

# General trends in freshwater ecological restoration practice in China over the past two decades: the driving factors and the evaluation of restoration outcome

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## Research

**Keywords:** freshwater ecological restoration; economic growth; restoration outcome evaluation; China

**Posted Date:** March 19th, 2020

**DOI:** <https://doi.org/10.21203/rs.2.19860/v2>

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**Version of Record:** A version of this preprint was published at Environmental Sciences Europe on April 7th, 2020. See the published version at <https://doi.org/10.1186/s12302-020-00335-4>.

# Abstract

**Background** Although freshwater ecological restoration (FER) has undergone an immense development over the past two decades in China either in the number of projects or in the spatial scale of implementations, a dearth of clear and comprehensive trends in this field is still a particular concern. We conducted a literature survey through searching the database of Web of Science between 1997-2017 to investigate the driving force behind FER practice and to summarize the restoration outcomes. **Results** A total of 2047 publications were hit and 198 of them were finally retained after manual screening. The number of studies in this field has been steadily increasing in recent years and their provincial distribution is positively correlated with GDP growth and the investment to pollution control and environmental protection, suggesting that economic development is a key driving factor of FER practice. Among the remained articles, nearly half (46.5%) focus on lake ecosystems, and 34.8% and 32.8% of the studies indicate that land reclamation and eutrophication are the predominant causes of freshwater ecosystem degradation. The overarching target of the restoration is biodiversity increase (31.4%), followed by water quality improvement (24.7%) and ecosystem services (23.9%). Revegetation is a dominant restoration approach (40.9%). Reference sites for assessment of restoration projects are normally control locations without intervention (60%), or the status of the targeted sites before the interventions. For the restoration outcome evaluation, 86% of the studies present positive outcomes in terms of water quality improvement, and 79% have improvement in biological features. The most frequently monitored organisms are macrophytes (31%), followed by benthos as indicators of ecological condition. **Conclusions** Economic growth, water pollution and investment into environmental protection are the main driving factors of FER practice in China. The effort of restoration and evaluation over the past two decades has not been limited to improving hydrological function and water quality, but also pay increasingly more attention to biological processes and ecological integrity, and further the ecosystem services in recent years. However, the lack of long-term monitoring and socioeconomic attributes considered in restoration success assessments are still particular issues needed to be addressed in the future FER researches and projects.

## Background

As a young applied science, ecological restoration has undergone considerably rapid growth over the past decades around the globe. Due to the wide dependence of human activities on freshwater, freshwater ecological restoration (FER) has become a more highlighted topic compared to terrestrial ecosystem restoration. The issues of water resource shortage and water pollution, inevitably more severe in developing regions, make FER increasingly urgent and critical. Over the past decades, a large number of FER related research have been published in a broad range of scientific journals, in which theoretical development, modulation of ecological structure and function, restoration or mitigation approaches, and evaluation of restoration outcomes are the major research objectives. However, it seems that the focus of restoration has been shifting from achieving a previous or least-disturbed ecological state to a more utilitarian purpose: ecosystem services [12, 25]. The shift of restoration goal has been reflected in the

studies and findings, with a focus on the roles of particular species in supporting the ecosystem processes or products useful to humans [20].

In the unprecedented wave of economic development and urbanization, China has been experiencing a tremendous freshwater crisis. Water quality of the largest rivers, lakes and reservoirs dramatically declined in the 1990s and 2000s. Environmental communiqués issued by the Ministry of Environmental Protection indicate that the seven major river systems had the worst water qualities during 2001-2004, with over 26% of monitored river sections having water qualities worse than Grade V under the Environmental Quality Standards for Surface Water of China, while back to 1991, such water quality levels had not been observed. The deterioration of lakes and reservoirs is even more severe than the rivers, 48% of monitored water areas had water qualities below Grade V in 2006. In addition, the structure and function of freshwater ecosystems have been sharply degraded, mainly due to land reclamation, water shortage, water pollution and climate change [3, 34, 36]. Despite the abundant total water resource, the annual per capita renewable freshwater availability was 2007 m<sup>3</sup> in 2018, only accounting for 25% of the world's average [21]. The water scarcity, aggravated by pollution, leads to difficulties to meet the basic environmental and ecological demands for water in many freshwater ecosystems [15]. Moreover, the freshwater wetlands had shrunk by 8.82% from 52.43 million hectare in 2003 to 47.81 million hectare in 2013 [32]. The habitat losses were mainly resulted from the highly intensified land reclamation and climate change [36].

The degradation of ecological processes and ecosystem services have raised increasingly more awareness of scientists, public and governments in China, thus promoting an accelerated growth of FER researches and projects during the past 20 years. Since the beginning of 21th century, the Chinese central government has launched a number of national water pollution control projects, aiming to substantially constrain the water pollution and ecological degradation of important watersheds, including the most polluted “three rivers” and “three lakes”. The investment into water pollution control increased from 493.7 billion CNY (ca. US\$ 71.7 billion) in 2008 to 953.9 billion CNY (ca. US\$ 138.4 billion) in 2017 [19]. Given the specific governmental structure and institutional characteristics of China, the FER projects, particularly the large-scale ones, are mostly policy driven and invested by different levels of government. In addition, the dependence on political and economic progress in the evaluation and promotion of governmental officials determines that the implementation and outcome evaluation of restoration projects typically focus on short-term political and economic benefits rather than long-term environmental and ecological effects [1, 6, 17].

A focus on design and engineering approaches to recover the hydrological or geomorphological characteristics of the targeted ecosystem is broadly shared by a large proportion of the researches and projects [4,10, 42, 43]. Stabilizing the bank line, altering the slope and hydrology, manipulating the flow regime and dredging the sediment are typically employed in the implementation of these projects [14, 18, 45]. More recently, a focus on water quality improvement has driven many FER implementations, in which an array of in-situ physicochemical and biological techniques have been developed and applied with an attempt to remove or stabilize pollutants and nutrients in water column or sediment [8, 26, 37]. Among

these techniques, revegetation has gained considerable attention. Aquatic macrophyte populations were usually rebuilt as an approach to absorb the nutrients and to maintain the clear water, rather than a critical structural component of aquatic ecosystem or a goal of the restoration [2, 5, 35, 40, 44].

