangzhou: Chemical Industry Press; 2002.

[34] Chen W, Liu W, Geng Y, Brown MT, Gao C, Wu R. Recent progress on emergy research: A bibliometric analysis. Renew Sustain Energy Rev 2017;73:1051–1060.

[35] Czúcz B, Haines-Young R, Kiss M, Bereczki K., Kertész M, Vári Á, et al. Ecosystem service indicators along the cascade:

How do assessment and mapping studies position their indicators?. Ecol Indic 2020;118:106729.
[36] Guan X, Fu Y, Meng Y, Yan D. Water ecology emergy analytic system construction and health diagnosis. Energy Convers Manag 2022;270:116254.
[37] Van Leeuwen T. The application of bibliometric analyses in the evaluation of social science research. Who benefits from it, and why it is still feasible. Scientometrics 2006;66(1):133–154.
[38] Chadegani AA, Salehi H, Yunus MM, Farhadi H, Fooladi M, Farhadi M.A comparison between two main academic literature collections: Web of Science and Scopus databases. Asian Soc Sci 2013;9:18–26.
[39] Chen D, Liu Z, Luo Z, Webber M, Chen J. Bibliometric and visualized analysis of emergy research. Ecol Eng 2016;90:285–293.
[40] Li C, Wu K, Wu J. A bibliometric analysis of research on haze during 2000- 2016. Environ Sci Pollut Res 2017;24:24733–24742.
[41] Khan A, Goodell JW, Hassan MK, Paltrinieri A. A bibliometric review of finance bibliometric papers. Financ Res Lett 2022;47:102520.
[42] Shi Y, Zhang HY. Research Hotspot and Trend of Employee Creativity Based on Bibliometric Analysis. Front Psychol 2022;13:914401.
[43] Vaismoradi M, Turunen H, Bondas T. Content analysis and thematic analysis: implications for conducting a qualitative descriptive study. Nurs Health Sci 2013;15:398–405.
[44] Braun V, Clarke V. Using thematic analysis in psychology. Qual Res Psychol 2006;3:77–101.
[45] Brown MT, Herendeen RA. Embodied energy analysis and EMERGY analysis: a comparative view. Ecol Econ 1996;19(3):219–235.
[46] Hau JL, Bakshi BR. Promise and problems of emergy analysis. Ecol Modell 2004;178(1-2):215–25.
[47] Zhao S, Li Z, Li W. A modified method of ecological footprint calculation and its application. Ecol Modell 2005;185(1):65-75.
[48] Hoeinghaus DJ, Agostinho A A, Gomes LC, Pelicice FM, Okada EK, Latini JD, et al.Effects of river impoundment on ecosystem services of large tropical rivers: embodied energy and market value of artisanal fisheries. Conserv Biol 2009;23(5):1222–1231.
[49] Zhang YI, Singh S, Bakshi BR. Accounting for ecosystem services in life cycle assessment, Part I: a critical review. Environ Sci Technol 2010;44(7):2232–42.
[50] Hau JL, Bakshi BR. Expanding exergy analysis to account for ecosystem products and services. Environ Sci Technol 2004;38(13):3768–3777.
[51] Peterson MJ, Hall DM, FELDPAUSCH‐PARKER AM, Peterson TR. Obscuring ecosystem function with application of the ecosystem services concept. Conserv biol 2010;24(1):113–9.
[52] Häyhä, T., & Franzese, P. P. (2014). Ecosystem services assessment: A review under an ecological-economic and systems perspective. Ecological Modelling, 289, 124-132.
[53] Ukidwe NU, Bakshi BR. Industrial and ecological cumulative exergy consumption of the United States via the 1997 input–output benchmark model. Energy 2007;32(9),1560–1592.
[54] Vassallo P, Paoli C, Rovere A, Montefalcone M, Morri C, Bianchi CN. The value of the seagrass Posidonia oceanica: A natural capital assessment. Mar Pollut Bull 2013;75(1-2):157–167.
[55] Song F, Su F, Mi C, Sun D. Analysis of driving forces on wetland ecosystem services value change: A case in Northeast China. Sci Total Environ 2021;751:141778.
[56] Sharifi A. Resilient urban forms: A macro-scale analysis. Cities 2019;85:1–4.
[57] McDougall R, Kristiansen P, Rader R. Small-scale urban agriculture results in high yields but requires judicious management of inputs to achieve sustainability. Proc. Natl. Acad. Sci. U.S.A. 2019;116(1):129–134.
[58] Pauna VH, Buonocore E, Renzi M, Russo GF, Franzese PP. The issue of microplastics in marine ecosystems: A bibliometric

network analysis. Mar Pollut Bull 2019;149:110612.

[59] Santagata R, Zucaro A, Viglia S, Ripa M, Tian X, Ulgiati S. Assessing the sustainability of urban eco-systems through Emergy-based circular economy indicators. Ecol indic 2020;109:105859.

[60] Yang Q, Liu G, Giannetti BF, Agostinho F, Almeida CM, Casazza M. Emergy-based ecosystem services valuation and classification management applied to China's grasslands. Ecosyst Serv 2020;42,101073.

