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REVIEW

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Terrestrial ecological restoration in China: identifying advances and gaps

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Abstract

Background: China has made great progress in ecological restoration. However, there have been no analyses on ecological restoration for specific terrestrial ecosystems. This study identified the important knowledge gaps and advances related to terrestrial ecological restoration in China.

Results: 7973 papers published between 1978 and 2020 were investigated and about 962 articles were used in this analysis after manually screening. Since the first large national ecological restoration project in 1978, the most frequently studied ecosystem has shifted from farmland ecosystems in 1978–2000 to forest ecosystems after 2000. Forests were the most common ecosystem type investigated, while less attention was paid to wetlands and riparian systems. Meanwhile, the most common ecological issue shifted from environmental pollution in 1978–2000 to the declining resource-carrying capacity of ecosystems after 2000. Studies of ecoregions on the Loess Plateau catchment accounted for more than 40% of papers reviewed in this study, with predominant emphasis on soil and water conservation functionality. Besides, revegetation and afforestation characterized most ecological restoration projects in China, but the natural restoration was relatively less adopted. Additionally, the important tool of reference ecosystem was only used in four studies.

Conclusions: Ecological restoration has made significant progress in China. We investigated how the ecological restoration can be implemented more effectively. More projects should be implemented for restorative work in wetlands and riparian systems in future. The tradeoff between restorative activities, water resources, and carbon sink needs further research efforts. More emphasis on biodiversity conservation is warranted. Newly developed theory (e.g., stepwise ecological restoration) and the recently issued Chinese National Guidelines for Ecological Restoration Projects should be more effectively implemented in future restorative works. This study provides essential information for future restorative work in China. It also provides insights into the development of policy relevant to restoration and adaptive management during the U.N. restoration decade.

Keywords: Ecological restoration, Ecological rehabilitation, Restorative activities, China, Bibliometrics

Background

The United Nations (UN) General Assembly declared 2021–2030 as the "Decade of Ecosystem Restoration", which positions ecosystem restoration as an important nature-based solution to meet sustainable development goals and global priorities. Effective and sustainable ecological restoration programs can help protect biodiversity, deliver goods and services, and improve human health and well-being. Moreover, it can provide benefits such as mitigating climate change and improving the resilience and adaptive capacity of ecosystems. Thus, restoration is the basis for the realization of ecological civilization and sustainable development. In addition to this UN priority, other exemplary targets for ecological restoration have been established. The *New York Declaration*, for example, was extended from the *Bonn Challenge* and signed in 2014 by 32 countries, 19 regions, 56 companies, 16 indigenous people organizations, and 58 nongovernmental

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organizations (NGOs) with the goal of restoring 200 million ha of degraded lands by 2030 [1]; the *EU Biodiversity Strategy* was agreed upon by 28 European Union member states with the goal of restoring at least 15% of degraded ecosystems by 2030 [2]; *AFR100* was implemented with the goal of restoring 100 million ha of land in Africa by 2030 [3]; and Initiative *20* × *20* is a country-led effort with the goal of restoring 20 million ha of land in Latin America and the Caribbean by 2020 [4].

Since China's "reform and opening-up" policy started in the late 1970s, consistently rapid economic growth has been achieved. Energy-driven heavy industry caused severe environmental problems and ecosystem degradation. The Chinese government successively implemented several key ecological restoration programs to alleviate ecological problems, such as the Three-North Natural Forest and Grain for Green program. To date, China has achieved great success in ecological restoration practices that increased the global greening area by 25% [5].

With support at the national level, many studies have been carried out on various types of ecosystems in different regions with diverse climates and physiographic contexts in China [6, 7]. The studies covered rivers, wetlands, forests, grasslands, farmlands, post-mining lands, and others [6] and assessed the critical aspects of particular restored ecosystems [7]. For example, Deng et al. [8] investigated the effects of forest planting on water–energy balance over the Three-North region of China. Tong et al. [9] compared the effects of afforestation and reforestation projects on carbon stocks at different scales in the karst area. Although Wu et al. (2020) identified the general trend of ecological restoration over the past two decades for all the freshwater ecosystems, it still lacks a comprehensive picture of ecological restoration practices for all the types of terrestrial ecosystems. There is an urgent need to know where and what to restore, as well as what techniques are most appropriate for different regions, before future restoration projects are implemented [10]. This study tries to fill in this gap to identify the current stage of ecological restoration in China and answer the following questions: (1) What environmental issues have been addressed through ecological restoration activities in China? (2) With respect to China's ecoregions, where were ecological restoration projects located and where will more ecological restoration efforts be needed? (3) How can future ecological restoration work be improved in China?

Faced with these questions, there are urgent demands for knowledge and guidance to assist the implementation of restoration projects and related decision-making. One of the main demands is the need for a systematic review of published studies to support the implementation of restorative works, relevant policy, and scaling-up projects. Here, we fill this gap and present an overview of the current ecological restoration works across Chinese ecoregions.

Methods

To identify the gaps and advances in ecological restoration studies in China, we conducted a search of papers published from 1978, when the first key ecological restoration project (i.e., Three-North Shelter Forest Program) was implemented, until September 18, 2020. In this study, we adopted the definition of ecological restoration as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" [11]. Based on the Web of Science database (www.webofknowledge.com), we used the following terms as key words: *ecological restoration in China, ecological engineering in China, rehabilitation in China, afforestation in China,* and *revegetation in China* and obtained 7973 papers. Since this study focuses on the aspects directly related to ecological restoration (e.g., restoration techniques and restoration targets), studies that only provided implications for ecological restoration were excluded. After manual filtering, we identified 962 articles for evaluation.