Although an increasing number of FER projects are undertaken, the ecological effects of restoration are rarely assessed comprehensively and substantially and only few of such assessments show an improvement [25]. Besides of physical and chemical variables, the evaluation of restoration outcome often rely on one or a few assessed organism groups, which are generally monitored pre- and post-restoration. The pre-restoration data may be absent in some cases, to facilitate drawing general conclusions about project outcomes as a function of restoration measures, a reference site that is not to be restored needs to be selected. Facing a lack of integrative methods or tools, restoration ecologists and practitioners have been trying to develop integrative multi-variable evaluation methods and modules to evaluate the restoration effects and to support management decision making [24, 33, 38].

There are some published studies reviewing on the theoretical and practical progresses of FER in China [30, 37, 41], most of which merely focus on summarizing policy changes, or providing general descriptions of developing trend, but lacks a quantitative assessment on this topic. Our goal is to comprehensively comb the developing processes of FER practice over the past two decades and to identify the current status of FER efforts in China, hoping it could offer a reliable guidance for the field in the future.

## Methods

### Literature search

A literature search was conducted in January 2018 using the ISI Web of Knowledge database (<http://apps.webofknowledge.com>) to obtain the publications from 1997-2017 with the methods outlined by Kollmann et al. [13]. The database includes the Web of Science core collection, Chinese Science and Citation Database (CSCD), Derwent Innovations Index, KCI-Korean Journal Database, MEDLINE, Russian Science Citation Index and SciELO Citation Index. Aside from international journals, due to inclusion of CSCD in the database, most of predominant Chinese journals published in China were also the targets of the search. We used the following querying strings to conduct the search:

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TITLE= (restor* OR recover* OR conserv* OR reestab* OR revegeta*OR reintro* OR rehabil* OR rewet*OR repair*) AND TOPIC= (freshwater OR stream OR waterway OR channel OR river OR lake OR estuary OR pond OR marsh OR swamp OR wetland OR watershed OR basin) AND Research Area= (biological sciences OR environmental sciences ecology) AND Country= (China OR PRC OR People's Republic of China)
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The document type was set as all document types, and language as all languages. The title (TI) and topic (TS) were specified as the above to focus on restoration of freshwater ecosystems, based on the experience with literature that these terms allow us to nearly pick up all the relevant papers. Since the

country where a restoration project or research has been undertaken is almost likely consistent with the authors' country, we limited the "CU" to China to rule out the research conducted in other countries.

### **Manual screening and categorizing**

The targeted publications were manually screened to identify research that presented actual full-scale restoration projects in field, and monitored and evaluated of restoration outcome. The pilot-scale studies conducted in laboratory were excluded. Furthermore, reviews and general strategic or policy discussions without specific case studies were ruled out. Because it was indicated that a substantial proportion of the papers merely provided describing and non-quantified assessments of project outcome, these papers were also removed. Similarly, modelling analyses merely focusing on modelling for evaluation of restoration success without any specific projects were discarded as well.

The extracted papers were categorized with the criteria in Table 1 characterizing the publication details, background of the ecosystems, details of restoration projects, and assessments of restoration outcome. Since most of the monitoring and evaluations were conducted with comparisons to reference sites or controls without artificial interventions, three types of reference site were also taken into account in the paper classification: simultaneous control site without intervention, previous state before intervention, and others. "Others" means that the evaluations were conducted using assessment methods that could be completed without comparison to specific reference sites, or just with comparison to the published results that were obtained with similar ecosystems and restoration techniques. The criteria used for evaluating restoration outcomes mainly included 4 sub-categories: (1) morphological or physical characteristics of ecosystem or habitat; (2) water quality; (3) biological characteristics and (4) ecological processes. The criteria of the first sub-category included hydrological parameters (i.e. flow velocity and hydraulic dynamics), sediment/soil characteristics, structural stability, and diversity and integrity of habitat. The second sub-category included COD, BOD, transparency, TSS, DO, nutrients, metals, POPs, pathogens and other chemical variables. The third sub-category included biodiversity, species richness, population and biomass of organisms. The fourth sub-category included primary and secondary production, nutrient dynamics, organic matter cycling, food web diversity, et al. The fifth sub-category included aquatic production, navigation, aesthetic and educational value, etc. Depending on whether changes in the monitored criteria after a project indicated progress towards the restoration goal, the outcome was classified into "improved (Yes)", "not improved (No)", and "not decided due to the inconsistent changing pattern of monitored indicators (Hard to decide)". Number and ratio of papers classified into the criteria under each category were recorded.

Table 1 Categories and criteria of literature classification

Categories	Sub-categories	Criteria
Publication details		Publishing year Journal Language
Background information of ecosystem		Ecosystem type Project location (province or city) Type of ecosystem Degradation cause
Details of restoration project		Spacial scale of project or research Duration of artificial intervention Duration of monitoring Restoration goal  Restoration measures
Evaluation of restoration outcome	Morphological or physical characteristics of ecosystem or habitat	Hydrological parameters (i.e. flow velocity and hydraulic dynamics) Sediment/soil characteristics  Structural stability  Diversity and integrity of habitat
		Water quality
	Biological characteristics	Biodiversity and species richness Abundance Community structure Presence of endangered species
	Ecological processes	Primary and secondary production Cycling of nutrient and organic matter Food web diversity
	Socioeconomic benefits	Aquatic production, navigation, aesthetic and educational value, etc.

## Data analyses

In order to explore the impact of socioeconomic development on FER practice in China, statistical data of population, GDP growth, water resource, amount of wastewater discharge, and investment into water pollution control of each province were obtained from the website of National Bureau of Statistics of China (NBSC). The selection of these socioeconomic indices is supported by the following assumptions: (1) with an increasing population and wastewater discharge, ecological issues will be increasingly more severer, consequently provoking more investment into environmental pollution control; (2) economic growth relates positively to the production of applied ecological research and practice. The correlations between number of filter papers and the socioeconomic variables were respectively analyzed as a function of year.

