




# A Comparison of the Development of Wetland Restoration Techniques in China and Other Nations

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## Abstract

Based on retrieved results of literature and patents related to international wetland ecological restoration, the current status and development of ecological restoration techniques for degraded wetlands in both China and international states were analyzed synthetically. The results showed that the United States was the pioneering country in studies on the wetland ecological restoration, while China began to pay widespread attention from 2000. Compared to the international developed countries, the start time of concern for wetland ecological restoration in China was about 10 years later. The phytoremediation and engineering restoration were the most popular among all the wetland ecological restoration techniques. Besides the United States, the number of publications increased most quickly in China since 2004. The Louisiana State University published most of the researching findings among the international institutions related to wetland ecological restoration. The Chinese Academy of Sciences was the most important institution for wetland restoration study in China. The analysis of the wetland ecological restoration practice in China and international states indicated that the study and application of combined bioremediation techniques would receive more attention for wetland ecological restoration in the future.

**Keywords** Degraded wetland · Ecological restoration technique · Development trend · Phytoremediation · Current status · China

## Introduction

Wetlands, caused by the interaction of land and water, are one of the most important and irreplaceable ecosystems with diverse ecological functions, i.e. biodiversity protection, water storage, groundwater replenishment, retention of nutrients, sediment and other substances, storehouses (sinks) of carbon, etc. (Mitsch and Gosselink 2000; Ullah and Faulkner 2006). Wetlands distribute in each continent except Antarctic and the area of global wetlands is  $7 \times 10^6 - 9 \times 10^6$  km<sup>2</sup>, occupying 4% - 6% of the earth's surface (Matthews and Fung 1987; Aselmann and Crutzen 1989; Mitsch and Gosselink 1993). Therefore, wetlands together with cropland, forest land and grassland are called four major terrestrial ecosystems (Ma et al. 2017; Chen et al. 2013). Robert Costanza et al. (1997) estimated the value of our natural ecosystems was about US\$ 33 trillion, and the global value of wetland was about US\$ 14.9 trillion, 45% of the total. Unfortunately, wetland is one of the most threatened territory ecosystems in the world because of the land use change and the disturbance of human activities. Since the beginning of the twentieth century, a large area of wetland has been developed and numerous important

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wetlands in the world have disappeared sharply with the rapid growth of economy (Coleman et al. 2008; McCauley et al. 2013; Ahmed 2014; Lin and Yu 2018; Rebelo et al. 2018; Lamsal et al. 2019; Shen et al. 2019). About 90% wetlands have been destroyed or under serious degradation in many countries, resulting in severe losses in biodiversity and wetland's functions (Holland et al. 1995; Kingsford and Thomas 2002; Wang et al. 2012; McCauley et al. 2013). According to estimation of World Conservation Monitoring Centre (1990), about 50% wetlands in the world have disappeared from the earth's surface. American wetland has lost 87 million  $\text{hm}^2$ , accounting for about 54% of the total wetland area in USA, which were mainly used for agricultural production (Kesel 1989; Foy 1990; Allen and Feddema 1996; Coleman et al. 2008; Tweel and Turner 2012; Ryan et al. 2014). The average wetland loss in Europe was about 60% of the total area (Holland et al. 1995; Coleman et al. 2008; Paganelli and Sconfietti 2013). More than half of wetland in Asia has been lost and over 50% mangroves in India-Malaysia region have been deforested for aquaculture (Foote et al. 1996; Scott and Metts 2012). The coastal tidal wetlands in China have lost more than 50% of its total area since 1950s (Zhang et al. 2010; Yu et al. 2011; Wang et al. 2012; Li et al. 2014a; Sun et al. 2016). The loss rate of wetlands around the world is still astonishing at present (Rains et al. 2013; Li et al. 2014a; Ryan et al. 2014; Van Rees and Reed 2014). In order to protect and remediate degraded natural wetland ecosystems, the developed countries have started to carry out the research and practice projects about degraded wetlands' restoration and reconstruction since 1970s (Moss 1983; Zentner 1985; Lewis et al. 1994). Then, more and more funds have been established to support the protection and recovery of endangered wetlands with the global awareness of biodiversity conservation since 1990 (Bartels and Anderson 1993; Tuttle and Gray 1993; Goodwin 1994; Bijlmakers and Deswart 1995; Weller 1995; Zhao et al. 2016). Meanwhile, large numbers of researches related to degraded wetland vegetation restoration and reconstruction are carried out. The degraded wetland restoration techniques dominated by physical restoration, chemical restoration and bioremediation are developed and matured gradually (Goodwin 1994; Wetzel et al. 2001; Holden et al. 2004; Watts and Didham 2006; Guan et al. 2013; Hurry et al. 2013; Huang et al. 2016; Ivajnsic et al. 2016; Cui et al. 2018). In this study, the literature and patents were related to international wetland ecological restoration from Science Citation Index Expanded database in ISI Web of Science, CNKI Chinese Scientific Journal database, ISI Derwent Innovations Index database, Soopat patent database and CAS patent-online analysis system (<http://patent.casip.ac.cn/pat2/view/m05/A0500.xhtml>). The key words for literature and patents retrieval were (marsh, bog, wetland, swamp, Fen, peat land, river, lake, pond) & (ecological restoration, ecological remediation). The retrieval results were further manually