[61] David LH, Pinho SM, Agostinho F, Kimpara JM, Keesman KJ, Garcia F. Emergy synthesis for aquaculture: A review on its constraints and potentials. Rev Aquac 2021;13(2):1119–38.

[62] Alizadeh S, Zafari-Koloukhi H, Rostami F, Rouhbakhsh M, Avami A. The eco-efficiency assessment of wastewater treatment plants in the city of Mashhad using emergy and life cycle analyses. J Clean Prod 2020;249:119327.

[63] Shah SM, Liu G, Yang Q, Wang X, Casazza M, Agostinho F, Lombardi GV, Giannetti BF. Emergy-based valuation of agriculture ecosystem services and dis-services. J Clean Prod 2019;239:118019.

[64] Yang Q, Liu G, Hao Y, Coscieme L, Zhang J, Jiang N, Casazza M, Giannetti BF. Quantitative analysis of the dynamic changes of ecological security in the provinces of China through emergy-ecological footprint hybrid indicators. J Clean Prod 2018;184:678–95.

[65] Ye Q, Song H, Li T. Cross-institutional collaboration networks in tourism and hospitality research. Tour Manag Perspect 2012;2:55–64.

[66] Chen Y, Lin M, Zhuang D. Wastewater treatment and emerging contaminants: Bibliometric analysis. Chemosphere 2022;297:133932.

[67] Yu Y, Shen Y, Liu Y, Wei Y, Rui X, Li B. Knowledge mapping and trends in research on remote sensing change detection using CiteSpace analysis. Earth Sci Inform 2023;16(1):787–801.

[68] Bastianoni S. A definition of 'pollution'based on thermodynamic goal functions. Ecol Modell 1998;113(1–3):163–166.

[69] Cataldi M,Di Caro L. Schifanella C, Emerging topic detection on Twitter based on temporal and social terms evaluation, InProceedings of the tenth international workshop on multimedia data mining; 2010:1–10..

[70] Kleinberg J. Bursty and hierarchical structure in streams. In Proceedings of the 8th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining;2002:91–101.

[71] Kim W, Khan GF, Wood J, Mahmood MT. Employee engagement for sustainable organizations: Keyword analysis using social network analysis and burst detection approach. Sustainability 2016;8(7):631.

[72] Arroyo Esteban S, Urquía Grande E, Martínez de Silva A, P´erez Est´ebanez R. Big Data, Accounting and International Development: Trends and challenges; 2022.

[73] Cuadra M, Rydberg T. Emergy evaluation on the production, processing and export of coffee in Nicaragua. Ecol Modell 2006;196(3–4):421–433.

[74] Singh RJ, Ghosh BN, Sharma NK, Patra S, Dadhwal KS, Mishra PK. Energy budgeting and emergy synthesis of rainfed maize–wheat rotation system with different soil amendment applications. Ecol Indic 2016;61:753–765.

[75] Amini S, Rohani A, Aghkhani MH, Abbaspour-Fard MH, Asgharipour MR. Sustainability assessment of rice production systems in Mazandaran Province, Iran with emergy analysis and fuzzy logic. Sustain Energy Technol Assess 2020;40:100744.

[76] Agostinho F, Oliveira MW, Pulselli FM, Almeida CM, Giannetti BF. Emergy accounting as a support for a strategic planning towards a regional sustainable milk production. Agric Syst 2019;176:102647.

[77] Kocjančič T, Debeljak M, Žgajnar J, Juvančič L. Incorporation of emergy into multiple-criteria decision analysis for sustainable and resilient structure of dairy farms in Slovenia. Agric Syst 2018;164:71–83.

[78] Rojas-Moreno DA, Nacimento RA, Pena-Bermudez YA, Rezende VT, Sartorello GL, Da Silva Filho C, et al. Can we obtain high productivity allied to environmental gains? An emergy-economic study of sheep meat production systems. J Clean Prod 2022;365:132722.

[79] Rótolo GC, Francis C, Craviotto RM, Viglia S, Pereyra A, Ulgiati S. Time to re-think the GMO revolution in agriculture. Ecol Inform 2015;26:35–49.

[80] Brown MT, Viglia S, Love D, Asche F, Nussbaumer E, Fry J, et al. Quantifying the environmental support to wild catch Alaskan sockeye salmon and farmed Norwegian Atlantic Salmon: An emergy approach. J Clean Prod 2022;369:133379.

[81] David LH, Pinho SM, Agostinho F, Costa JI, Portella MC, Keesman KJ. Sustainability of urban aquaponics farms: An emergy point of view. J Clean Prod 2022;331:129896.

[82] Fu Y, Du X, Ruan B, Liu L, Zhang J. Agro-ecological compensation of watershed based on emergy. Water Sci Technol 2017;76(10):2830–2841.

[83] Lu H, Campbell DE. Ecological and economic dynamics of the Shunde agricultural system under China's small city development strategy. J Environ Manage 2009; 90(8):2589–2600.