We categorized these papers using the following indicators (also see Table 1): (1) ecosystem types, including forest, shrubland, grassland, farmland, desert, wetland, and artificial ecosystem, based on the classification of Chinese Academy of Science in 2010. Wetland ecosystem included rivers, lakes, reservoirs, and inland wetland and coastal marshes. Artificial ecosystems included urban area and mining pits. And farmland does not include open range grazing land; (2) ecoregions, which were classified based on ecosystem characteristics, ecosystem services, and ecological vulnerabilities recognized by the national ecological investigation; (3) ecosystem functions, including water conservation, sand stabilization, soil and water conservation, biodiversity protection and hydrological regulation; (4) ecological issues in China, including ecological disasters, reduced resource-carrying capacity, desertification, environmental pollution, soil salination, soil erosion, freeze–thaw erosion, invasive species colonization, and urban expansion; (5) study objectives, including vegetation dynamics induced by restoration activities, carbon sequestered by vegetation and soil, the influence on phosphorous and nitrogen cycles, soil chemical and physical properties (e.g., heavy metal toxicity, soil moisture and soil water content), soil microbials (e.g., fungi, microorganism), ecosystem services, ecological restoration management (e.g., comparing different restoration methods and landscape planning), ecosystem function and structure, and water resource (e.g., runoff, evapotranspiration, water use efficiency and water storage); (6) study methods, including

Table 1 Indicators used in this study

Indicators	Classifications	References	Related database	Accessed by
Ecosystem types	Forest, shrubland, grassland, farmland, desert, artificial ecosystem, coastal ecosystem	Ecosystem type classification in 2010, Chinese Academy of Science	Resource and Environment Science and Data Center	http://www.resdc.cn/data.aspx?DATAID=105
Ecological issues	Ecological disaster, reduced resource-carrying capacity, desertification, environmental pollution, soil salination, soil erosion, freeze–thaw erosion, invasive species, and urban expansion	Ministry of Ecology and Environment and Chinese Academy of Science, 2015	China Ecosystem Assessment and Ecological Security Database	http://www.ecosystem.csdb.cn/ecoass/ecoassess_list.jsp?func=wt
Ecosystem functions	Water conservation, sand stabilization, soil and water conservation, biodiversity protection, hydrological regulation, carbon sequestration	Ministry of Ecology and Environment and Chinese Academy of Science, 2015	Resource and Environment Science and Data Center and China Ecosystem Assessment and Ecological Security Database	http://www.ecosystem.csdb.cn/ecogj/tpcclasses_list.jsp?func=395F1E2FD6F0674C50076B29E1A108AB http://www.mee.gov.cn/gkml/hbb/bgg/201511/W020151126550511267548.pdf
Ecoregions	50 ecoregions based on the ecosystem characteristics, ecosystem services and ecological vulnerabilities	Ecoregion Plan in China	China Ecosystem Assessment and Ecological Security Database	http://www.ecosystem.csdb.cn/ecoass/ecoplanning.jsp
Study objectives	Vegetation dynamics induced by restoration activities; carbon sequestrated by vegetation and soil, the influence on phosphorous and nitrogen cycles; soil chemical and physical properties; soil microbials; ecosystem services; ecological restoration management; ecosystem function and structure, and water resource	Based on the results of literature review in this study, as well as Gurra et al. 2020 [13]	–	–
Study methods	Literature review, remote sensing, field sampling, ground-based monitoring, atmospheric and land modeling, and policy analysis	Gurra et al., 2020; Wu et al. 2020 [13, 14]	–	–
Restorative strategies	Natural regeneration, direct seeding, bioremediation, revegetation, afforestation, rehabilitation, habitat conservation, threat mitigation (e.g., pollutant removal and grazing exclusion), and wetland creation	Based on the results of literature review, as well as the Gurra et al. 2020 [13]	–	–
Reference ecosystem	presence or absence	Gurra et al. 2020 [13]	–	–

literature review, remote sensing, field sampling, ground-based monitoring, atmospheric and land modeling, questionnaire and interview results, and policy analysis; (7) restoration techniques, which includes natural regeneration, direct seeding, bioremediation, revegetation, afforestation, rehabilitation, habitat conservation, mitigation of impacts (e.g., pollutant removal and grazing exclusion), and wetland creation; (8) usage of reference ecosystems or models. Categories of ecological issues, ecosystem services, and ecoregions were adapted from the database of Resource and Environment Science and Data Center (http://www.resdc.cn/Default.aspx) and China Ecosystem Assessment and Ecological Security Database (http://www.ecosystem.csdb.cn/index.jsp). The database was supported by the 13th Five-Year Special Project for Informatization and Big Data, which was conducted by The Chinese Academy of Sciences. The other indicators were used in previous studies [12–14]. Indicators and related references are listed in Table 1.

Results

Publications and policies associated with ecological restoration since 1978

Given the fact that the success of ecological restoration largely depends on the political and financial supports from the national government of China, we firstly analyzed the number of publications on ecological restoration, the restoration relevant policies as well as the economic development by using the indicator of the gross domestic product (GDP). In general, the number of publications related to ecological restoration in China, as well as GDP, showed exponential growth from 1978 to 2020. Publications increased from less than 10 papers annually before 2005 to more than 150 papers after 2018 (Fig. 1a). With the ‘reform and opening-up’ policy that started in the late 1970s, GDP grew extremely quickly from 0.15 trillion US$ in 1978 to 14 trillion US$ in 2019 (Fig. 1b). According to the three development stages of ecological restoration in parallel with GDP suggested by Liu et al. [15], in the first period of rapid growth (i.e., 1978–2000), economic development was the first priority, and environment protection was not a main focus. In this period, due to that early economic development relied on energy-driven industries [16], ecosystems were significantly degraded. On the other hand, because of the heavy demand for food, large area of trees and grass were replaced by the farm and rangeland, which led to significant desertification and sandstorms [17]. In the second stage (i.e., 2000–2012), economic development and environmental protection were given equal attention by the Chinese government. Since 2000, national ecological restoration projects have been launched continuously. For example, in 2000, the national “Grain for Green” and “Graze for Green” ecological restoration projects were initiated to prevent soil erosion and vegetation degradation. “Grain for Green” represented the largest ecological restoration efforts in the world [18]. By the end of 2019, 2.1 million km^2 had been restored or was in the process of being restored, and the investment reached 74 billion USD. Ecological restoration entered a new era after 2012 when ‘ecological civilization’ was elevated to the rank of a paramount objective by the Chinese government. The priority of ecological protection became higher than that of economic development. In 2016, the Chinese state council suggested that China should accelerate the ecological restoration of mountains, rivers, forests, farmlands and grasslands. In 2017, the national park system was implemented by the Chinese Ministry of Environment and China’s National Tourism Administration, which started a new mode of environmental protection and resource utilization. In 2018, ecological civilization was listed as one of the constitutional principles in China. More recently, China approved the Master Plan for National Key Ecosystem Protection and Restoration Major Projects (2021–2035). In the three different stages, the tradeoff between economic development and environmental protection has been switched from the priority of higher GDP to the priority of ecological conservation. After several decades of efforts, the increase in green area in China has led the global effort for greening growth [5]. China has made great achievements in ecological restoration practices.