filtered. The publication time, author address, restoration technology and other necessary information were manually checked based on the content of each literature and patent. Based on the final retrieved results, the research status and the development of restoration technology for degraded wetlands in China and the international states were reviewed comprehensively. It is worth comparing the advantages and disadvantages of related techniques and estimating the disparity of the degraded wetland restoration techniques at different development stages between China and international states, in order to further develop and improve the core ecological restoration techniques for degraded wetlands.

## Development Stage of Degraded Wetland Ecological Restoration

The initial research on degraded wetland began in 1970s, with the main purpose of protection and restoration of nature degraded wetland ecosystem (Moss 1983; Zechner et al. 2003). By 1980s, the restoration ecology has been developing rapidly (Zechner et al. 2003; Peters et al. 2015; Zhao et al. 2016). The International Association for Ecology was founded in 1985 and the professional journal of "Restoration Ecology" was established in 1993. Thereafter, a large number of monographs, journals and papers related to restoration ecology symbolize that the ecological restoration studies becomes more and more active and concerned (Keddy 1999; Pfadenhauer and Grootjans 1999; Zedler 2000; Marchetti et al. 2010; Cui et al. 2018). The theme of the Fifth International Wetlands Conference was "Future of Wetland" and the main issues included how to enhance the benefit of wetland, preventing the wetland loss, function decline, biodiversity decrease, as well as the strategies and measures for wetland protection and reconstruction. Thereafter, the wetland restoration and reconstruction has become a common concern and a research hotpot for scientists. The current research of wetland restoration and reconstruction concentrated on the wetland types of swamps, lakes, rivers and coastal wetlands (Mitsch 2005; Nakamura et al. 2006; Tweel and Turner 2012; Li et al. 2014b; Ma et al. 2015; Moreno-Mateos et al. 2015; Cui et al. 2018).

The restoration and reconstruction of damaged wetlands studies were carried out early in the United States (Zentner 1985). The 313 wetland restoration research projects related to cleaning lake project which was proposed by U.S. Environmental Protection Agency were funded by government of USA during 1975 to 1985 (Wang 2008). These projects included the wastewater discharge control, feasibility study and response assessment of restoration plans, lake classification and nutrition status of lake, etc. (Wang 2008). The American Water Science and Technology Division evaluated