[84] Zou Z, Zeng F, Wang K, Zeng Z, Zhao L, Du H, et al. Emergy and economic evaluation of seven typical agroforestry planting patterns in the karst region of Southwest China. Forests 2019;10(2);138.

[85] Chen C, Cheng H, Jia J, Wang X, Zhao J. Use it or not: An agro-ecological perspective to flooded riparian land along the Three Gorges Reservoir. Sci Total Environ 2019;650:1062–1072.

[86] Aubin J, Callier M, Rey‐Valette H, Mathe S, Wilfart A, Legendre M, et al.Implementing ecological intensification in fish farming: definition and principles from contrasting experiences. Rev Aquac 2019;11(1):149–167.

[87] Skaf L, Buonocore E, Dumontet S, Capone R, Franzese PP. Food security and sustainable agriculture in Lebanon: An environmental accounting framework. J Clean Prod 2019;209:1025–1032.

[88] Hercher-Pasteur J, Loiseau E, Sinfort C, Hélias A. Identifying the resource use and circularity in farm systems: Focus on the energy analysis of agroecosystems. Resour Conserv Recycl 2021;169:105502.

[89] Cui J, Sui P, Wright DL, Wang D, Yang J, Lv Z, et al A revised integrated framework to evaluate the sustainability of given cropping systems. J Clean Prod 2021;289:125716.

[90] Falkowski TB, Chankin A, Diemont SA, Pedian RW. More than just corn and calories: A comprehensive assessment of the yield and nutritional content of a traditional Lacandon Maya milpa. Food Security 2019;11:389–404.

[91] Patrizi N, Niccolucci V, Castellini C, Pulselli FM, Bastianoni S. Sustainability of agro-livestock integration: Implications and results of Emergy evaluation. Sci Total Environ 2018;622:1543–1552.

[92] Almeida CM, Frugoli AD, Agostinho F, Liu GY, Giannetti BF. Integrating or Des-integrating agribusiness systems: Outcomes of emergy evaluation. Sci Total Environ 2020;729: 138733.

[93] Zheng X, Liu X, Pan H. Co-benefits assessment of integrated livestock and cropland system based on emergy, carbon footprint and economic return. Environ Sci Pollut Res 2022;30(3):6117–6131.

[94] Wang, Y., Liu, G., Cai, Y., Giannetti, B. F., Agostinho, F., Almeida, C. M., & Casazza, M. (2022). The Ecological Value of Typical Agricultural Products: An Emergy-Based Life-Cycle Assessment Framework. Frontiers in Environmental Science, 28.

[95] Cuadra, M., & Björklund, J. (2007). Assessment of economic and ecological carrying capacity of agricultural crops in Nicaragua. Ecological indicators, 7(1), 133-149.

[96] Fan J, Liu C, Xie J, Han L, Zhang C, Guo D, et al. Life cycle assessment on agricultural production: a mini review on methodology, application, and challenges. Int J Environ Res Public Health 2022;19(16):9817.

[97] Chen S, Chen B. Sustainability and future alternatives of biogas-linked agrosystem (BLAS) in China: an emergy synthesis. Renew Sustain Energy Rev 2012;16(6):3948-59.

[98] Chen HS.Establishment and Applied Research on a Wetland Ecosystem Evaluation Model in Taiwan. Sustainability 2015;7(12):15785–15793.

[99] Bastianoni S, Marchettini N, Niccolucci V, Pulselli F M. Environmental accounting for the lagoon of Venice and the case of fishing. Annali di Chimica: Journal of Analytical, Environmental and Cultural Heritage Chemistry 2005;95(3–4):143–152.

[100] Marchi M, Jørgensen SE, Bécares E, Fernández-Aláez C, Rodríguez C, Fernández-Aláez M,et al. Effects of eutrophication and exotic crayfish on health status of two Spanish lakes: a joint application of ecological indicators. Ecol Indic 2012;20:92–100.

[101] Zhong S, Geng Y, Qian Y, Chen W, Pan H. Analyzing ecosystem services of freshwater lakes and their driving forces: the

case of Erhai Lake, China. Environ Sci Pollut Res 2019;26:10219–10229.

[102] Li H, Lv C, Ling M, Gu C, Li Y, Wu Z, et al.Emergy Analysis and Ecological Spillover as Tools to Quantify Ecological Compensation in Xuchang City, Qingyi River Basin, China. Water 2021;13(4):414.

[103] Song F, Su F, Zhu D, Li L, Li H, Sun D. Evaluation and driving factors of sustainable development of the wetland ecosystem in Northeast China: An emergy approach. J Clean Prod 2020;248:119236.

[104] Sun J, Yuan X, Liu G, Tian K. Emergy and eco-exergy evaluation of wetland restoration based on the construction of a wetland landscape in the northwest Yunnan Plateau, China. J Environ Manage 2019;252:109499.

[105] Li M, Yang W, Sun T. Effects of freshwater releases on the delivery of ecosystem services in coastal wetlands of the Yellow River Delta using an improved input-state-output approach. Wetlands 2016;36:103–112.

