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The ecosystem services concept in freshwater conservation and restoration

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Abstract

1. Intense efforts have focused on ecosystem conservation and restoration (ECR) over the past decades, promoting considerable advances in science and practice in this field. However, the applications of the ecosystem services (ESs) concept are rarely considered in the literature when assessing the success and targets of ECR.
2. The ECR literature was systematically reviewed to analyse the relevance of the ES concept in ECR research published from 2007 to 2019 and to assess how the ES concept is integrated into freshwater ECR.
3. In general, the number of publications focusing on ECR and ESs shows a temporal increase (from 12 to 101 publications, 685 in total). The proportion of publications considering ESs as freshwater ECR targets increased from 33 to 70% until 2019, while the proportion of publications that prioritized ecosystem processes and functions as the target declined from 33 to 16%. Despite the clear upward trend, most studies have focused only on the conceptual framework. In addition, the idea of using market-based approaches for ESs has spread quickly, but it has still not been broadly accepted.
4. The number of academic researchers who have contributed to this research field varies substantially across different countries. A country's economic conditions and the extent of freshwater withdrawal can affect efforts devoted to studies on freshwater ECR and ESs. Some ecosystems, such as rivers and wetlands, have attracted much more attention than others. Although most studies have discussed ESs in general, the provisioning and regulation of ESs are mainly considered in studies that differentiate specific ES categories.
5. Current limitations in applying the ES concept in ECR across different studies suggest that further collaboration is needed among ecologists, practitioners, stakeholders and policy-makers to develop a broad mix of approaches for the best and widest use of the ES concept in protecting and enhancing freshwater ecosystems.

KEYWORDS
ecosystem benefit(s), market-based mechanisms, systematic review, target setting, trade-offs

1 | INTRODUCTION

Freshwater ecosystems are vital to human life and societal well-being. However, owing to the fundamental dependence of human activities on freshwater resources (e.g. domestic water supply, irrigation, food and energy production, recreation and transportation), they are among the most extensively and profoundly altered ecosystems on Earth (Baron et al., 2002; Carpenter, Stanley & Vander Zanden, 2011; Sanchez et al., 2020). Intensifying climate change has also caused measurable deterioration in freshwater ecosystems that can no longer be neglected (Harris et al., 2006; Markovic et al., 2017). Therefore, finding an efficient way to conserve and restore the biological complexity and functional intactness of freshwater ecosystems is a pressing issue for human societies. In recent decades, remarkable progress has been achieved, reflected by numerous theoretical studies and a few well-established ecosystem conservation and restoration (ECR) practices (Strayer & Dudgeon, 2010; Palmer, Hondula & Koch, 2014; Perring et al., 2015). The concept of ecosystem services (ESs), which was brought to media attention by the Millennium Ecosystem Assessment in 2005 (Pesche et al., 2013), is one of the most notable driving factors for the development of ECR. ESs are broadly defined as the benefits that humans derive from ecosystems (Costanza et al., 1997; Millennium Ecosystem Assessment, 2005). These benefits can be categorized into provisioning services (such as the production of water, food and fuel), regulating services (including the control of climate), cultural services (including spiritual and recreational benefits) and supporting services (including nutrient cycling and primary productivity) (Costanza et al., 2017).

Setting a target is the first and most crucial step for the successful conservation or restoration of any ecosystem (Reside, Butt & Adams, 2018). Detailed action plans can be developed based on clearly defined targets, and the method and scale of post-implementation monitoring can be determined (Slocombe, 1998; Ehrenfeld, 2000). However, what the target of ECR should be has been the subject of considerable discussion and controversy. In the history of ECR, individual species, the composition and structure of biological communities, and the processes and functions of ecosystems have been greatly valued as ECR targets (Palmer, Ambrose & Poff, 1997; Lockwood & Pimm, 1999; Davis et al., 2000). Since the early 2000s, ecosystem processes and functions have gradually replaced the focus on individual species and community structure as ECR targets (Euliss et al., 2008; Bennett et al., 2009). There are three main reasons for this shift. First, it is often difficult or even impossible to restore an ecosystem to its historical state with the same species composition (Hilderbrand, Watts & Randle, 2005; Dufour & Piégay, 2009; Palmer, 2009). Second, an ecosystem that is restored by following past community metrics is unlikely to be sustainable in the changing environment of the future (Choi et al., 2008). Third, targeting species based on their rarity would lead to significant resource allocations to a specific taxonomic group or even to a single species, which might limit the resources for ecosystem integrity and functioning (Harvey et al., 2017).

Owing to rapidly increasing attention in both political and scientific arenas, ESs are now becoming a mainstream goal and priority in ECR (Bullock et al., 2011; Noe et al., 2017; Villarreal-Rosas et al., 2020). Although increasing effort has been devoted to integrating ESs into the strategies of ECR, it remains unclear to what extent the ES concept has been considered for freshwater ECR, especially when setting targets. Some researchers note that targeting ESs can raise public interest in biodiversity conservation, which may contribute to obtaining more support for ECR (Patterson & Coelho, 2009; Braat & De Groot, 2012). However, this trend has been hampered to some extent by the potential trade-offs between biodiversity and ESs (McCauley, 2006; Meyer et al., 2018) and the fact that the enhancement of one or several kinds of specific ESs may be at the cost of some ecosystem processes and functions (Bennett, Peterson & Gordon, 2009; Hermoso et al., 2018). For example, enhancing freshwater ESs, such as energy production via flow regulation, dam construction and water abstraction, might compromise the delivery of other related services, such as recreational uses and, ultimately, the persistence of biodiversity (Dudgeon, 2014; Dudgeon, 2019). To popularize further the ES concept in ECR policies, many researchers claim that it is possible to achieve a 'win–win situation' (Cowling et al., 2008; Van der Biest et al., 2020) by obtaining both ecological and socio-economic benefits.