The general trend of temporal variations of ecosystem types and ecological problems studied in three periods

Ecosystem types

Among all the ecosystem types shown in previous studies (Fig. 2a), forest ecosystems were most commonly investigated. Tree planting was regarded as one of important restoration techniques in China [19]. Most forest ecosystem studies pertained to several projects in national forests (e.g., Three-North Shelter Forest Program). Grassland and shrubland contributed the second and third highest numbers of publications, with 315 and 276 papers, respectively. The least studied ecosystems were farmland ecosystems, with fewer than 70 articles. Only 122 papers pertained to rivers, lakes and wetlands. In the first period, 30% studies were associated with the artificial ecosystems. Farmland and wetland ecosystems accounted for about 20% (Fig. 2b). The high percentage of papers which pertained to the restoration of formerly mined lands and converted farmland in the first period were consistent with China’s reliance on energy-driven industries and agricultural production before 2000. During the three periods, investigations into green ecosystems (e.g., forest, shrubland, and grassland) expanded.

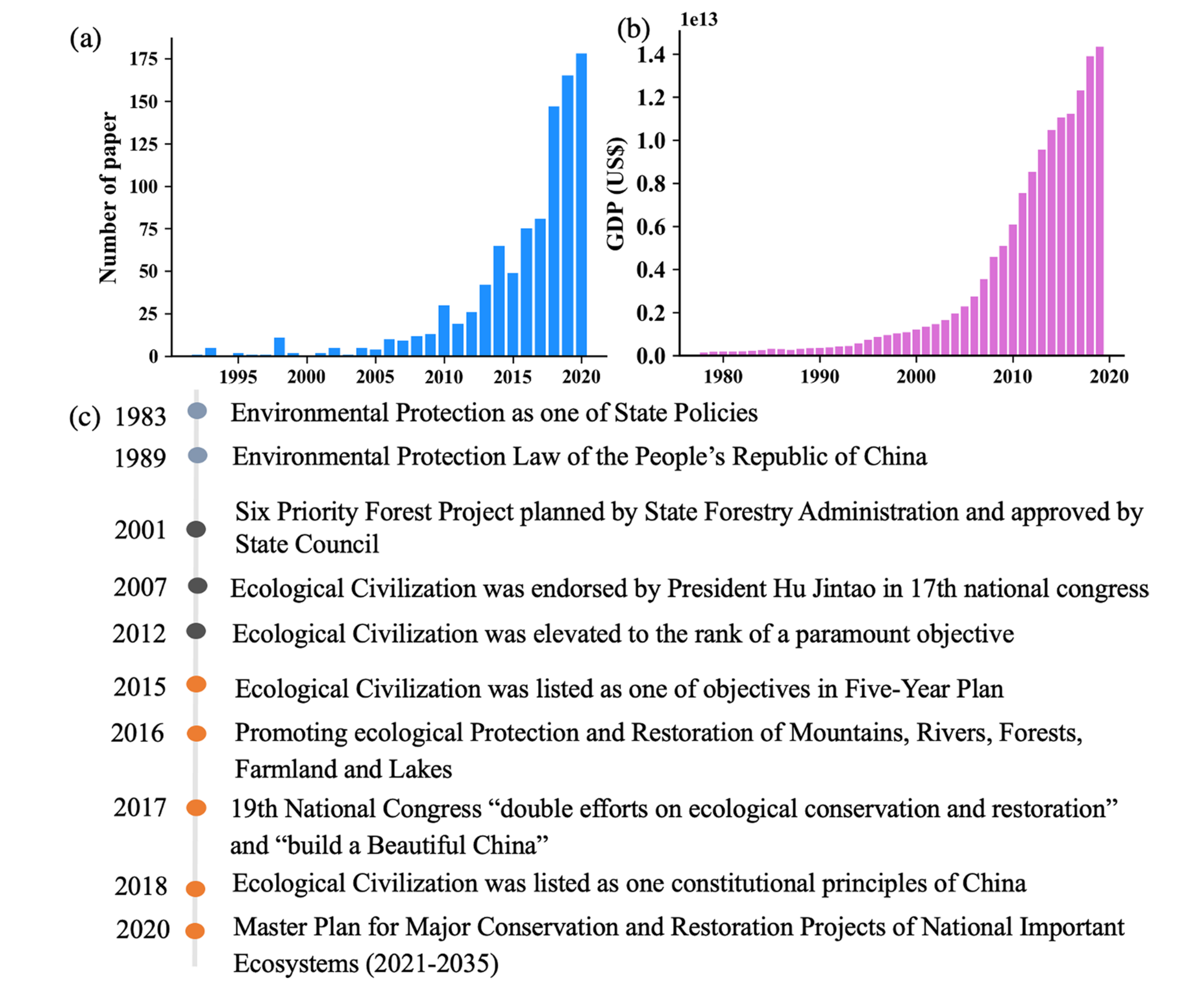

Fig. 1 The number of publications reviewed in this study (**a**), which was related to ecological restoration in China during the period of from Jan 1978 to Sep 2020. GDP (US$) growth during 1978 to 2019 (**b**). The Chinese policies related to environmental protection and ecological restoration during 1978 to 2020 (**c**)

For example, research associated with forest ecosystems increased during the three periods, from 17% in the first period to 55% in the second and third periods.

Ecological problems

Overall, as shown in Fig. 3a, soil erosion and a decline in resource-carrying capacity attracted the largest number of studies, both with 266 published papers. Issues related to freeze–thaw erosion, invasion of alien species and soil salination were less studied, represented by less than 10 publications. In the first period, in parallel with increased GDP, the pollution problems attracted the most attention, with an overall percentage of papers greater than 40% (Fig. 3b). The pollution emission associated with energy production and industrial development was the main problem [20, 21]. The ecological issue of reduced resource-carrying capacity also comprised a large fraction of about 30% due to the degradation of natural ecosystems. Although the issues of freeze–thaw erosion and increases in non-native species have seldom been investigated in the past few decades, both issues are now serious ecological problems. For example, the introduction of inappropriate forest species in afforestation projects could lead to maladaptation of whole forest ecosystems [22]. Moreover, the alternations of freezing–thawing change the mechanism and process of soil erosion and have a severe influence on soil erosion, thus affecting crop yields and food security [23]. Additional studies are needed to select the appropriate species for restoration, as well as for preventing the freeze–thaw erosion.