[106] Chen ZM, Chen B, Chen GQ. Cosmic exergy based ecological assessment for a wetland in Beijing. Ecol Modell 2011;222(2):322–329.

[107] Chen J, Sun B M, Chen D, Wu X, Guo LZ,Wang G. Land use changes and their effects on the value of ecosystem services in the small Sanjiang plain in China. Sci Word J 2014.

[108] Xue X, Schoen ME, Ma XC, Hawkins TR, Ashbolt NJ, Cashdollar J, et al. Critical insights for a sustainability framework to address integrated community water services: Technical metrics and approaches. Water Research 2015;77:155–169.

[109] Sun J, Yuan X, Liu H, Liu G, Zhang G. Emergy evaluation of a swamp dike-pond complex: A new ecological restoration mode of coal-mining subsidence areas in China. Ecol Indic 2019;107:105660.

[110] Liu C, Yang M. An empirical analysis of dynamic changes in ecological sustainability and its relationship with urbanization in a coastal city: The case of Xiamen in China. J Clean Prod 2020;256:120482.

[111] Yang W, Yang Z. Integrating ecosystem-service tradeoffs into environmental flows decisions for Baiyangdian Lake. Ecol Eng 2014;71:539–550.

[112] Zhong S, Geng Y, Huang B, Zhu Q, Cui X, Wu F. Quantitative assessment of eco-compensation standard from the perspective of ecosystem services: A case study of Erhai in China. J Clean Prod 2020;263:121530.

[113] Zhao Y, Wu FP, Li F, Chen XN, Xu X, Shao ZY. Ecological compensation standard of trans-boundary river basin based on ecological spillover value: A case study for the Lancang–Mekong River Basin. Int J Environ Res Public Health 2021;18(3):1251.

[114] Peng Z, Wu H, Ding M, Li M, Huang X, Zheng R, et al. Ecological compensation standard of a water-receiving area in an inter-basin water diversion based on ecosystem service value and public willingness: a case study of Beijing. Sustainability 2021;13(9):5236.

[115] Liu, G. Y., Yang, Z. F., Chen, B., Zhang, Y., Zhang, L. X., Zhao, Y. W., & Jiang, M. M. (2009a). Emergy-based urban ecosystem health assessment: A case study of Baotou, China. Communications in Nonlinear Science and Numerical Simulation, 14(3), 972-981.

[116] Huang SL, Wu SC, Chen WB. Ecosystem, environmental quality and ecotechnology in the Taipei metropolitan region. Ecol Eng 1995;4(4):233–248.

[117] Su MR, Yang ZF, Chen B, Ulgiati S. Urban ecosystem health assessment based on emergy and set pair analysis—A comparative study of typical Chinese cities. Ecol modell 2009;220(18):2341–2348.

[118] Liu GY, Yang ZF, Chen B, Ulgiati S. Emergy-based urban health evaluation and development pattern analysis. Ecol Modell;220(18):2291–2301.

[119] Huang SL, Chen YH, Kuo FY, Wang SH. Emergy-based evaluation of peri-urban ecosystem services. Ecol Complex 2011;8(1):38–50.

[120] Su MR, Yang ZF, Liu GY, Chen B. Ecosystem Health Assessment and Regulation for Urban Ecosystems: A Case Study of the Yangtze River Delta Urban Cluster, China. J Environ Inform2011;18(2).

[121] Zhang P, Jing W, Chen Y. Weighted Voronoi diagram-based simulation and comparative analysis of ecosystem service coverage: case study of the Zhongyuan urban agglomeration. J Sensors 2018.

[122] Yu X, Geng Y, Dong H, Fujita T, Liu Z. Emergy-based sustainability assessment on natural resource utilization in 30 Chinese provinces. J Clean Prod 2016;133:18–27.

[123] Almeida CM, Mariano MV, Agostinho F, Liu GY, Yang ZF, Coscieme L, et al. Comparing costs and supply of supporting and regulating services provided by urban parks at different spatial scales. Ecosyst Serv2018; 30:236–247.

[124] Liu W, Zhan J, Li Z, Jia S, Zhang F, Li Y. Eco-efficiency evaluation of regional circular economy: A case study in Zengcheng, Guangzhou. Sustainability 2018;10(2):453.

[125] Viglia S, Civitillo DF, Cacciapuoti G, Ulgiati S. Indicators of environmental loading and sustainability of urban systems. An emergy-based environmental footprint. Ecol indic2018;94: 82–99.

[126] Rutebuka E, Zhang L, Asamoah EF, Pang M, Rukundo E. Resource dynamism of the Rwandan economy: An emergy approach. Sustainability 2018;10(6):1791.

[127] Li Q, Wu J, Su Y, Zhang C, Wu X, Wen X, et al.Estimating ecological sustainability in the Guangdong-Hong Kong-Macao Greater Bay Area, China: Retrospective analysis and prospective trajectories. J Environ Manage 2022;303:114167.