Since the preliminary result of the analysis indicated that the distribution of projects in province was extremely uneven, we classified all provinces or cities of China into 6 regions as shown on the website of NBSC: Northeast, North, East, Northwest, Southwest and Central south. The correlations between the number of published papers and the socioeconomic indices in the level of region were analyzed.

## Results

### Temporal and regional distribution of FER studies

A total of 2047 publications have been targeted in the literature searching, most of which were published after 2002. After the manual screening, 198 publications were remained to be categorized, and 67 of them were in English, the rest were in Chinese. Similar to the temporal distribution of the unscreened publications, the number of filtered papers showed a general growing pattern with time, increasing from 6 in 2003 to 18 in 2007, and experienced a valley point between 2009-2010 with numbers less than 10, then increased again to 22 in 2017 (Fig. 1).

The regional distribution of the publications was highly uneven across the provinces and regions. More than half (54.0%) of the filtered studies were performed in the eastern region, and 20.2% in the central southern area (Fig. 2). The rest areas, including North, Northeast, Northwest and Southwest, totally contribute only 1/4 (25.8%) of the studies. The centralization of studies in the eastern region was reasonably related to the biggest population and GDP contribution in this region. Correlations among the socioeconomic indices and the numbers of filter FER publications indicated that, the publication number was significantly correlated with the regional population, GDP growth, wastewater discharge and investment into water pollution control, but had no relation with the water resources (Table 2). And as expected, there were notable correlations among population, GDP, wastewater discharge and investment into water pollution control.

Table 2 Correlations among socioeconomic indices of each region in 2017 and the numbers of filter freshwater ecological restoration publications.

Correlation coefficient	GDP	Water resource	Wastewater discharge	Water pollution control investment	FER publication number
Population ( $\times 10^6$ )	0.972***	0.405	0.996***	0.819*	0.902*
GDP ( $\times 10^9$ RMB)		0.197	0.979***	0.923**	0.968***
Water resource ( $\times 10^9$ m <sup>3</sup> )			0.360	-0.068	0.098
Wastewater discharge ( $\times 10^6$ m <sup>3</sup> )				0.845*	0.924**
Water pollution control investment ( $\times 10^9$ RMB)					0.977***

\* Indicates  $P < 0.05$ , \*\* Indicates  $P < 0.01$ , \*\*\* Indicates  $P < 0.001$ .

### Details of the FER projects

Fig. 3 indicated that nearly half of the FER practice studies have been conducted in lakes (46.5%), followed by estuaries (15.2%) and channels (13.6%). Surprisingly, the proportion of project research completed at large rivers is only 7.6%, lower than that in marshes/swamps (9.1%). The biggest two causes of ecological degradation were land reclamation (accounting for 35%) and eutrophication (33%), water pollution alone was merely the third cause (12%). Moreover, water shortage was not one of the major reasons leading to the degradation of freshwater ecosystems, not consistent with some previous reviewing literatures. The scale of FER projects were mainly river reaches or lake regions, accounting for 75% of the total number of the studies, only a small part of the studies were conducted in whole ecosystems (12%) or watersheds (2%). More than 60% of the studies simultaneously monitored the sites or points without intervention as the references to evaluate the restoration outcome, and 28.8% compared the status before and after the projects to decide whether there were progresses made with the restorations.

The goals of the restoration projects predominantly focused on improving biodiversity (31.4%), water quality (24.7%) and ecosystem services (23.9%). Other goals include protecting endangered species, stabilizing physical structure of ecosystems, improving nutrient cycling, invasive species control, etc., only accounting for 20% (Fig. 4). About 40% of the filter studies applied revegetation as the main approach to restore the freshwater ecosystems, while much less proportions of studies employed physical or chemical measures (17.2%) and biomanipulation (11.4%).

The period of restoration intervention and monitoring have also been recorded in the publication classification. The artificial intervention put into the restoration did not have long period. Nearly half of the studies indicated a period of continuous restoration intervention shorter than one year and about 1/3 had 1 to 5-year intervention (Fig. 5A). Only 12% and 10% of the studies showed 6-10 and >10 years of intervention duration. Similar to the intervention period, the monitoring period was also short, with 55% of studies having <1 year of monitoring duration, and only approximately 1/3 having 1-5 years of monitoring (Fig. 5B).

### **Outcome evaluation of FER projects**

Given the multiple restoration goals, the indices considered in the assessments of project outcome were accordingly diverse, which were categorized to 4 major dimensions as described above. The most predominant aspect considered in evaluating improvements achieved on the physical or morphological dimension was the characteristics of sediment or soil, followed by hydrological dynamics (Fig. 6A). Habitat diversity was also an important factor, generally specified with diversity of environmental conditions of the ecosystems. For the studies aiming at antierosion of bank, or landscape effect, the slope stability or channel form were also considered. More than half of the studies (58%) showed positive results in terms of the monitored indices. However, due to the incompatibility of the changes in different indices, 1/3 of the studies did not indicate precise results.

For the projects addressing water quality improvement, the most frequently monitored parameters included nutrient, chemical oxygen demand (COD), transparency and dissolved oxygen (DO), among

which nutrients (nitrogen and phosphorus in particular) were absolutely the dominant factor, accounting for 32% of the publications (Fig. 6B). Most of these studies made progresses on water quality improvement (86%), namely the concentration of nutrients, COD, BOD, TSS and so on declined, transparency and DO increased. There was still a small proportion of studies showing ambiguous feedbacks for water quality improvement.

Most of the studies monitored the traditional ecological indices including species richness, population, biomass and biodiversity (Fig. 6C). Macrophytes were one of the most frequently monitored organisms, which had a ratio of 31% in all organisms involved in evaluating the biological outcomes of FER project. Phytoplankton and benthos were also the other biological groups regularly appeared in the monitoring and evaluation work. Nearly 80% of papers achieved notable improvement in biological characteristics.