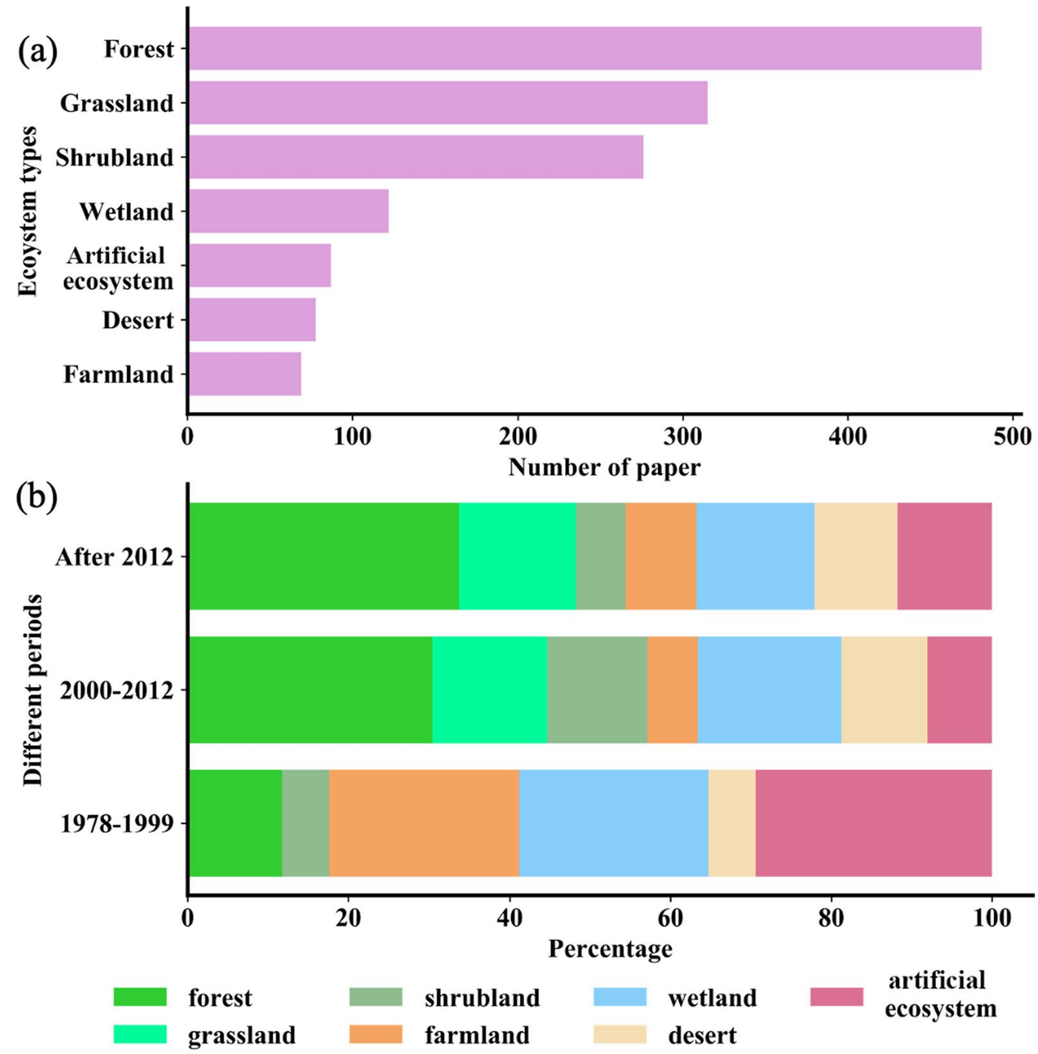

Fig. 2 The numbers of papers with different ecosystem types (**a**) and percentages of different ecosystem types in three periods (**b**)

Spatial distribution of the studies over the ecoregions

Figure 4a shows the distribution of studies over 50 ecoregions, each with different ecosystem functions. When the study area was all of China or the whole northern part, or the whole southern part, ecoregions cannot be appropriately identified. Hence these studies were excluded in our data, which numbered around 10% of the total. Figure 4a shows that ecoregions with the most studies (i.e., the darkest area) were located on the Loess Plateau. This finding was consistent with the fact that soil and water conservation received the most emphasis in the literature, consisting of more than 300 papers (Fig. 4b). Additionally, restoration activities were numerous in the South China Karst region which is one of largest exposed carbonate rock areas in the world [24]. Increasing resource exploitation and population pressure have led to the soil erosion in the karst area [24, 25]. According to the document, *Planning of Protection and Ecological Restoration (2021–2035)*, ecoregions in Tibet Plateau area, Loess Plateau, Yangtze River Basin, Northeast Forest, Northern Sand Prevention Area, Southern Hilly Area and coastal areas were also regarded as critical ecological areas. However, recent research has mostly focused on the regions located in Loess Plateau. We observed a large gap in the remaining ecoregions, where ecosystems were also critically in need of more research. For example, in Tibet, Liu et al. [26] pointed out that the climate and anthropogenic changes are altering the biogeochemical cycles of the third pole and they have accelerated ecosystem degradation. Monaco and Prouzet [27] suggested that coastal wetlands were highly vulnerable, because they are exposed to both natural and anthropogenic pressures. In the coming fifteen years proposed by the *Planning of Protection and Ecological Restoration*