[128] Nikodinoska, N., Buonocore, E., Paletto, A., & Franzese, P. P. (2017). Wood-based bioenergy value chain in mountain urban districts: An integrated environmental accounting framework. Applied Energy, 186, 197-210.

[129] Falahi M, Avami A. Optimization of the municipal solid waste management system using a hybrid life cycle assessment–emergy approach in Tehran. Journal of Material Cycles and Waste Management 2020;1–17.

[130] Xu X. Multi-System Urban Waste-Energy Self-Circulation: Design of Urban Self-Circulation System Based on Emergy Analysis. Int J Environ Res Public Health 2021;18(14):7538.

[131] Lee YC, Liao PT. The effect of tourism on teleconnected ecosystem services and urban sustainability: An emergy approach. Ecol Modell 2021;439:109343.

[132] Shah AM, Liu G, Huo Z, Yang Q, Zhang W, Meng F, et al. Assessing environmental services and disservices of urban street trees. an application of the emergy accounting. Resour Conserv Recycl 2022;186:06563.

[133] Lv C, Liao H, Ling M, Wu Z, Yan D. Assessment of eco-economic effects of urban water system connectivity project. Environ Sci Pollut Res 2022;29(35):53353–53363.

[134] Guo X, Dong S, Wang G, Lu C. Emergy-based urban ecosystem health evaluation for a typical resource-basedcity: A case study of Taiyuan, China. Appl Ecol Environ Res 2019;17(6).

[135] Wei Y, Li Y, Liu X, Wu M. Sustainable development and green gross domestic product assessments in megacities based on the emergy analysis method—A case study of Wuhan. Sustainable Development 2020;28(1):294–307.

[136] Ge F, Tang G, Zhong M, Zhang Y, Xiao J, Li J, et al. Assessment of ecosystem health and its key determinants in the middle reaches of the yangtze river urban agglomeration, china. Int J Environ Res Public Health 2022;19(2):771.

[137] Su M, Fath BD, Yang Z, Chen B, Liu G. Ecosystem health pattern analysis of urban clusters based on emergy synthesis: Results and implication for management. Energy Policy 2013;59:600–613.

[138] Lei K, Liu L, Hu D, Lou I. Mass, energy, and emergy analysis of the metabolism of Macao. J Clean Prod 2016;114:160–170.

[139] Cui B, Hu B, Zhai H. Employing three ratio indices for ecological effect assessment of Manwan Dam construction in the Lancang River, China. River res appl 2011;27(8):1000–1022.

[140] Liu C, Liu G. An Emergy-based Assessment of the Impact of Dam Construction on River Ecosystem Service Values: A Case Study of the Three Gorges Dam. J Environ Account Manag 2019;7(3):337–361.

[141] Häyhä T, Franzese PP, Ulgiati S. Economic and environmental performance of electricity production in Finland: a multicriteria assessment framework. Ecol modell 2011;223(1):81–90.

[142] Fan Y, Qiao Q, Fang L, Yao Y. Emergy analysis on industrial symbiosis of an industrial park–A case study of Hefei economic and technological development area. J Clean Prod 2017;141:791–798.

[143] Liu Z, Geng Y, Zhang P, Dong H, Liu Z. Emergy-based comparative analysis on industrial clusters: economic and technological development zone of Shenyang area, China. Environ Sci Pollut Res 2014;21:10243–10253.

[144] Srinivasan RS, Ingwersen W, Trucco C, Ries R, Campbell D. Comparison of energy-based indicators used in life cycle

assessment tools for buildings. Build Environ 2014;79:138–151.

[145] Yi H, Srinivasan RS, Braham WW, Tilley DR. An ecological understanding of net-zero energy building: Evaluation of sustainability based on emergy theory. J Clean Prod 2017;143:654–671.

[146] Mellino S, Ripa M, Zucaro A, Ulgiati S. An emergy–GIS approach to the evaluation of renewable resource flows: a case study of Campania Region, Italy. Ecol Modell 2014;271:103–112.

[147] Zaimes GG, Khanna V. Assessing the critical role of ecological goods and services in microalgal biofuel life cycles. Rsc Advances 2014; 4(85):44980–44990.

[148] Pang M, Zhang L, Ulgiati S, Wang C. Ecological impacts of small hydropower in China: Insights from an emergy analysis of a case plant. Energy policy 2015;76:112–122.

[149] Arbault D, Rugani B, Tiruta-Barna L, Benetto E. Emergy evaluation of water treatment processes. Ecol Eng 2013;60:172–182.

[150] Arbault D, Rugani B, Marvuglia A, Benetto E, Tiruta-Barna L. Emergy evaluation using the calculation software SCALE: Case study, added value and potential improvements. Sci Total Environ 2014;472:608–619.

[151] Shao L, Chen GQ, Hayat T, Alsaedi A. Systems ecological accounting for wastewater treatment engineering: method, indicator and application. Ecol indic 2014;47:32–42.

[152] Meng Y, Zhang H, Jiang P, Guan X, Yan D. Quantitative assessment of safety, society and economy, sustainability benefits from the combined use of reservoirs. J Clean Prod 2021;324:129242.