Given this continuing debate, a growing number of theoretical and experimental studies have examined the concept of ESs (Boulton, Ekebom & Gislason, 2016). Different aspects of ESs have been addressed. For instance, some researchers consider ESs an adjunct to a target such as biodiversity protection (Palumbi et al., 2009; Rands et al., 2010). They prioritize natural benefits (diversity and ecosystem functioning) over socio-economic benefits. Others ultimately adopt the ES concept and claim that providing benefits to humans should be the primary motivation for ECR actions (Grizzetti et al., 2016; Hagger, Dwyer & Wilson, 2017). Among supporters of the ES concept, some researchers further propose a market-based mechanism (e.g. payments for ESs) for ECR (Farley & Costanza, 2010; Kinzig et al., 2011). They assert that human benefits or economic value are paramount, and the creation of financial incentives for conservation and restoration is efficient and operable (Pirard, 2012). In addition, payments for ESs can create new funding opportunities for biodiversity protection and contribute to protecting or enhancing long-term societal benefits (Wendland et al., 2010; Spears et al., 2022). Supporters provide evidence of payments for ESs as a mechanism for supporting biodiversity conservation (Ingram et al., 2014). However, dissenters are strongly opposed to this idea, asserting that selling out on nature (the monetary valuation of ESs) could lead to or accelerate an imbalance between ecosystem sustainability and human benefits (Muradian et al., 2013). Other researchers argue that despite the contribution from payments for ESs, it is not sufficient to rely on a market-based mechanism alone to finance the actions necessary to substantially reduce biodiversity loss (Hein, Miller & De Groot, 2013).

In recent decades, ESs have been a central topic of published freshwater studies. Researchers have aimed to identify all types of freshwater ESs and highlight their importance (Jiang et al., 2015; Hossu et al., 2019). Formal approaches to mapping freshwater ESs and valuing them have been explored (Costanza et al., 2014; Thiele et al., 2020). In addition, scientists and practitioners have worked together to integrate the concept of ESs within practice, particularly by approaching environmental management from a socio-ecological systems perspective to protect biodiversity and use ESs sustainably (Anzaldua et al., 2018; Langhans et al., 2019). Nevertheless, research on freshwater ESs is still in its infancy (Vári et al., 2022). Therefore, recognizing how the research field understands and studies ESs in the context of freshwater ecosystems could be a vital step in developing strategies to guide future research directions and ultimately integrate ESs into decision-making. Several reviews have focused on specific types of freshwater ecosystems, such as river ESs (Hanna et al., 2018) and lake ESs (Reynaud & Lanzanova, 2017). However, it appears that no general review of freshwater ESs has yet been conducted. Therefore, a scientific literature survey was conducted to reveal the spatio-temporal patterns for applying the ES concept in freshwater ecosystems. The objectives of this review were to address the following questions: (i) How has the concept of ESs been discussed across different types of freshwater ecosystems and geographical locations? (ii) How have human activities, such as economic development (gross domestic product, GDP) and freshwater resource use, influenced the application of the ES concept in freshwater ECR? (iii) How does the ECR research field understand and apply the ES concept? (iv) To what extent has the concept of ESs been adopted as one of the targets of freshwater ECR? Building on the findings, research gaps are outlined, and several recommendations are provided to align the ES concept with future freshwater ECR.

2 | MATERIALS AND METHODS

2.1 | Literature survey and selection

The 'systematic quantitative approach' of Pickering & Byrne (2014) was adopted for literature processing. Relevant scientific papers published before January 2020 were searched via the ISI Web of Science. As fewer papers were published before 2007, only papers published after 2007 were included in the analysis. The search strings were TOPIC: ((conservation OR restoration) AND (ecosystem services) AND (freshwater OR waterway OR canal OR river OR lake OR estuary OR pond OR marsh OR swamp OR wetland OR watershed (a synonym for 'catchment') OR basin)); RESEARCH AREA: ((biological sciences OR environmental sciences OR ecology)); DATA BASE: all database; LANGUAGE: English (full text in English). The document type, including editorial material, book chapters and corrections, was excluded. These searches resulted in 4,129 publications being obtained.

As this review aimed to explore the status of the ES concept integrated into freshwater ECR, the search focused on publications whose framework was explicitly within the concept of ESs and freshwater ECR. Therefore, publications were only included when (i) freshwater or any kind of freshwater ecosystem, such as a lake, river, pond or wetland, appeared in the title or was mentioned within the main body of the text more than three times (with direct relevance to the results or discussion); (ii) ESs were mentioned within the main body of the text more than three times (with direct relevance to study design or research implications); and (iii) one or more types of freshwater ECR and ESs contributed to the main research results or were a prominent feature in the discussion. Ultimately, 685 publications matching these criteria were selected for the analysis (Figure 1; see the full list of compiled studies in the Supporting Information Data S1).