Apart from the traditional biological indices, some ecological processes or function, e.g., nutrient cycling, organic dynamics, primary production, food web, and other ecosystem services were also considered in a few studies (Fig. 6D). Among them, nutrient cycling and organic dynamics were the two predominant factors evaluated in these projects. And similarly, 85% of the papers showed good performance in improving the ecological processes and functions.

## Discussion

### Growth of FER studies with time and socioeconomic development

The growth of FER research and practices with time is approximately consistent with the deterioration of water quality and ecological functions in freshwater ecosystems. During the first five years of 21 century, the water qualities of surface freshwater exhibited the worst status. Meanwhile, the freshwaters were also facing increasingly serious issues, such as habitat losses, species extinction, ecological invasion, ecosystem service decline, and so on [16, 31, 36, 46]. That is also when a number of nation-wide FER projects have been launched to alter the situation (e.g., Major National Scientific and Technological Projects on Water Pollution Control and Treatment). The rapid increase in FER studies during the same period (Fig. 1) was mostly the outcome of these projects and efforts. The studies conducted in Suzhou River, Shanghai and Taihu Lake, Jiangsu Province contributed the majority of publications in the East China, which is inevitably ascribed to the severity of water pollution of these two waters. Additionally, the regional GDP and investment into environmental protection had significant correlations with the number of FER studies (Table 1), highlighting the importance of overall economic development and financial investment into the scientific research and environmental protection [12, 23].

### Quantitative details of the FER projects

Almost half of the FER studies were conducted in lakes (Fig. 3A), which was likely associated with the bigger pressure from improving the deteriorated water qualities in the large lakes compared to other ecosystem types. And it in some way reflects the fact that it is more difficulty to perform small-scale projects or studies in large running waters. In most studies in which the authors mentioned about the

causes of ecosystem degradation, the predominant causes are land reclamation and eutrophication (Fig. 3B), which is consistent with what we mentioned in the introduction.

Most restoration projects are completed at reach scale for rivers and area scale for lakes, the ratio of studies at watershed scale is only 2% (Fig. 3C). It is associated with the fact that, in the past decade, many FER projects were implemented as demonstrations of the national wide and government-driven projects aiming to mitigate water pollution and ecological degradation. The disassembling of watershed-scale planning and over-dispersed investment and management result in the relatively small scales of restoration project. However, there is no doubt that an effective restoration requires coordinated efforts at the watershed, because the sources of impacts to ecosystems are largely generated outside of the freshwaters in the watershed, thus restoration potential may be very limited when entire watersheds are impaired [27, 39]. The tangling of property ownership, expectation for socioeconomic development from the government, interest demand from the public, and the investment mechanism, usually complicates the planning, implementation and evaluation of the restoration projects at the watershed level. Thus, it requires more interactions between different interest groups, more profound pre-restoration planning, and longer-term and bigger-scale monitoring for the watershed-scale FER projects.

Over 60% of the studies assess the project outcome by comparing to a reference site as the simultaneous control without intervention (Fig. 3D). This is particularly the case if the pre-restoration information about the ecological status is lacking. Actually, for the studies using the status before restoration as the reference, the “status before restoration” in most cases does not necessarily refer the status before degradation, and most project outcome assessments have just suggested whether the restoration actions worked compared with the situation without them.

The most frequently mentioned goals of restoration are improvement of biodiversity and water quality, and ecosystem services (Fig. 4A). The emphasize on biodiversity and water quality is similar with what was found in the study reviewing on the status of river restoration in the United States by Palmer et al. [25], while the difference is that the goals related to stabilizing channels, improving riparian and in-stream habitat for the US projects account for considerable percentages in the overall projects. Additionally, the methods used in our FER projects are dominated by revegetation (accounting for over 40%, Fig. 4B), which is greatly different from the focus on geomorphic measures for channels and streams in the US projects. It is partly ascribed to the popularity of the Natural Channel Design (NCD) approach for river restoration in the US in 20<sup>th</sup> century [28]. In addition, the limnological theory of alternative equilibria has been widely recognized when explaining the eutrophication of shallow lakes, in which aquatic macrophytes serve as a critical component remaining the clear water state. The broad application of revegetation as an restoration measure also has its practical cause. Although spontaneous colonization by plants following habitat recovery, is normally preferred, sometimes the re-introduction of native pioneer species is necessary in case the habitats are isolated or fragmented, or the seed bank is lacking [22]. Besides, from an perspective of cost and landscape effect, revegetation has a competitive superiority over the physical or chemical restoration techniques in improving water quality and rehabilitating ecological functions.

Time scale of the intervention and monitoring are typically shorter than 1 year (Fig. 5). Since most biogeochemical and ecological processes delay the responses of freshwater ecosystems to the interventions, potentially for decades [7], it is important to recognize that some restoration goals may only be achieved in a long run, which make the short-term monitoring compromising in offering substantial evidences underpinning the solid conclusions about whether the project outcomes are positive. Thus, the expanded duration, at least of post-restoration monitoring is needed to support the evaluation of FER outcomes.

### **Outcome evaluation of the FER projects**

Defining the success of a restoration project has always been an issue for restoration ecologists [25], and the main categories and key attributes that used to evaluate the outcome of the FER projects have been kept revised and updated during the past years. Besides of morphological and physical characteristics, water quality, biological characteristics and ecological processes, the categories of metrics for evaluating the outcome of FER projects we used in this study also include socioeconomic benefits (Table 1).

However, only 3 publications provided direct results concerning economic benefit from the restoration projects. Unlike the most previous studies which mainly used morphological or physical characteristics as indicators, our study shows that biological characteristics and water quality are the most commonly used categories for outcome evaluations (Fig. 6), and at least nearly 80% of the publications provided positive results based on the improvement of the monitored indicators, which can be considered to meet the restoration goals.