[153] Liu X, Pan H, Zheng X, Zhang X, Lyu Y, Deng S, et al. Integrated emergy and economic evaluation of 8 hydropower plants in Zagunao Basin, Southwest of China. J Clean Prod 2022;353:131665.

[154] Yu X, Geng Y, Dong H, Ulgiati S, Liu Z, Liu Z, et al. Sustainability assessment of one industrial region: A combined method of emergy analysis and IPAT (Human Impact Population Affluence Technology). Energy 2016;107:818–830.

[155] Zhang L, Geng Y, Dong H, Zhong Y, Fujita T, Xue B, et al. Emergy-based assessment on the brownfield redevelopment of one old industrial area: a case of Tiexi in China. J Clean Prod 2016;114:150–159.

[156] Tian X, Geng, Y, Ulgiati S. An emergy and decomposition assessment of China-Japan trade: Driving forces and environmental imbalance. J Clean Prod 2017;141:59–369.

[157] Huang S, An H, Viglia S, Buonocore E, Fang W, Ulgiati S. Revisiting China-Africa trade from an environmental perspective. J Clean Prod 2017;167:553–570.

[158] Yang S, Yang S, Qian Y. The inclusion of economic and environmental factors in the ecological cumulative exergy consumption analysis of industrial processes. J Clean Prod 2015;108:1019–1027.

[159] Spagnolo S, Gonella F, Viglia S, Ulgiati S. Venice artistic glass: Linking art, chemistry and environment–A comprehensive emergy analysis. J Clean Prod 2018;171:1638–1649.

[160] Corcelli F, Ripa M, Ulgiati S. Efficiency and sustainability indicators for papermaking from virgin pulp—An emergy-based case study. Resour Conserv Recycl 2018;131:313–328.

[161] Santagata R, Viglia S, Fiorentino G, Liu G, Ripa M. Power generation from slaughterhouse waste materials. An emergy accounting assessment. J Clean Prod 2019;223:536–552.

[162] Kennedy C, Cuddihy J, Engel‐Yan J. The changing metabolism of cities. J Ind Ecol 2007;11(2):43–59.

[163] He J, Li Y, Zhang L, Tan J, Wen C. A county-scale spillover ecological value compensation standard of ecological barrier area in China: based on an extended emergy analysis. Agriculture 2021;11(12):1185.

[164] Chen W, Geng Y, Wang C, Zhong S. Life cycle thinking–based eco-compensation for gold ingot production: a case study in China.Environ Sci Pollut Res 2021;28:4463–4471.

[165] Dong X, Yang W, Ulgiati S, Yan M, Zhang X. The impact of human activities on natural capital and ecosystem services of natural pastures in North Xinjiang, China. Ecol Modell 2012;225:28–39.

[166] Dong X, Brown MT, Pfahler D, Ingwersen WW, Kang M, Jin Y, et al.Carbon modeling and emergy evaluation of grassland management schemes in Inner Mongolia. Agric Ecosyst Environ 2012;158:49–57.

[167] Nan B, Li B, Yang Z, Dai X, Fan Y, Fu Q, et al. Sustainability of sown systems of cultivated grassland at the edge of the Junggar Desert Basin: An integrated evaluation of emergy and economics. J Clean Prod 2020;276:122800.

[168] Tilley, D. R., & Brown, M. T. (2006). Dynamic emergy accounting for assessing the environmental benefits of subtropical wetland stormwater management systems. Ecological Modelling, 192(3-4), 327-361.

[169] Schaubroeck T, Staelens J, Verheyen K, Muys B, Dewulf J. Improved ecological network analysis for environmental sustainability assessment; a case study on a forest ecosystem. Ecol modell 2012;247:144–156.

[170] Campbell ET, Tilley DR. Valuing ecosystem services from Maryland forests using environmental accounting. Ecosys Serv 2014;7:141–151.

[171] Turcato C, Paoli C, Scopesi C, Montagnani C, Mariotti MG, Vassallo P. Matsucoccus bast scale in Pinus pinaster forests: a comparison of two systems by means of emergy analysis. J Clean Prod 2015;96: 539–548.

[172] Neri E, Rugani B, Benetto E, Bastianoni S. Emergy evaluation vs. life cycle-based embodied energy (solar, tidal and geothermal) of wood biomass resources. Ecol Indic 2014;36:419–430.

[173] de Oliveira RK, Higa AR, Silva LD, Silva IC, Gonçalves MD. Emergy-based sustainability assessment of a loblolly pine (Pinus taeda) production system in southern Brazil. Ecol Indic 2018;93:481–489.

[174] Ali A. Linking forest ecosystem processes, functions and services under integrative social–ecological research agenda: current knowledge and perspectives. Sci Total Environ 2023;164768.

[175] Lu H, Campbell D, Chen J, Qin P, Ren H. Conservation and economic viability of nature reserves: an emergy evaluation of the Yancheng Biosphere Reserve. Biol Conserv 2007;139(3–4):415–38.