2.2 | Data collection

The general information on publications (such as timing and disciplinary focus) can offer insights into the intended audience of the research field and can place literature trends within broader environmental research results (Weitzman, 2019). Therefore, quantitative data were extracted from each study on the year of publication, disciplinary focus, publication type, location of the study and country of the first author's affiliation (Table 1). The features related to freshwater ecosystem types were also extracted to understand how different types of freshwater systems are viewed within the ECR and ESs framework and to identify potential literature gaps. To illustrate how ES concepts are understood and integrated within freshwater ECR, the research approach of each study was documented. The specific ESs mentioned, assessed or evaluated in each study were also documented to explore whether there was a bias in emphasis among the different ESs.

Given the divergent opinions on the target setting of ECR, each publication was carefully checked to obtain an unbiased

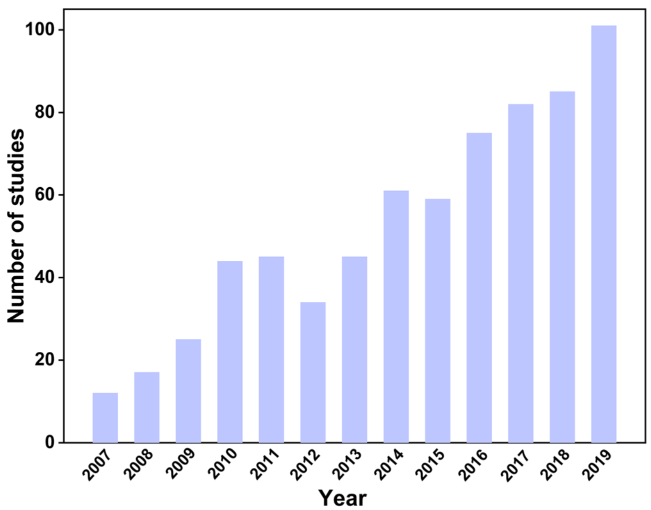

FIGURE 1 Temporal trend in the number of studies from 2007 to 2019 focusing on freshwater ecosystem conservation and restoration and making reference to the concept of ecosystem services either explicitly or implicitly.

TABLE 1 Features extracted from all 685 selected publications during the systematic literature review

Extracted feature	Specific categorization	Notes
1. General characteristics of the paper	• Publication year: 2007–2019 • Disciplinary focus: Field of study of the article • Publication type: Review, Opinion, Methodology, Case study, Concept • Location of study: Country • **Country of the first author's affiliation**	If the first author had several affiliations in different countries, the first one was chosen
2. Type of freshwater system involved in the study	*Categories:* River, Lake, Stream, Reservoir, Estuary, Pond, Channel, Wetland (Marsh/Swamp), **Overview**	**Overview**: Did not refer to any specific type of freshwater ecosystem
3. Approaches and methods used in the study	*Categories:* Laboratory experiment, Field experiment, Observation, Modelling, **Choice experiment, Argument, Synthesis and integration**	**Choice experiment**: A survey method that involves asking people to state their preference for hypothetical alternative scenarios, goods or services, which have combinations of attribute levels generated by the experimental design **Argument**: Discuss new theories and conceptual frameworks for new research directions and resolutions of old questions **Synthesis and integratio**n: Begin by reviewing a topic and then go beyond the review to provide a new synthesis and blending of those ideas and data in new ways
4. Categories of ecosystem services (ESs) discussed within the study	Combinations of the four ESs: Cultural, Provisioning, Regulating and Supporting services	According to the definitions of the different categories of ESs outlined in the Millennium Ecosystem Assessment (2005)
5. Priority of ecosystem services within the study	*1. Ecosystem processes and functions*: Prioritizing ecosystem processes and functions *2. Ecosystem services:* Supporting or adopting the ES concept*Sub-categories:* (a) merely focusing the 'ecosystem-service-based' concept – that is, prioritizing ESs purely for motivating public interests and thus advancing ecosystem conservation and restoration (ECR); (b) supporting or adopting the 'market-based or human benefit-driven' approach, that is, focusing on the economic value of ESs as the motive and gain of ECR *3. Others:* Without giving an unambiguous priority, e.g. those investigating the imbalance between the significance of the ES concept in scientific literature and its actual implementation	

understanding of the extent to which the researchers prioritized the ES concept in ECR studies. Most of the publications could be placed into one of two main categories by their distinct focus on the ECR target: (i) those prioritizing ecosystem processes and functions; and (ii) those supporting or adopting the ES concept (Table 1). Publications without a clear focus were classified as 'other'. In addition, the category 'supporting or adopting the ES concept', was divided into two sub-categories: (a) those focusing only on the 'ecosystem service-based' concept by prioritizing ESs purely for motivating public interests and thus advancing ECR; and (b) those supporting or adopting the 'market-based or human-benefit-driven' approach by focusing on the economic value of ESs as the motive and gain of ECR (Table 1).

All information from the selected publications was manually categorized.

2.3 | Data analysis

As the ES concept is highly relevant within the modern policy agenda for sustainable development, and intertwines with resource utilization and management (Braat & De Groot, 2012; Geijzendorffer et al., 2017), there are possible associations between these freshwater ES and ECR studies and human activities. In this study, the relationship between the number of studies (according to the country of the leading author's affiliation, which generally provides the primary financial support for the researcher) and the GDP per capita of the country of the first author's affiliation was analysed together with its relationship to the annual freshwater withdrawal (AFW) of each country (54 countries in total). The data on the number of studies and GDP according to the country of the leading author's affiliation were used rather than the study location because there were 148 studies (22% of the total selected studies) without a specific location and 54 studies (8%) conducted in more than two countries. The GDP per capita and AFW data from 2007 to 2019 were obtained from the World Bank Open Data (https://data.worldbank.org/). The relationship between the number of studies and the mean GDP per capita and the mean AFW was analysed using the generalized linear model with Poisson error distribution. The GDP per capita and AFW were log-transformed and then scaled to a mean of zero and a standard deviation of one. The correlation between the GDP per capita of the country and AFW was not significant (Supporting Information Figure S1); both were included as explanatory variables in the model. Model fitting was performed with R (R Core Team, 2019).