Although numerous studies of stream or river restoration indicate that the restoration of channel form and stream bank can lead to rehabilitation of physical habitat, biological recovery is not common even when the in-stream/channel structural variables are completely restored. Simply, habitat may be important ecologically, but it is not sufficient for assessing ecological outcomes, and in the vast majority of cases restoration of habitat does not certainly lead to biological restoration [9]. In fact, as one of the most frequently considered categories in evaluating the restoration effectiveness in our study, water quality usually limits the biological recovery of freshwaters, and thus ecological recovery will not occur until the source of pollutant is removed [11]. Many studies show and interpret the relationships between nutrient levels and ecological structure and function in freshwater ecosystems, and it is the classic theory of eutrophication of shallow lakes underpinning the most of FER practices in China.

In most projects aiming to improve water quality, physical/chemical measures and revegetation are employed, and in most cases, they are proved to be efficient in achieving the goal in our study. However, the pollution mitigations are typically carried out at relatively small scales (e.g., river section or lake region), and the monitoring of water quality and ecological status is almost accordingly conducted within limited spatial and temporal ranges (Fig. 5B), which makes whether the restoration effect can exists in a broader range and a longer term questionable. While, the best management practices at a watershed scale may reduce and delay pollution to the waterbodies and may improve water quality conditions and ultimately restore the ecological processes successfully [28]. But the projects focusing on the watershed-

scale restoration is still scarce over the past decades (Fig. 3C), not only in China but across the global [17, 20]. However, there is an increasing number of FER studies starting to include larger-scale and longer-term targets, which is hopeful for more thoroughly understanding restoration ecology and better FER practice.

## Conclusions

The present literature research indicated that economic growth, water pollution and investment into environmental protection are the main driving factors of FER practice in China. Additionally, the effort of restoration and evaluation over the past two decades has not been limited to improving hydrological function and water quality, but also paid increasingly more attention to biological processes and ecological integrity, and further the ecosystem services in recent years. However, FER researches and practice are mostly carried out at limited spatial and temporal ranges, and long-term monitoring and socioeconomic attributes considered in restoration success assessments are still lacking. Therefore, watershed or landscape-wide FER practice, and more integrative outcome evaluation methodology are the goals of future FER researches and projects.

## Abbreviations

FER: freshwater ecological restoration; CNY: China Yuan; CSCD: Chinese Science and Citation Database; NBSC: National Bureau of Statistics of China; GDP: gross domestic product; COD: chemical oxygen demand; BOD: biochemical oxygen demand; TSS: total solid substance; DO: dissolved oxygen; POPs: persistent organic pollutants.

## Declarations

### Acknowledgements

The paper is based on the projects initiated and financed by the National Natural Science Foundation of China (No. 51778455) and the National Major Program of Science and Technology (2017ZX07603-003).

### Authors' contributions

All authors contributed to the conception and design of the study. The literature search, manual screening, analyses and the manuscript writing were performed by JW. All authors commented and revised on the first draft of manuscript.

### Funding

This study was funded by the National Natural Science Foundation of China (No. 51778455) and the National Major Program of Science and Technology (2017ZX07603-003).

### Availability of data and materials

All data generated or analysed during this study are included in this published article.

### **Ethics approval and consent to participate**

Not applicable.

### **Consent for publication**

Informed consent was obtained from all individual participants included in the study.

### **Competing interests**

The authors declare that they have no competing interests.