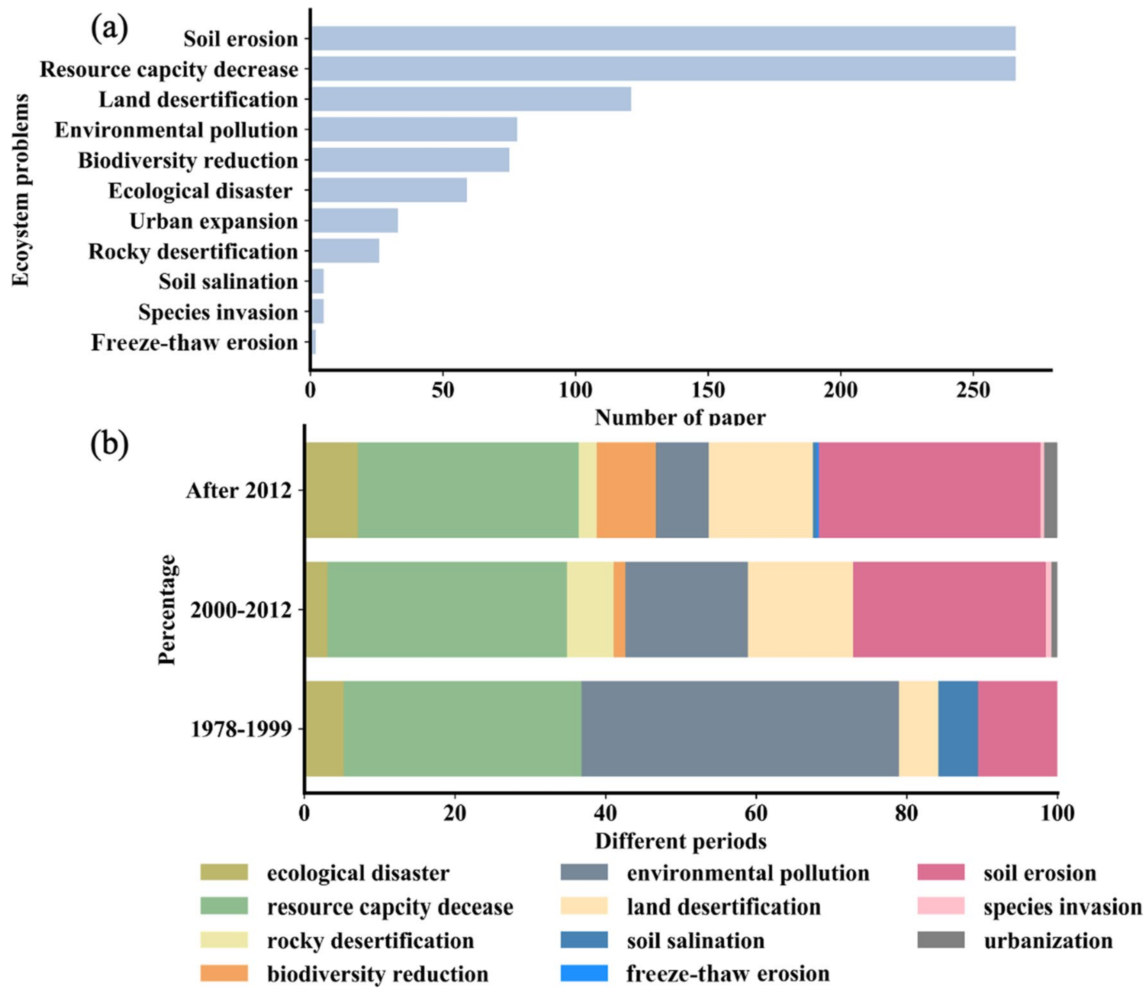

Fig. 3 The numbers of papers with different ecosystem problems (**a**) and percentages of different ecosystem problems in three periods (**b**)

(2021–2035), the mechanism and effectiveness of ecological restoration in the remaining Chinese ecoregions (e.g., Tibet Plateau, coastal areas) warrant further study.

Overall evaluation of the ecological restoration ecoregions

Study objectives

About one-third of the papers we reviewed were associated with the improvements in vegetation cover and soil properties related to ecological restoration (Fig. 5). For example, Chen et al. [5] suggested that the normalized difference vegetation index increased significantly on the southern slope of the Qilian Mountain area. Because soil properties are fundamental components of an ecosystem, it is not unexpected that 25% of studies investigated the changes in soil properties (e.g., soil moisture) and microbial communities caused by degradation and restoration. For example, Ren et al. [28] compared the impacts of afforestation and natural revegetation on soil moisture in the Loess Plateau of China and found that afforestation was the better choice only for areas with an annual rainfall exceeding 500 mm. Hu et al. [29] found shifts in the functional genetic structure of soil microbial organisms due to revegetation in desert ecosystems. The most direct influence of ecological restoration was increased vegetation cover, induced by restoration, which received the second highest research interest in the publications we surveyed (approximately 160 papers). In the context of climate change, research related to carbon sequestration by vegetation and soil characteristics represented a large fraction of the total research pertaining to the mitigation effects caused by ecological restoration. Research related to ecosystem services provided by ecological restoration deserves more attention. Lack of emphasis on freshwater ecosystems and water chemistry (Fig. 5) also indicates that more attention would be valuable.