3 | RESULTS

There was a temporal increase in the number of publications focusing on ECR and ESs in general (Figure 1). The authors were spread over 54 different countries (Figure 2), with 230 from Europe, 219 from the Americas (North America and South America), 167 from Asia, 43 from Oceania and 26 from Africa. The top five countries ranked by the number of publications were the USA (172), mainland China (130), the UK (59), Spain (38) and Australia (37). The publications covered different geographical scales, including local studies of a single country (483 publications), multicountry studies that conducted regional assessments through system-scale approaches or multiple case studies (148 publications), and global studies that had an undefined geographical focus (54 publications). When considering single-country studies, China (114 publications), the USA (108 publications) and Australia (29 publications) had the most. Among the 54 countries, the number of studies was significantly correlated with GDP per capita and AFW (Figure 3). The results of generalized linear models also revealed that the number of studies increased significantly with both GDP per capita and AFW (Figures 3a,b). However, AFW showed a stronger influence on the number of studies compared with GDP per capita (Figure 3c).

The selected studies were published in a variety of journals across different academic disciplines (see the full list of the compiled journals and books, and the number of studies in each publication in the Supporting Information Table S1). The journal with the largest number of selected publications was *Ecosystem Services* (77), followed by *Science of the Total Environment* (50), *Ecological Economics* (42), *Ecological Indicators* (29), and 150 other journals and scientific books. Freshwater ECR and ES research was not limited to environmental science or ecology disciplines but also included other specific disciplines (such as biology and limnology) as well as interdisciplinary fields such as management and conservation (Figure 4a).

Most of the selected studies were based on case studies (56%), followed by methodological research, opinion, review and concept publications (Figure 4b). As some studies referred to more than one specific type of freshwater ecosystem, the sum of the number of studies in each ecosystem type was greater than the number of the selected studies. These publications covered a wide variety of freshwater ecosystems, with far more studies on natural ecosystems than semi-natural ecosystems and only 24 studies focusing on reservoir, pond and canal systems (Figure 5a). In addition, studies that referred to all kinds of freshwater ecosystems (e.g. focus on catchments, regions), which were categorized as 'overviews', accounted for the largest proportion of selected studies. The two most commonly used methods to study freshwater ECR and ESs were multimethod and modelling approaches (Figure 5b).

Across the 685 studies compiled, most discussed ESs in a general way and did not differentiate specific ES categories (69%, Figure 6). The remaining studies included those focusing only on one specific category of ESs (15%) and those referencing two or three categories of ESs (16%). Across the studies that were grounded in specific ESs, provisioning quantified services appeared most often (131 studies), followed by regulating services (124 studies), supporting services (73 studies) and cultural services (58 studies).

There were 536 publications in which the specific focus (ecosystem processes and functions or ES concept) could be identified, while 149 publications without specified information were categorized as 'other'. In general, the number of studies supporting or adopting the ES concept showed an increasing trend, while the proportion of studies prioritizing ecosystem processes and functions declined (Figure 7a). In 2010, there was a shift towards publications

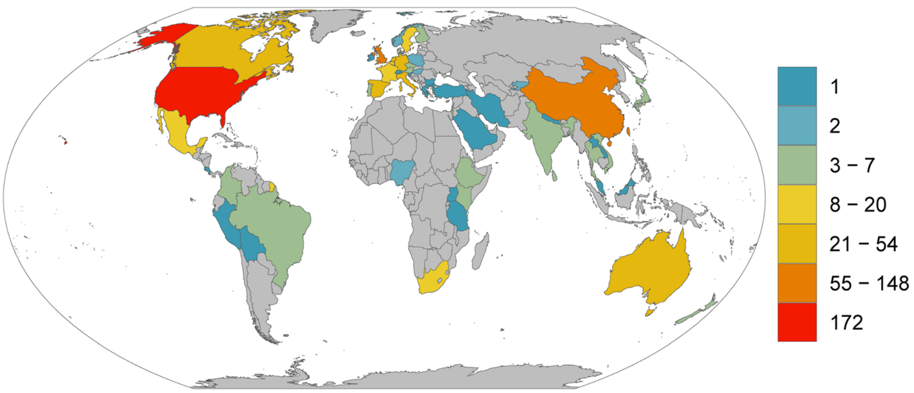

FIGURE 2 The number of studies in each country (685 studies and 54 countries in total). For each country, the studies were identified for which the leading author's affiliation (the first affiliation if there were multiple affiliations) was located in that country.