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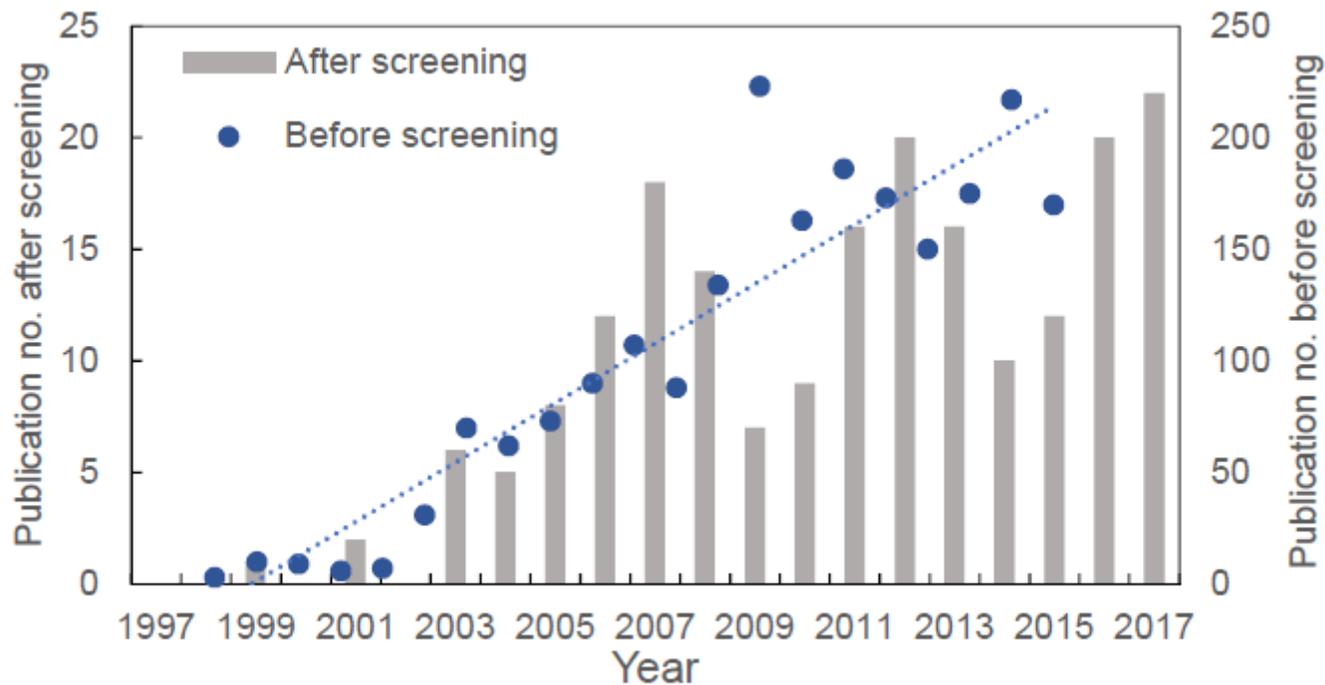
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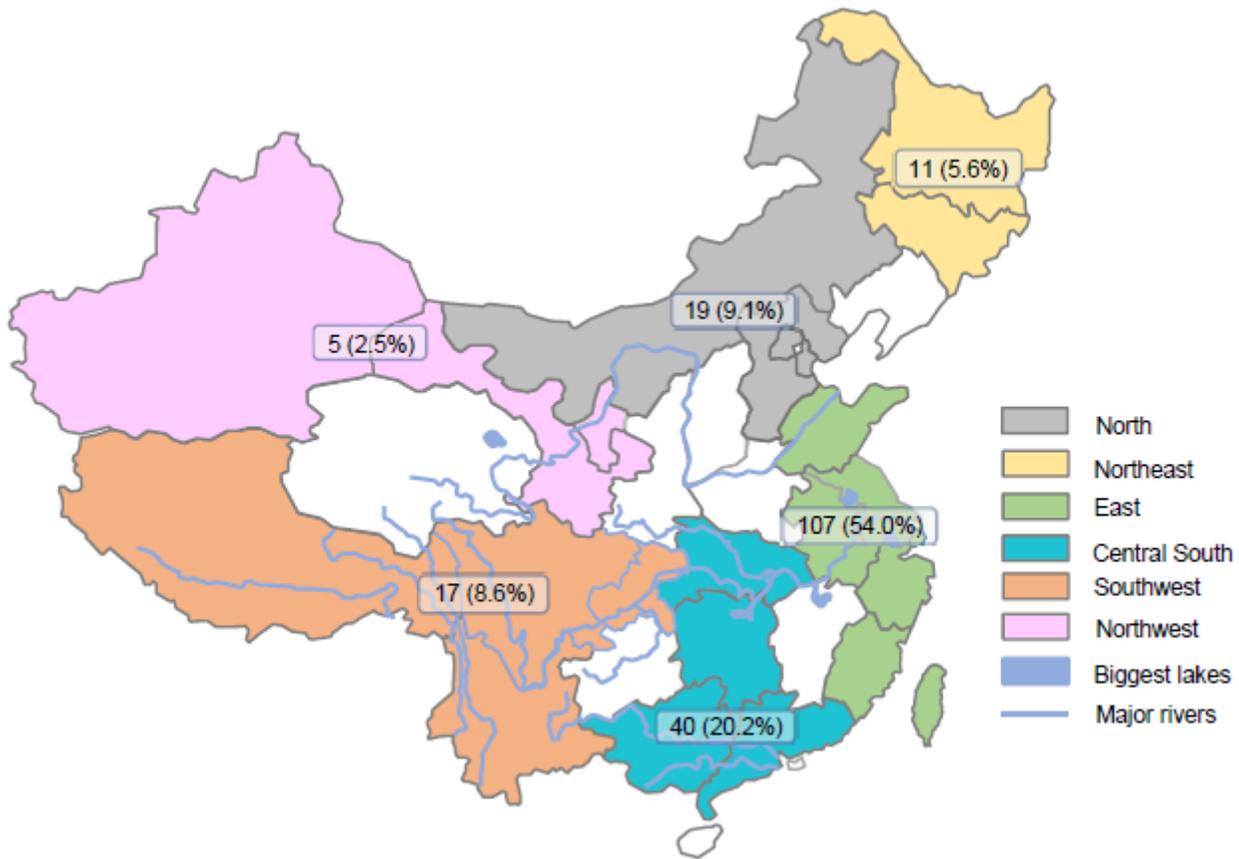
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## Figures