[176] Zhao S, Wu C. Valuation of mangrove ecosystem services based on emergy: a case study in China. Int J Environ Sci Technol 2015;12:967–974.

[177] Berrios F, Campbell DE, González JE. Assessment of long-term changes in the emergy indexes of an intertidal kelp bed in northern Chile: implications for fisheries management. J Appl Phycol 2021;33:4149–67.

[178] Zhou H, Qin P, Zhou J, Wang G. Comparisons of ecosystem services among three conversion systems in Yancheng National Nature Reserve. Ecol Eng 2009;35(5):609–629.

[179] Toscano F, Alongi G, Conti E, Turnaturi R, Mulder C. Capitalizing the blue world: What can we learn from an Eastern Mediterranean case study?. Ecol Indic 2020;115:106420.

[180] Ding J, Feng C, Ye G, Zhong G, Chou LM., Chen X, et al. Incorporating ecological values into the valuation system of uninhabited islands in China. Int J Appl Earth Obs 2022;110:102819.

[181] Zuidema C, Plate R, Dikou A. To preserve or to develop? East bay dredging project, South Caicos, Turks and Caicos Islands. J Coast Conserv 2011;15(4):555–563.

[182] Berrios F, Campbell DE, Ortiz M. Emergy evaluation of benthic ecosystems influenced by upwelling in northern Chile: contributions of the ecosystems to the regional economy. Ecol Modell 2017;359:146–64.

[183] Zhan J, Zhang F, Chu X, Liu W, Zhang Y. Ecosystem services assessment based on emergy accounting in Chongming Island, Eastern China. Ecol Indic 2019;105:464–473.

[184] Wang C, Li X, Yu H, Wang Y. Tracing the spatial variation and value change of ecosystem services in Yellow River Delta, China. Ecol Indic 2019;96:270–277.

[185] Paoli C, Vassallo P, Dapueto G, Fanciulli G, Massa F, Venturini S, et al.The economic revenues and the emergy costs of cruise tourism. J Clean Prod 2017; 166:1462–1478.

[186] Liu C, Liu G, Yang Q, Luo T, He P, Franzese PP, et al. Emergy-based evaluation of world coastal ecosystem services. Water Research 2021; 204:117656.

[187] Picone F, Buonocore E, D'agostaro R, Donati S, Chemello R, Franzese PP. Integrating natural capital assessment and marine spatial planning: A case study in the Mediterranean sea. Ecol Modell 2017;361:1–3.

[188] Burgos E, Montefalcone M, Ferrari M, Paoli C, Vassallo P, Morri C, et al. Ecosystem functions and economic wealth: Trajectories of change in seagrass meadows. J Clean Prod 2017;168:1108–1119.

[189] Mattei F, Buonocore E, Franzese PP, Scardi M. Global assessment of marine phytoplankton primary production: Integrating machine learning and environmental accounting models. Ecol Modell 2021;451:109578.

[190] Franzese PP, Buonocore E, Donnarumma L, Russo GF. Natural capital accounting in marine protected areas: The case of the Islands of Ventotene and S. Stefano (Central Italy). Ecol Modell 2017;360:290–299.

[191] Vassallo, P., Paoli, C., Buonocore, E., Franzese, P. P., Russo, G. F., & Povero, P. (2017). Assessing the value of natural capital in marine protected areas: A biophysical and trophodynamic environmental accounting model. Ecological Modelling, 355, 12-17.

[192] Sun C, Wang Y, Zou W. The marine ecosystem services values for China based on the emergy analysis method. Ocean Coast Manage 2018;161:66–73.

[193] Hu W, Hu Y, Hu Z, Huang Y, Zhao Y, Ren M. Emergy-based sustainability evaluation of China's marine eco-economic system during 2006–2015. Ocean Coast Manage 2019;179:104811.

[194] Coscieme L, Pulselli FM, Marchettini N, Sutton PC, Anderson S, Sweeney S. Emergy and ecosystem services: A national biogeographical assessment. Ecosyst Serv 2014;7:152–9.

[195] Lomas PL, Álvarez S, Rodríguez M, Montes C. Environmental accounting as a management tool in the Mediterranean context: The Spanish economy during the last 20 years. J Environ Manage 2018;88(2):326–347.

[196] Rugani B, Roviani D, Hild P, Schmitt B, Benetto E. Ecological deficit and use of natural capital in Luxembourg from 1995 to 2009. Sci Total Environ 2014;468:292–301.

[197] Dong XB, Yu BH, Brown M, Zhang YS, Kang MY, Jin Y, et al. Environmental and economic consequences of the overexploitation of natural capital and ecosystem services in Xilinguole League, China. Energy Policy 2014;67:767–780.

[198] Xu Z, Wei H, Fan W, Wang X, Huang B, Lu N, et al. Energy modeling simulation of changes in ecosystem services before and after the implementation of a Grain-for-Green program on the Loess Plateau—A case study of the Zhifanggou valley in Ansai County, Shaanxi Province, China. Ecosyst Serv 2018;31:32–43.