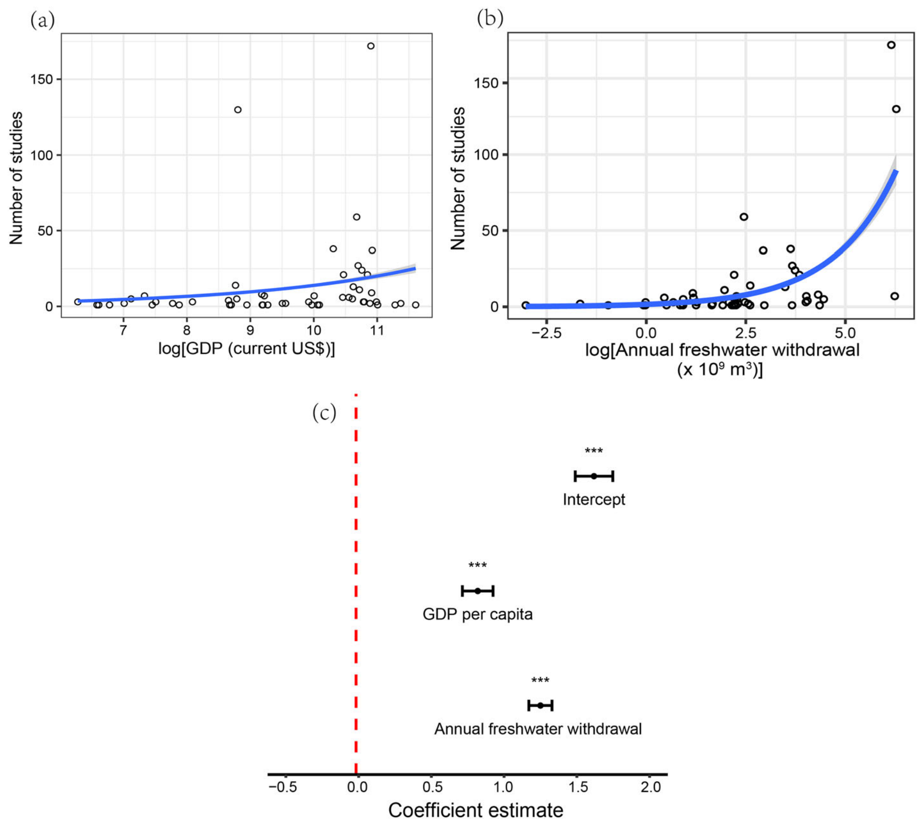

FIGURE 3 The change in the number of studies (685 in total) along the gradient of GDP per capita (a) and annual freshwater withdrawal (b) in each country (54 in total). In both (a) and (b), the blue curve represents the fitting of the single-predictor generalized linear model. (c) The coefficient estimates of the generalized linear model include both GDP per capita and annual freshwater withdrawal as explanatory variables. Error bars represent the 95% confidence interval of the coefficient estimates, which were all significantly larger than zero in this analysis ($P < 0.001$).

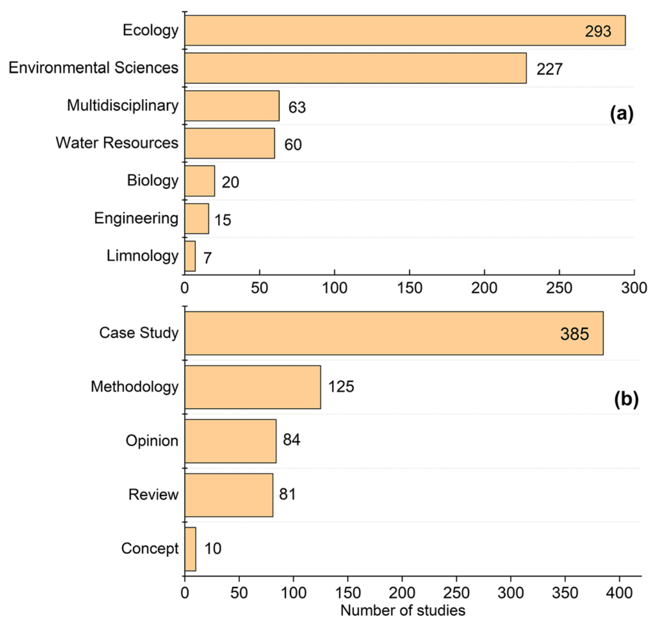

FIGURE 4 Number of studies ($N = 685$), based on (a) the contribution of referencing journals and books to the academic disciplines and (b) the type of studies.

focusing on the ES concept, with a majority of publications after this year. In addition, in this year the idea of 'market-based or human-benefit-driven' gained the most attention (43%; Figure 7b). In 2013, the ratio between publications prioritizing ESs and those prioritizing

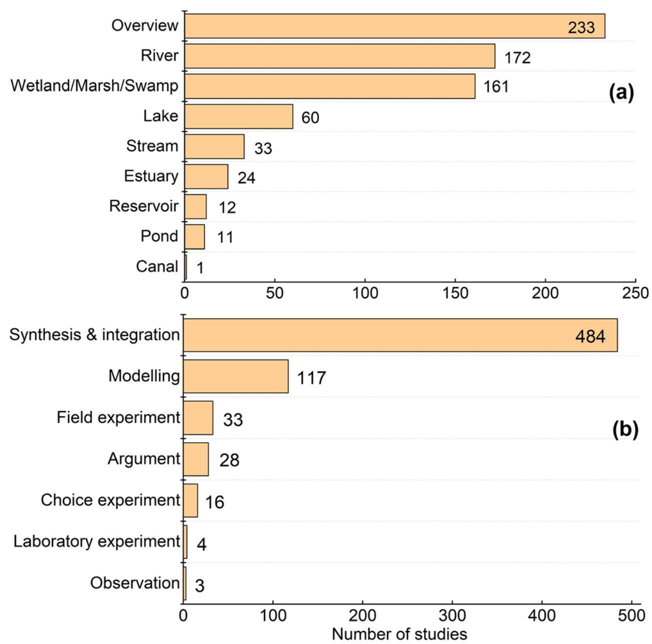

FIGURE 5 Number of studies ($N = 685$) based on (a) the type of freshwater ecosystem specified in the study (overview: without specific type, such as watershed (i.e. catchment), etc. – the total number by summing the number of studies in different research-approach groups was larger than the number of the selected studies because some studies were referenced for more than one specific type of freshwater ecosystem – and (b) the method used in the study to discuss freshwater ecosystem conservation and restoration and ecosystem services.