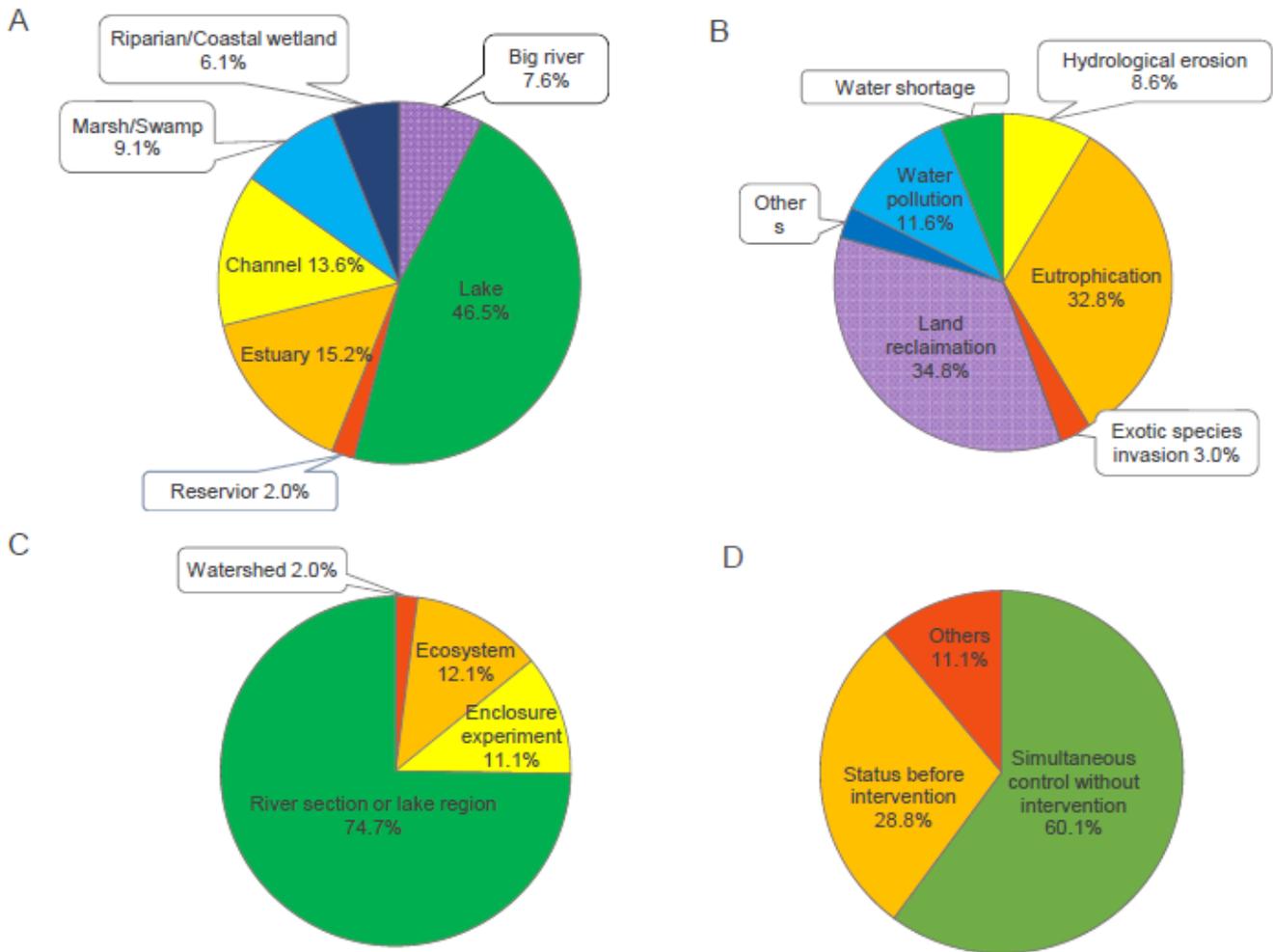
**Figure 1**

Changes in the number of publications of freshwater ecological restoration in China before and after manual screening



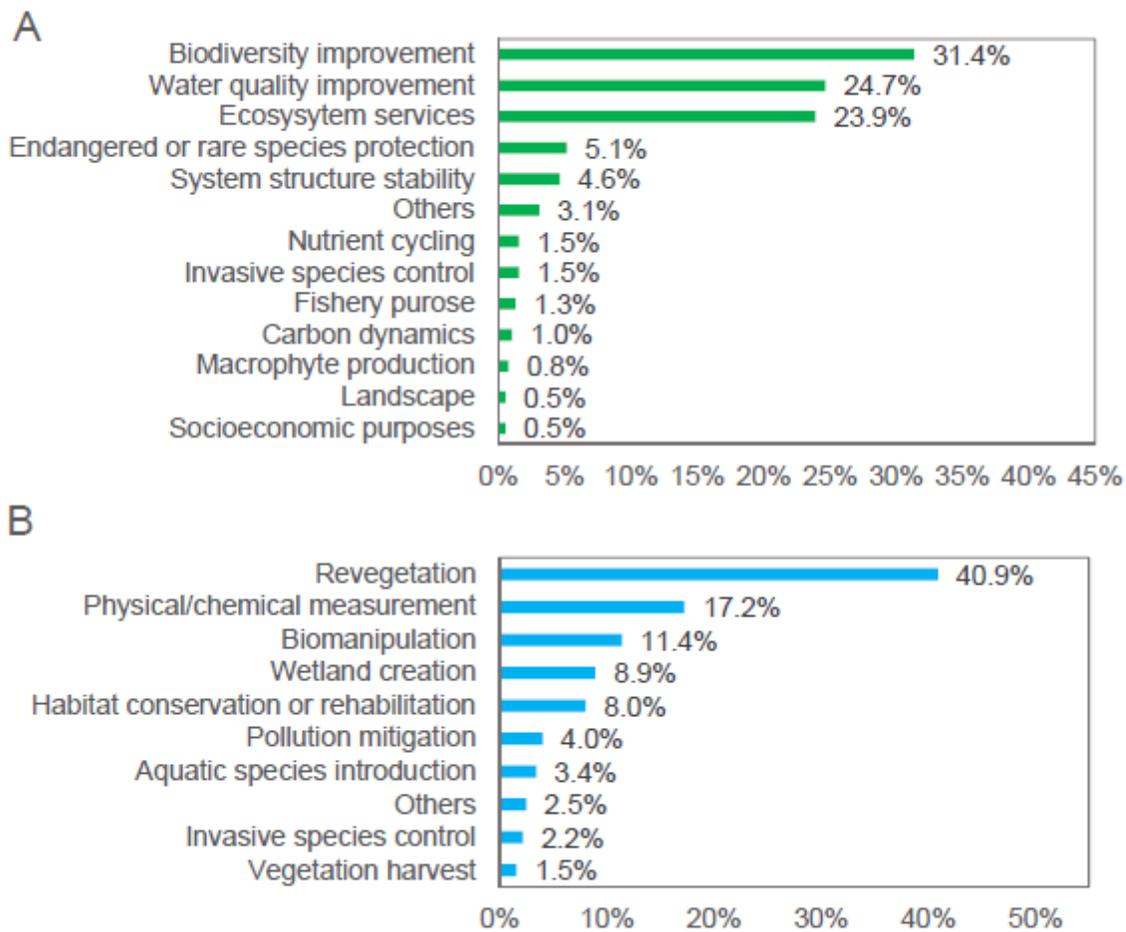
**Figure 2**

Regional distribution of filtered publications of freshwater ecological restoration across China. The number and percentage in each bracket on the map represent the publication number of each region and its ratio of the total publications. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