[199] Gao Y, Han Z, Cui Y, Zhang H, Liu L. Determination of the agricultural eco-compensation standards in ecological fragile poverty areas based on emergy synthesis. Sustainability 2019;11(9):2548.

[200] Ma S, Xue M, Ji S. An improved emergy ecological footprint method for ecological security assessment and quantitative analysis of influencing factors: a case study of Zhejiang Province. J Environ Plan Manag 2022;1–25.

[201] Zhang Z, Zhu Z, Tang L, Su K, Yang Q. Donor-side evaluation of the spatiotemporal variation in the rural land natural capital value and its influencing factors: A case study of Chongqing, China. Ecol Indic 2022;136:108640.

[202] Safriel U, Adeel Z, Niemeijer D, et al. Dryland systems//Ecosystems and Human Well-being: Current State and Trends. Washington DC: Island Press 2005;623–662.

[203] Su B, Xiao C, Chen D, Qin D, Ding Y. Cryosphere services and human well-being. Sustainability 2019;11(16):4365.

[204] Wang J, Zhai T, Lin Y, Kong X, He T. Spatial imbalance and changes in supply and demand of ecosystem services in China. SciTotal Environ 2019;657:781–791.

[205] Cappellano F, Makkonen T. Cross-border regional innovation ecosystems: the role of non-profit organizations in cross-border cooperation at the US-Mexico border. GeoJournal. 2020 Dec;85(6):1515-28.

[206] Petrova, S., & Rogin, B. (2016). Exploring the potential of the smart specialization strategies approach in terms of cross-border, transnational and regional cooperation to boost the economic growth. Paper presented at the First SMARTER Conference, Seville.

[207] Wang P, Deng X, Zhou H, Qi, W. Responses of urban ecosystem health to precipitation extreme: A case study in Beijing and Tianjin. J Clean Prod 2018;177: 124–133.

[208] Metzger JP, Villarreal-Rosas J, Suárez-Castro AF, López-Cubillos S, González-Chaves A, Runting RK, Hohlenwerger C, Rhodes JR. Considering landscape-level processes in ecosystem service assessments. Sci Total Environ 2021;796:149028.

[209] Setturu B, Ramachandra TV. Modeling landscape dynamics of policy interventions in Karnataka State, India. J Geovis Spat Anal 2021;5(2):22.

[210] Villard MA, Metzger JP. Beyond the fragmentation debate: a conceptual model to predict when habitat configuration really matters. J Appl Ecol 2014;51(2):309–18.

[211] Herrero-Jáuregui C, Arnaiz-Schmitz C, Herrera L, Smart SM, Montes C, Pineda FD, et al. Aligning landscape structure with ecosystem services along an urban–rural gradient. Trade-offs and transitions towards cultural services. Landsc Ecol 2019;34:1525–45.

[212] Xu M, Dong X, Yang X, Wang R, Zhang K, Zhao Y, et al. Using palaeolimnological data and historical records to assess long-term dynamics of ecosystem services in typical Yangtze shallow lakes (China). Sci Total Environ 2017;584:791–802.

[213] Mitchell MG, Suarez-Castro AF, Martinez-Harms M, Maron M, McAlpine C, Gaston KJ, et al. Reframing landscape fragmentation's effects on ecosystem services. Trends Ecol Evol 2015;30(4):190–8.

[214] Siche R, Agostinho F, Ortega E. Emergy net primary production (ENPP) as basis for calculation of ecological footprint. Ecol Indic 2010;10(2):475–483.

[215] Rugani B, Benetto E. Improvements to emergy evaluations by using life cycle assessment. Environ Sci Technol 2012;46(9):4701–4712.

[216] Coscieme L, Pulselli FM, Jørgensen SE, Bastianoni S, Marchettini N. Thermodynamics-based categorization of ecosystems in a socio-ecological context. Ecol Modell 2013;258:1–8.

[217] Coscieme L, Pulselli FM, Bastianoni S, Elvidge CD, Anderson S, Sutton PC. A thermodynamic geography: Night-time satellite imagery as a proxy measure of emergy. Ambio2014;43:969–979.

[218] Mellino S, Buonocore E, Ulgiati S. The worth of land use: A GIS–emergy evaluation of natural and human-made capital. Sci Total Environ 2015;506:137–148.

[219] Liu Y, Yan Y, Li X. An empirical analysis of an integrated accounting method to assess the non-monetary and monetary value of ecosystem services. Sustainability 2020;12(20): 8296.

[220] Raji SA, Odunuga S, Fasona M. Spatially explicit scenario analysis of habitat quality in a tropical semi-arid zone: Case study of the sokoto–rima basin. J Geovis Spat Anal 2022;6(1):11.

[221] IPBES: Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S; 2019.

[222] Donthu N, Kumar S, Mukherjee D, Pandey N, Lim WM. How to conduct a bibliometric analysis: An overview and guidelines. J Bus Res 2021;133:285–96.

[223] Wallin JA. Bibliometric methods: pitfalls and possibilities. Basic Clin Pharmacol Toxicol 2005;97(5):261–75.