ecosystem processes and functions was more than 9:1. Moreover, there was a surge in the number of publications in 2018 prioritizing ESs. The popularity of the idea of market-based or human-benefit-driven showed a remarkable rise and subsequent decline from 2008 to 2012. Despite the fluctuations over the years, since 2012 a significantly larger number of studies have merely supported or adopted the ecosystem-service-based concept in comparison with those advocating the market-based or human-benefit-driven approach.

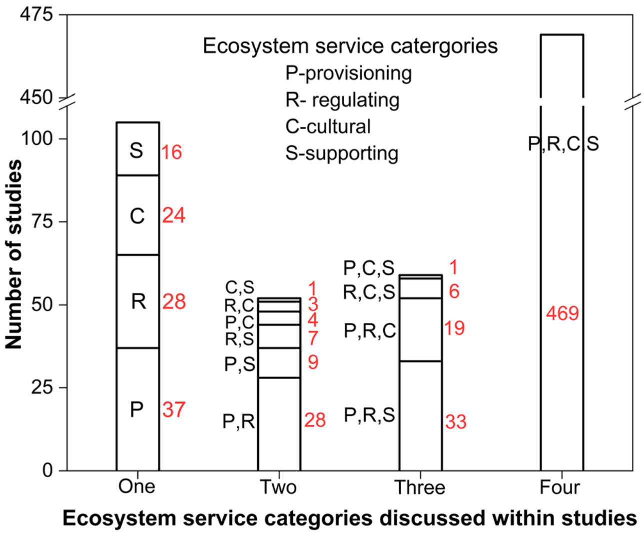

FIGURE 6 Combinations of ecosystem services from the overarching Millennium Ecosystem Assessment categories mentioned, assessed or valued within the 685 compiled studies. Numbers next to the histograms are the number of studies discussing different ecosystem service categories.

4 | DISCUSSION

The results demonstrate worldwide interest in integrating the ES concept into freshwater ECR across a range of academic disciplines. Consistent with the findings of similar systematic reviews for different ecosystems (Seppelt et al., 2011; Liquete et al., 2013; Hanna et al., 2018; Weitzman, 2019), most of the researchers who devoted efforts to freshwater ECR and ES research over the past 12 years were from European countries, the USA and mainland China. In addition, local studies of a single country were unevenly distributed. This geographical distribution pattern may be due in part to the alignment in ES research from prominent local academic institutions and researchers in this field (Liquete et al., 2013; Zhang et al., 2019). How to conserve and manage freshwater ecosystems and thereby achieve sustainable freshwater resources has been a controversial issue for decades (Richter et al., 2003; Poff, 2009; Poff et al., 2016). Most of the controversy is driven by socio-economic conditions. A country with higher GDP per capita generally spends more money on ECR (Pergams et al., 2004; Gelissen, 2007). Weitzman (2019) suggested that ES studies in aquaculture are driven by common environmental or conservation concerns more than by motivations to assess the environmental and social impacts of aquaculture. It is reasonable, therefore, to expect that a country's economic condition and the quantity of freshwater withdrawal are significant factors that may have impacts on freshwater ECR and ESs studies. The results confirm the significantly positive relationships between the number of studies and these two factors. However, it seems that AFW had a stronger effect than GDP per capita in the regions where AFW exceeded 1.22×10^{10} m^3. This result indicates that the nation's level of concern for freshwater ESs could be driven by its freshwater withdrawal and use. Since the early 2000s, water provisioning has