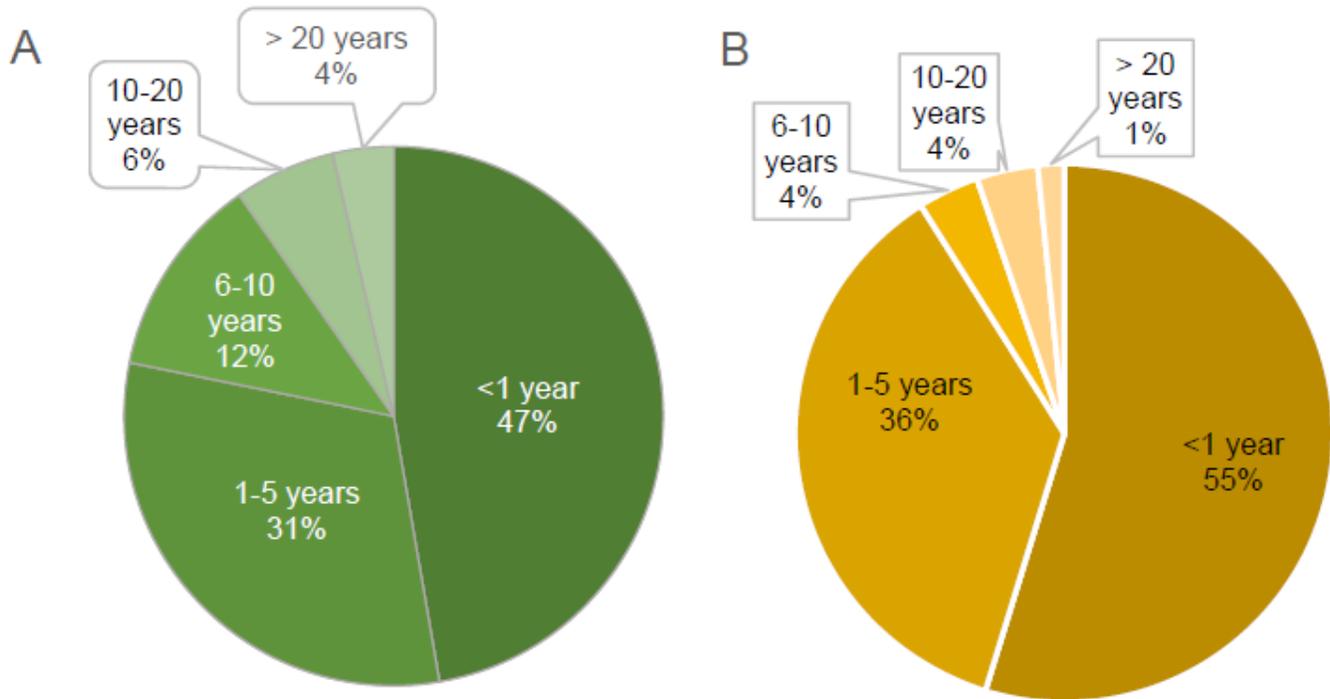
**Figure 3**

The ratios of publications addressing details of the FER projects including the type of targeted ecosystem (A), degradation cause (B), scale of the restoration project (C) and reference site for outcome evaluation (D).



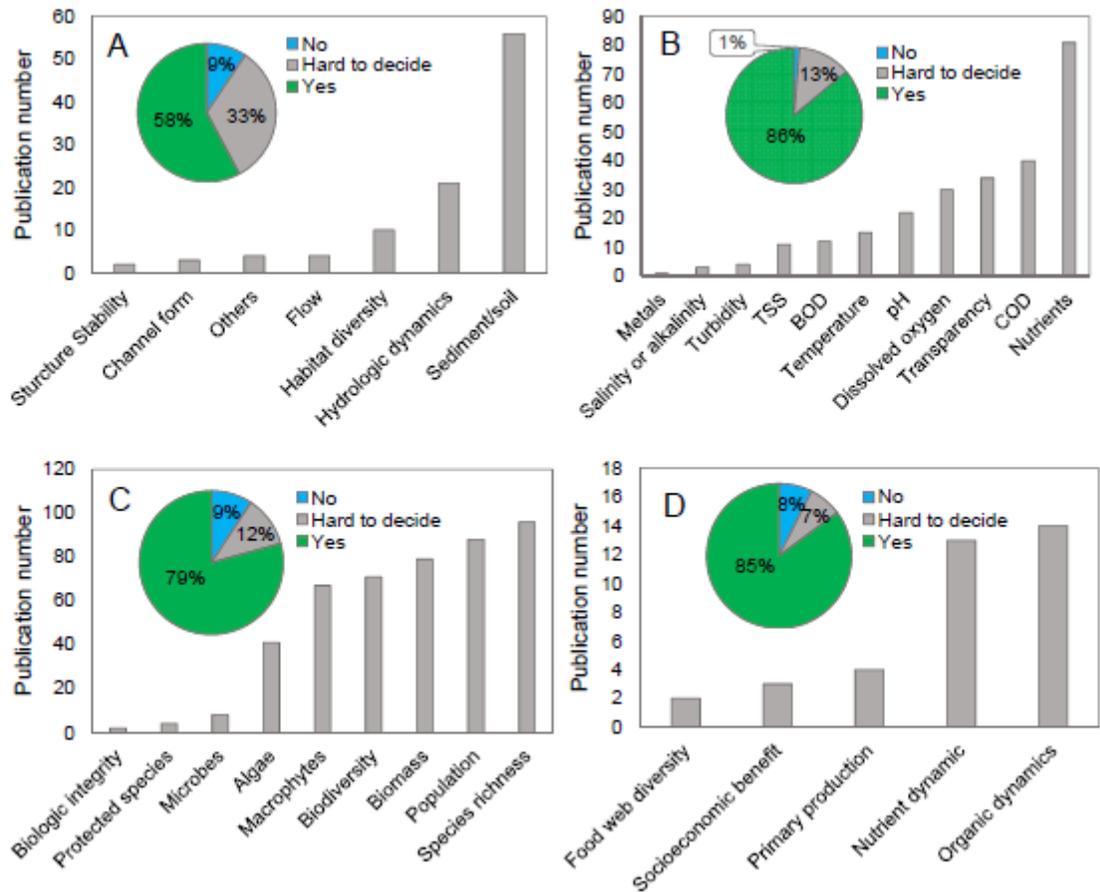
**Figure 4**

The ratios of publications presenting different restoration goals (A) and applying different restoration measures (B).



**Figure 5**

The ratios of publications indicating different ranges of restoration intervention (A) and monitoring period (B).



**Figure 6**

Number of publications presenting the outcomes of freshwater ecological restoration projects and ratios of them indicating improvement or not (A for morphological or physical characteristics, B for water quality parameters, C for biological metrics, and D for biological/ecological processes).