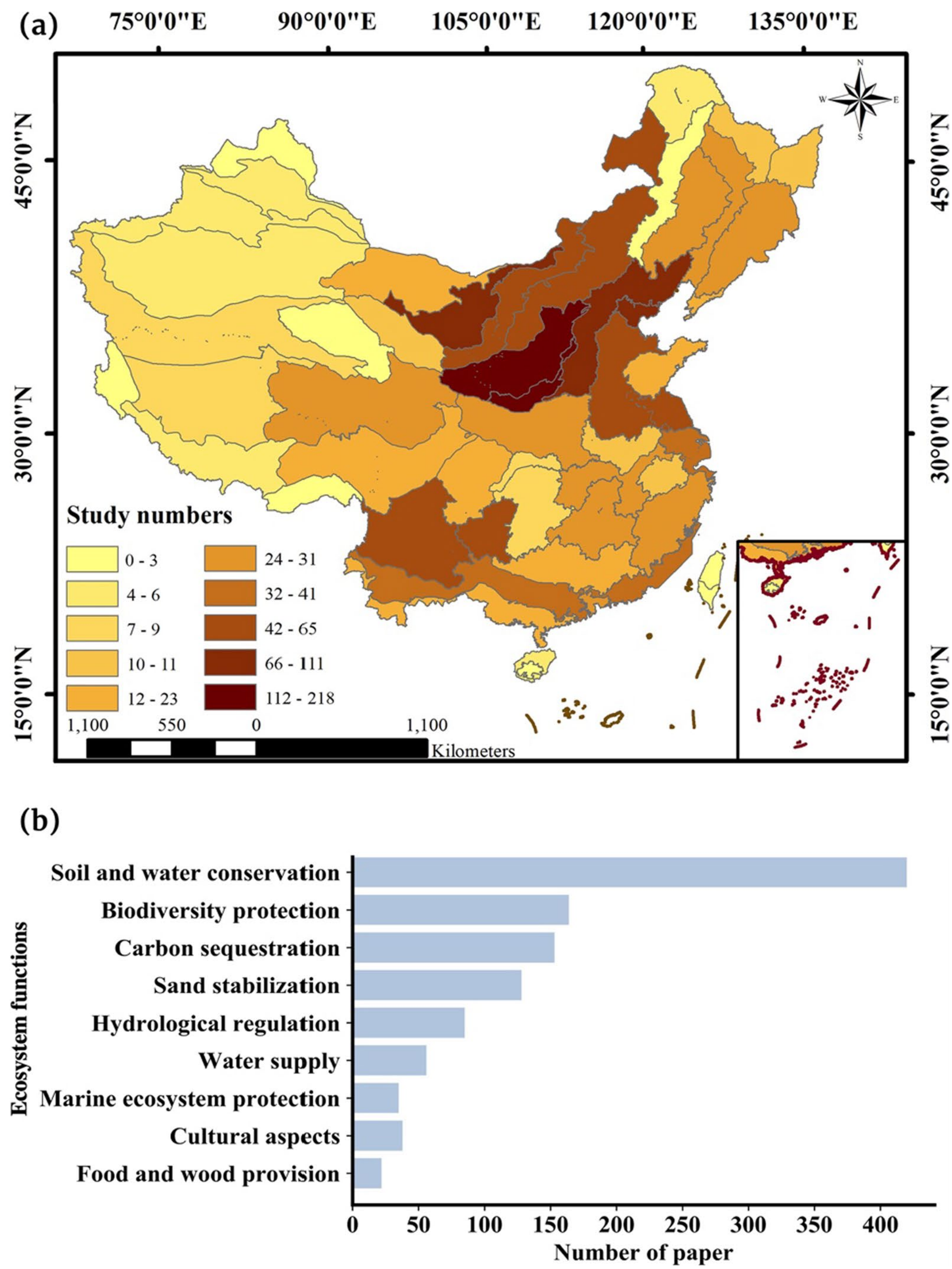

Fig. 4 The distribution of studies over 50 ecoregions (**a**). The numbers of papers on various ecosystem functions (**b**)

Study methods and restoration techniques

Corresponding to the largest number of studies (more than 400) associated with soil properties, data obtained from samples at restoration project sites were published in those papers we reviewed (Fig. 6a). However, it should be noted that the field sampling work was mainly performed by researchers rather than by ecological restoration managers. Baseline sampling prior to the initiation of restoration project activities was generally lacking. Monitoring usually lasted about one year constrained by the funding support. Some studies were based on long-term monitoring, which were usually implemented by

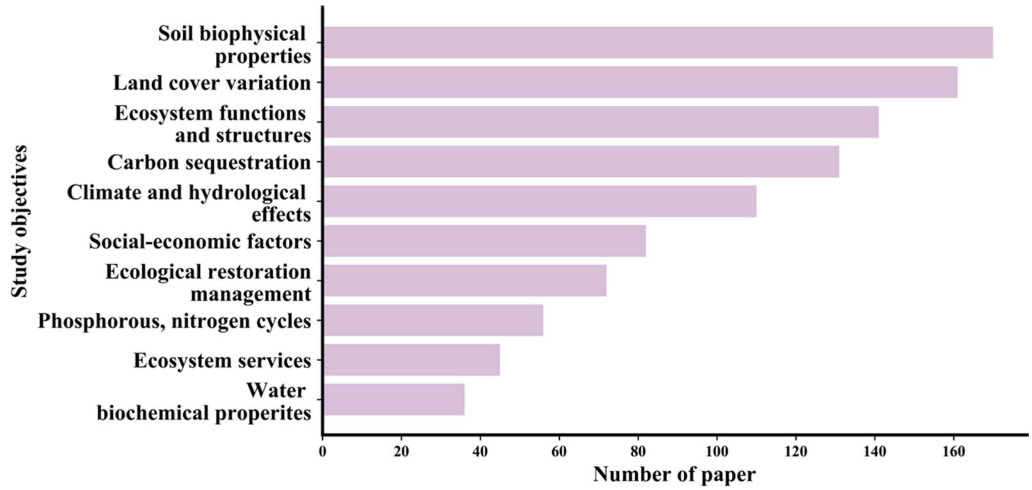

Fig. 5 The numbers of papers present different study objectives in prior investigations