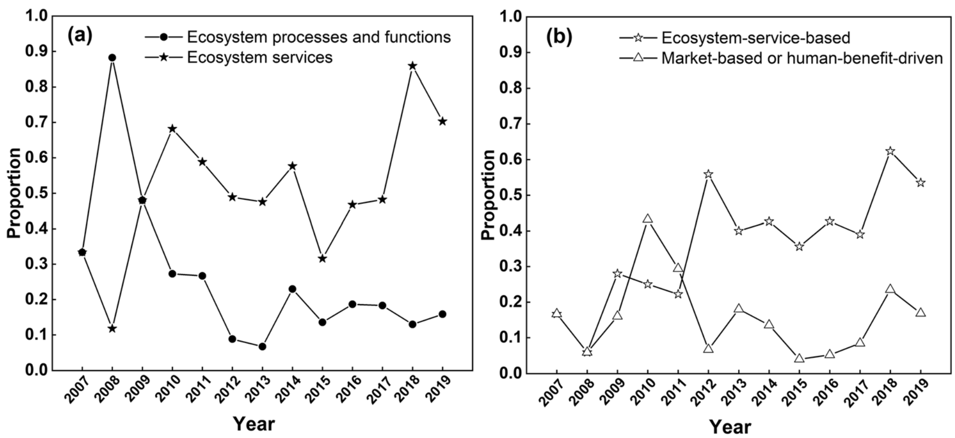

FIGURE 7 Temporal trends in the proportion of target setting as ecosystem processes and functions or ecosystem services (a), and ecosystem-services-based and market-based or human-benefit-driven (b). To facilitate visual comparisons among divergent research focuses, the studies that presented no explicit priority (classified as 'others', 149 studies) were excluded; 'ecosystem processes and functions' refers to studies prioritizing ecosystem functions and considering ecosystem services (ESs) as an adjunct to targets such as biodiversity protection; 'ecosystem services' refers to studies taking ES provision as the main motivation for ecosystem conservation and restoration (ECR) actions; 'ecosystem-services-based' refers to studies prioritizing ESs merely for motivating public interests to conserve or restore ecosystems; and 'market-based or human-benefit-driven' refers to studies focusing on the economic value of ESs. All proportions were calculated by the respective classified number to the total number of selected 685 studies.

been well beyond levels that can sustain present and future demands (Millennium Ecosystem Assessment, 2005). The high demand for fresh water, including public water use, agricultural water use, livestock water use, energy water use (e.g. for cooling), industrial use, environmental flow requirements and green (precipitation) water consumption, has drawn attention to the mapping of water provisioning services (Karabulut et al., 2016). Therefore, studies focusing on provisioning services accounted for the largest number. In addition, the results indicate that there was more emphasis on regulating services than cultural and supporting services, which has a significant effect on the provisioning capacity of other ESs (Boyd & Banzhaf, 2007). These results are in line with other literature reviews on river ecosystems, in which the authors attributed the bias to the fact that ESs can increase the perceived importance of river ecosystems and facilitate their quantification and monetary valuation, such as producing or sustaining the production of material goods included in these two categories (Martín-López et al., 2012; Hanna et al., 2018).

Most publications conducted specific case-study research. The researchers mapped or evaluated ESs, addressed the impacts of human activities or used the ES framework to conserve and restore freshwater ecosystems within the study area, implying that the ES concept had been integrated into freshwater ecosystem management practices. The second most common study type was categorized as 'methodological research', which mainly focused on exploiting or developing modelling tools or frameworks for evaluating and applying the ES concept or calculating the economic value of ESs. In addition, the modelling tools and frameworks used in studies to address their corresponding topics were diverse. These results suggest that despite widespread attention to the sustained provision of crucial ESs (Boulton, Ekebom & Gislason, 2016), the research field is still developing standards and aiming to reach consensus on how to apply the concept of ESs and quantify ESs in ECR (Hanna et al., 2018). As trade-offs can occur between biodiversity and ESs as well as between multiple ESs and among stakeholders (Peterson et al., 2010; Howe et al., 2014; Turkelboom et al., 2018), arguments about the possibility of achieving win–win outcomes or synergies are continuing, as reflected by the considerable number of opinion-dominated publications. There was a clear research trend following the call for studies to quantify a range of freshwater services at regional scales (Qiu & Turner, 2013), with the result that the majority of the compiled studies covered all types of ecosystems at the catchment scale. In addition, the results indicate that unequal attention has been given to various types of surface freshwater ecosystems, with much more effort devoted to rivers and wetlands (marshes or swamps). Similar results were found by Feld et al. (2009) in a synthesis of the indicators of biodiversity and ecosystem services across ecosystems.

Although the ES concept is widely discussed (Gómez-Baggethun et al., 2010; Aggestam, 2015; Droste, D'Amato & Goddard, 2018), this is the first study to show results confirming that it is perceived increasingly to contribute to freshwater ECR. There is strong evidence that the term 'ecosystem services' has appeared in conservation plans globally (e.g. the Aichi Biodiversity Targets in the Strategic Plan for Biodiversity 2011–2020, Convention on Biological Diversity, 2010). In addition, as Daily & Matson (2008) anticipated, the ES concept is moving from theory to practice, as reflected by its implementation in many case studies (Hoeinghaus et al., 2009; Gunderson, Cosens & Garmestani, 2016). In 2012, the journal *Ecosystem Services*, the most cited journal in the analyses, was established (Braat & De Groot, 2012), which initiated the proliferation of ES research and the further development of the ES concept. Although the proportion of publications explicitly supporting or adopting the ES concept was not as high as expected, most of the 'other' publications, which accounted for a considerable proportion, also implied a shift to ESs because the underlying premise of these publications was the essential role of ESs (e.g. mapping or evaluating the value of ESs, discussing the factors influencing ESs or developing tools for assessing ESs). By examining ES publications from 1997 to 2017, Costanza et al. (2017) highlighted progress over the past 20 years, including the development from definitions to classification to valuation, and from integrated modelling to public participation and communication, as well as the evolution of institutions and governance innovation. Notably, however, there is a long path ahead to apply the ES concept in ECR practices, which can be inferred from the finding that 43% of the publications belonged to ecological disciplines, followed by environmental science (33%) and a sizeable proportion of methodology and opinion publications.

By providing net benefits for human welfare and economic development, ESs have provoked a conceptual debate on their trading and market-based instruments (Muradian et al., 2013). Various organizations and researchers argue that the degradation of ESs can be reversed by integrating ES values into traditional markets, which have the potential to take advantage of the limited funding and investment in environmental management and alleviate poverty (Pagiola, Arcenas & Platais, 2005; Gutman, 2007; Russi et al., 2013). However, others suggest that it may be counterproductive to expect that payments for ESs can address both environmental degradation and economic development (Wunder, 2008). The results show that in 2010, the market-based or human-benefit-driven ES concept gained more attention than the ecosystem-service-based concept in freshwater ecosystems, possibly because of an important landmark article referring to market-based instruments (Ten Brink, 2011). However, compared with the ecosystem-service-based concept, the market-based or human-benefit-driven concept was found less often in scientific publications despite detectable growth around the globe in active programmes that exchange value for land management practices intended to provide or ensure ESs (Salzman et al., 2018). McCauley's statement that 'we will make more progress in the long run by appealing to people's hearts rather than to their wallets' (McCauley, 2006) probably still represents the dominant view in the scientific community. In addition, some researchers have noted that market-based approaches tend to favour single ESs rather than multiple benefits (Muradian & Rival, 2012) because marketization normally results in the itemization of services to create distinct, tradable 'commodities'. In parallel, this could lead to a moral difficulty in making decisions for specific ESs because of the trade-offs of ESs (Congreve & Cross, 2019). Although some researchers have proposed the concept of ES bundles (sets of ESs that repeatedly appear together across space or time) and assert that this would be a useful approach to manage multiple ESs (Kareiva et al., 2007; Raudsepp-Hearne, Peterson & Bennett, 2010), there is still a high probability of inadvertent trade-offs within bundles and some services being overlooked (Kosoy & Corbera, 2010). Another notable fact that could impose restrictions on the rise of market-based or human-benefit-driven studies is the lack of effective and legitimate market-based instruments that explain how to price accurately the various ESs and what the technical and normative boundaries of implementing and generalizing the market approach are (Kroeger & Casey, 2007; Gómez-Baggethun & Muradian, 2015).

Should the market-based or human-benefit-driven concept be rejected? Based on a recent discussion on this topic (Gómez-Baggethun & Muradian, 2015), we argue that market-based mechanisms are truly controversial and may not be suitable for all ecosystems, but they may find their own 'fertile land'. For example, Wunder (2007) suggested that the market-based approach was arguably the best choice for scenarios of moderate conservation opportunity costs on marginal lands and in settings with emerging but not yet realized threats. In terms of lake management, the need for mainstream preventative lake management actions has recently been highlighted, because in practice it is difficult to promote costly interventions to achieve no ecological change (Spears et al., 2022). In addition, some researchers believe that stark preservation-vs.-conversion choices among distinct ESs can be optimized by calculating their relative importance and value (Barbier et al., 2008). Thus, the ES concept can be expected to contribute to the protection of the intrinsic value of nature as the cultural ES domain covers non-material value as well (Schröter et al., 2014).

5 | CONCLUSIONS AND RECOMMENDATIONS

As expected, research effort in integrating the ES concept into freshwater ECR has shown a growing trend across the globe since 2007 as governments and researchers have realized that this is a critical time to ensure long-term prosperity for people and nature (Villarreal-Rosas et al., 2020). However, the compiled studies present an uneven geographical distribution pattern, which is significantly related to the AFW and GDP per capita of each country. This review also found that the ES literature for freshwater ECR was characterized by unbalanced coverage of different kinds of freshwater systems; some ESs attracted much more attention than others, such as provisioning services. In addition, a clear research trend was detected in which a range of freshwater ESs was quantified at a regional scale.

One main goal of this study was to explore the extent to which freshwater ECR strategies consider targeting ESs and how this perspective has changed over time. By synthesizing the literature and statistical analysis of the change in target setting for freshwater ECR, this review found that ESs have been increasingly accepted by many conservationists and restoration practitioners as the primary target for freshwater ECR. Although applying the ES concept is indeed a promising avenue to improve freshwater ECR, it is worth noting that ES research on freshwater ecosystems is still a rapidly developing research field. In addition, considerable efforts have been devoted to market-based approaches to enhance ES integration. However, controversy continues regarding the monetary valuations of freshwater ESs.

Based on this review, there are several recommendations for the future application of ES concepts in freshwater ECRs:

1. Integrate the ES concept with biodiversity protection and other ECR goals (Boulton, Ekebom & Gislason, 2016; van Rees et al., 2021) and try to achieve win–win situations or create synergies by understanding why (and what) trade-offs are generated between biodiversity and ESs as well as among the ES being delivered (Howe et al., 2014).
2. Fill data gaps on specific ecosystem functions and their links to ESs and incomplete ES information to better implement freshwater ECR policies at regional and national levels. The implementation of conservation or management policies at regional and national levels needs to consider the full range of species and habitats. At present, the research field appears to be driven by clusters in the USA, China and Europe.
3. Build collaborative participatory platforms that can bring together experts across disciplines (eco-environmental, social, and economic) to develop interdisciplinary approaches that consider multiple ES values for provisioning, regulating, supporting and cultural services. In addition, researchers need to improve communication and outreach with stakeholders and decision-makers to promote a better understanding of the ES concept and its application in practice (Lopes & Videira, 2018; Saarikoski et al., 2018).

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

AUTHOR CONTRIBUTIONS

Yanran Dai: Conceptualization; writing – original draft; funding acquisition; investigation; visualization; methodology; validation; formal analysis; software; writing – review and editing; project administration; data curation; resources. **Juan Wu**: Validation; writing – review and editing; formal analysis; methodology. **Qiang Yang**: Visualization; methodology; writing – review and editing.

Shuiping Cheng: Formal analysis. **Wei Liang**: Formal analysis. **Thomas Hein**: Conceptualization; funding acquisition; writing – review and editing; supervision; formal analysis.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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