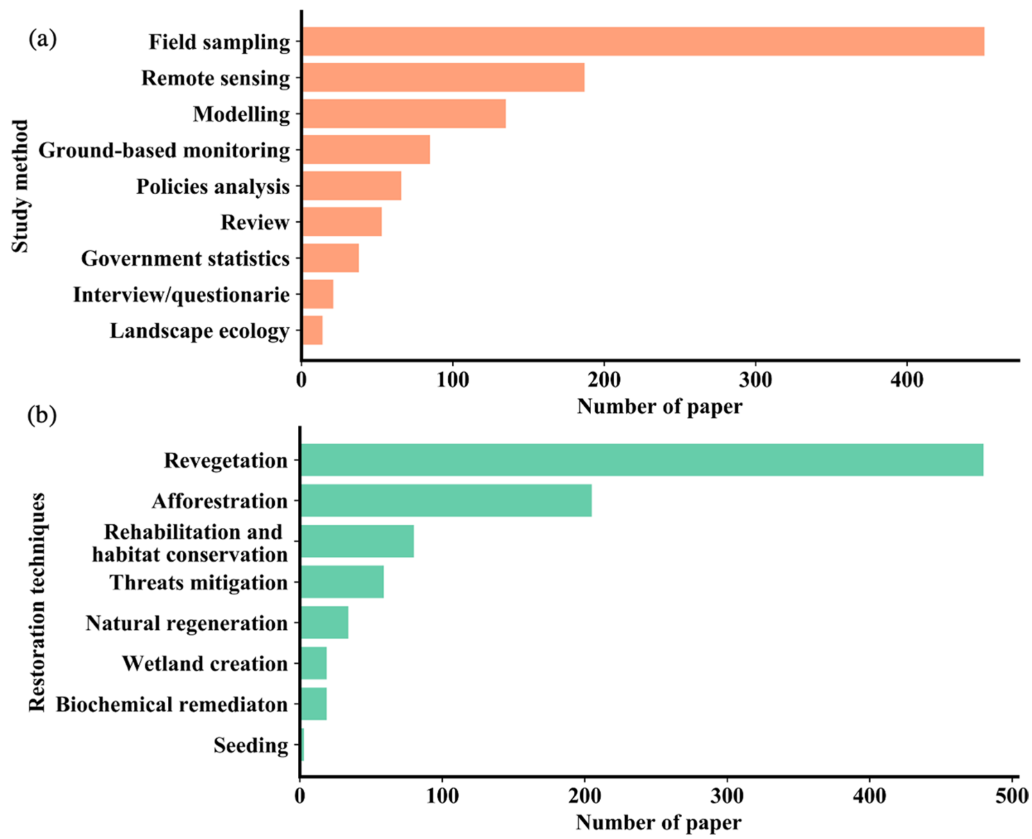

Fig. 6 The numbers of papers show the study methods (**a**) and restoration techniques (**b**) used in the previous studies

national ministries (e.g., Ministry of Ecology and Environment, Ministry of Water Resource). The process of baseline sampling prior to the implementation of restoration project implementation rarely occurs. Few studies presented monitoring data of this kind. More than 200 studies related to vegetation dynamics and land cover changes only provided monitoring data obtained by remote sensing. Interviews and questionnaires were used to investigate the local community's response to ecological restoration and the relationship between livelihoods and ecological restoration. 18 publications of this type of study were included in this review. For example, Chu et al. [30] investigated the willingness of local households to accept compensation to adhere to afforestation policies. They reported that a threshold of 480 CNY/mu/year prompted local participation in restoration projects. The results showed that combined with the green economy, exploring ways to eradicate poverty and improving the living conditions of residents in ecologically critical areas are prerequisite for successful ecological restoration [30, 31].

With regard to restoration techniques, strategies of revegetation and afforestation were involved in more than 600 studies, as shown in Fig. 6b. Around 120 studies have focused on habitat conservation and natural succession. Additionally, there were 60 studies related to mitigation threats and the restorative works in 17 studies pertained to wetland creation. The results exhibited that the main restoration techniques in China were revegetation and afforestation. However, vegetation expansion in arid or semiarid areas and its induced acceleration of evapotranspiration could lead to water shortages [18, 32]. For example, the revegetation activities in China's Loess Plateau, where the "Grain to Green" has been implemented since 1999, are approaching sustainable water resource limits [33]. Moreover, the net benefits from afforestation were less than satisfactory. For example, Cao et al. [34] and Ma et al. [35] found that the net benefits were negative for intentional afforestation in the Three-North Shelter Forest program and the Natural Forest Conservation Program. Alternative and more effective restoration practices should be encouraged in upcoming ecological restoration project work.

Discussion

Ecosystem restoration is more than forest restoration

The ecological restoration has become an effective tool used to address many environmental issues [10]. Of the ten significant ecological problems associated with ecosystem degradation which are identified in this study, decreased resource-carrying capacity, soil erosion, and desertification are most common. The main restoration methods to address these issues were afforestation and revegetation for restorative projects in China. One reason is that afforestation has been proved to be an effective way for carbon sequestration and climate change mitigation [36–38]. Another reason is associated with the low cost and high feasibility of the vegetation re-establishment [37, 39]. Correspondingly, more than 30% of restoration practices focused on forest ecosystems in the papers reviewed in this study. However, the tree planting was found to raise to the environmental degradation and increase the burial groundwater depth, which could further induce the water scarcity, especially in the arid and semiarid regions of China [40, 41]. Meantime, increasing evidence has confirmed that many non-forested ecosystems also offer great restoration potential for biodiversity protection and climate mitigation [10]. For example, Yang et al. [42] found that the restoration of grassland biodiversity could accelerate soil carbon sequestration. Joosten et al. [43] noted that the conservation and rehabilitation of peatlands could benefit the mitigation of climate change. In many landscapes, non-forested ecosystems are regarded as having the same or higher priority than forests [44].

Beyond the forest restoration, the remediation and restoration to address the other ecological issues needs further efforts. For example, freeze–thaw erosion is also notable in China. Understanding the mechanism and critical impacts factors are the first step for mitigating this issue through restoration [45]. Non-forested coastal wetlands have great potential to deliver ecosystem services because of their substantial ecological interactions with marine resources [46]. According to the document, *Planning of Protection and Ecological Restoration Programs* issued by the Chinese government, more ecological restoration projects should be implemented for the coastal wetland protection in the future. Preliminary studies, such as identifying the hotspots of wetland degradation and biodiversity reduction, could provide a scientific basis for the future ecological programs.

Improved water resource and biodiversity monitoring

Hydrological responses to large, landscape-scale ecological restoration programs are variable in China [47]. As previously mentioned, in semiarid and arid regions, the groundwater level decreased after afforestation [32, 48]. In southeastern China, increased precipitation caused by increased revegetation can offset the enhanced evapotranspiration and decreased soil moisture [47]. Variation in the water provision through forest restoration depends on the coupling influences of climate change and anthropogenic water use. Moreover, current hydrological models do not identify quantitatively the uncertainties related to ecological restoration and the tradeoffs between water and carbon [49, 50]. More comprehensive restoration models should be developed. Beyond the impacts of ecological restoration on the water resource, biodiversity protection through ecological restoration is still controversial. Tree planting in grasslands, shrublands and open canopy woodlands can destroy biodiversity and reduce their ecosystem services [51]. For example, Heilmayr et al. [52] found that Chile's forest subsidies probably decreased biodiversity due to the invasion of exotic species. More studies with better measurements and simulations are needed to quantify the role of different ecosystems in affecting water resources and biodiversity. In the restoration process, tradeoffs in delivering various ecosystem services (e.g., carbon mitigation, biodiversity, and water conservation) should be more clearly addressed [10].

Ecological restoration management under a changing climate

Ecological restoration is usually regarded as an important strategy to mitigate climate change since such activities can benefit carbon sequestration [53]. On the other hand, climate change can greatly affect restoration progress and outcomes by modification of the biophysical properties of ecosystems. Climate change not only increases temperature but also causes changes in precipitation patterns in both frequency and magnitude [54]. It is necessary to understand the ecological dynamics related to climate impacts and identify the hotspots with high vulnerability. Furthermore, restorative activities could be effectively implemented to increase ecosystem resilience and assist ecosystems to adapt to these changes [54]. For example, exploitation of natural resources has led to severe degradation in karst areas in China [9]. Meanwhile, the increasing climate variability accelerates its degradation and poses more challenges for ecological restoration of karst areas [9]. Future restoration must acknowledge the changing environment and link the changing ecosystem elements to improve ecosystem functions and services [55]. Ecosystem dynamics with multiple trajectories require an adaptive management approach and a database relying on the scientific monitoring [56].

Standards for future ecological restoration in China

In 2017, Liu and Clewell recommended the application of reference models and emphasized the importance of monitoring and evaluating success of ecological restoration works [57]. In September 2020, China's Ministry of Natural Resources, Ministry of Finance, and Ministry of Ecology and Environment co-launched the *Guideline for Ecological Restoration Projects of Mountain, River, Forest, Farmland, Lake and Grassland Ecosystems* (http://www.mnr.gov.cn/dt/ywbb/202009/t20200923_2559488.html). The innovative restoration methods and tools, such as reference models and use of the ecosystem recovery wheel [11], are strongly recommended in this guideline. Recently, a new stepwise ecological restoration theory was proposed by Liu et al. [15], which suggested a more scientific decision-making method for attaining restoration goals based on site-specific criteria. This theory emphasizes the importance of monitoring and dynamic assessment. Both government policy and the scientific advancement show that ecological restoration in China has stepped into a new stage. However, based on the results shown in this study, these advanced protocols and guidelines are not effectively applied in current ecological restoration work. Baseline inventories are essential to determine the degree of impact regarding specific ecosystem attributes and to allow empirical assessment of the efficacy of restoration activities [11]. Reference ecosystems allow development of appropriate restoration goals [57, 58]. However, according to the literature reviewed in this study, only four studies used reference ecosystems during the restorative process [58–61]. Few studies have performed baseline investigations before implementing ecological restoration projects. Strategic monitoring and assessments using standardized methods could help restoration practitioners understand what types of activities are accomplishing restorative goals. However, monitoring and assessments are not sufficient in current ecological restoration projects [7]. According to this review, most were implemented by researchers rather than by restoration practitioners. In future restoration practice, these protocols should be more effectively implemented in China.

Project database establishment

Although there have been many ecological restoration projects in China, an ecological restoration database has not yet been established. Current ecological restoration works are scattered and lack summarization, which hardly provide the common elements of successful projects and strategic methods to accomplish restorative goals [62]. The US, Australia, and some European countries have achieved significant success in ecological restoration and have developed their own restoration database at an early stage. For example, the US developed the National River Restoration Science Synthesis in 2005 [62], which summarizes more than 30,000 river restoration case studies. The Environment Agency of England established a RiverWiki database and collected case studies cases from 31 countries around Europe [63]. The above database includes substantial information, such as the ecological issues and related strategies, which provided the fundamental experience for the following restorative projects and benefit the restoration success. The large number of ecological restoration projects in China would allow construction of a database covering government censuses, local surveys, monitoring and field experiments, remote sensing, and interviews and questionnaires. Moreover, collaborations among those with expertise in restoration ecology, social science, remote sensing, GIS, landscape ecology and climate should be encouraged in future ecological restoration work.

Conclusion

The Chinese government has recently issued its *Master Plan for National Key Ecosystem Protection and Restoration Major Projects (2021–2035).* In the past several decades, China has made great progress in ecological restoration; however, there have been no comprehensive investigations into ecological restoration conducted on terrestrial ecosystems. This study identified the advances and gaps of the ecological restoration since the first large national restoration project was initiated in 1978.

Temporally, the development of ecological civilization is divided into three periods (i.e., 1978–2000, 2000–2012, after 2012) [15], parallel with the rapid economic development in China. The attention for the ecological protection from the Chinese government gradually exceeded that of GDP growth during the period of 2000–2012. Spatially, according to the document *Planning of Protection and Ecological Restoration* (2021–2035), ecoregions on the Tibetan Plateau, Loess Plateau, Yangtze River Basin, Northeast Forest, Northern sand prevention area, Southern Hilly area and coastal areas were considered to be of key importance as ecological areas. However, this study indicated that as much as 40% of studies were located on the Loess Plateau. Ecological restoration implemented in other key ecosystem functional areas are warranted.

In terms of the specific ecosystems, forests were the most commonly studied type of ecosystems among the investigated types, and several large national ecological restoration projects have been directly related to forest. Ecological restoration of riparian and wetland ecosystems still needs further efforts in future. Regarding the study objectives, the influence of ecological restoration on soil biophysical properties (e.g., soil moisture and soil microbes) and land cover (vegetated areas) were studied primarily. However, in the context of climate change, the compounding effects of ecological restoration and climate change on these properties remain unclear. Afforestation and revegetation were the most frequently applied strategies of restoration. But their net benefits were not as high as those of other natural restorative methods. The tradeoff between ecological restoration and water resources, as well as ecological restoration and biodiversity protection, is still uncertain in different parts of China.

Additionally, only 4 studies used the reference ecosystem to assess restorative effectiveness among the 970 reviewed papers and only 3 out of 962 papers provided a baseline inventory. The future ecological restoration projects should be complemented with much more monitoring, to better evaluate the restoration success and effectiveness. Meantime, the national guidelines for the ecological restoration of mountain, river, forest, farmland, lake and grassland ecosystems, as well as the new proposed stepwise ecological restoration theory by Liu et al. [15] should be intentionally and effectively applied in future restorative activities. Moreover, we further recommend the establishments of an ecological restoration database and an adaptive management framework, particularly regarding projects pertinent to ameliorating climate change. This study provided the fundamental and essential information for the future restorative work in China. It also sheds insights relevant to policy-making and sustainable management in the upcoming restoration decade.

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Authors' contributions
WC and JL designed this study. WC analyzed the results and wrote the draft. JL revised it and contributed the supervision. JJ and PW helped to complement the bibliometric survey and wrote parts of this manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
Not applicable.

Declarations

Ethics approval and consent to participate
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Competing interests
The authors declare that they have no competing interests.

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