the wetland restoration project which was carried out by the National Research Council in 1988. The overall evaluation including science, technology, policies and regulations of wetland restoration was carried out by the Water Ecosystem Remediate Committee of USA in 1989. With the total investment of \$ 685 million, a wetland project which aimed at the rebuilding of Florida everglades was conducted in United States in 1995 (Weller 1995). The Federal government was allocated special funds of \$ 200 million for the ecological restoration in the upper Mississippi river and the wetland ecological restoration was a critical component (Callahan and Heard 1994; Hey and Philippi 1995; Rothe 1995; Theiling et al. 2015). Some European countries such as Sweden, Spain, Switzerland and Denmark have also made great advances on wetland restoration research (Tuttle and Gray 1993; Bijlmakers and Deswart 1995; Stuurman and de Louw 2000; Martinez-Santos et al. 2008). The restoration projects in Austria, Belgium, France, Germany, Hungary, Holland, Switzerland, and UK mainly concentrated in flood plain (Tuttle and Gray 1993; Schneider 2014; Elliott et al. 2016). By planting aquatic plants, the lakes built for the deposition of rare metal ores near-by Capel, Australia, have been restored to a healthy wetland ecosystem. The degraded riparian ecosystem of the Rihand River (India) under extensive deforestation, dam construction, industrialization process and open-cast mining has been improved and restored by taking protective measures such as grazing exclusion, sewage division and treatment and native vegetation restoration. In Vietnam, the massive drainage in Mekong Delta resulted in the serious ecological degradation of 750,000 hm<sup>2</sup> tidal freshwater wetlands. In order to improve the natural hydrological processes of 7000 hm<sup>2</sup> wetlands, dams were built since 1988. The ecological engineering technique of oxidation pond based on the symbiosis of bacterial and algae was firstly used by the Institute of Hydrobiology, Chinese Academy of Sciences in 1970s. The technique greatly improved the seriously polluted environment of Yaer Lake area, Hubei province and promoted the study of wetland restoration in China. After then, the wetland restoration research successively developed in Taihu of Jiangsu, Chaohu in Anhui, East Lake in Wuhan and coastal wetland. Since 1998 when the catastrophic flood occurred in Yangtze River Basin, the “Returning farmland to lake” has been regarded as an important content of sustainable development and ecological reconstruction in China (Liu et al. 2004; Ma et al. 2015). In recent years, the coastal wetland restoration research mainly based on the fresh water resources regulation and the nutrient biogeochemistry in the Yellow River Delta, has become one of the core technologies for ecological restoration in degraded coastal wetland (Cui et al. 2009; Wang et al. 2012; Guan et al. 2013).

Currently, the international wetland restoration method mainly focuses on restoration of hydrological conditions in damaged wetland, halophytes and salt-tolerant plant breeding, as well as the species and habitat recovery (Callaway et al.

2003; Acreman et al. 2007; Kim et al. 2011; Rumm et al. 2016). The vegetation could restore gradually when the natural environment was remediated under the seed bank existence (VivianSmith and Handel 1996; Li et al. 2008; Stroh et al. 2012; Beas et al. 2013; Shang et al. 2016). By the study in California and Wisconsin, Zedler (Zedler 2000) found that the different restoration methods should be taken for different regions with different damaged reasons, and the restoration results with multiple species were much effective than that with the single species. The techniques of the condition improvement were mainly applied to develop the dominant plant populations for coastal wetland restoration in North and Western Europe area (Acreman et al. 2007). Although many countries have put forward a large number of schemes for coastal wetland and estuarine wetland restoration, a unified wetland restoration criteria is not proposed up to now. Therefore, we should select the reasonable methods based on the actual conditions and regional characteristics when these schemes were used for wetland restoration.

## Key Techniques for Degraded Wetland Ecological Restoration

Except the combined restoration technology (a new restoration technology formed by combination of two or more restoration technologies such as plant-microbial restoration, constructed wetland, etc.), wetland restoration technology can be basically divided into physical technology, chemical technology and biotechnology (Table 1). Physical technology achieves wetland restoration goals by improving water and soil conditions. Water-soil engineering of physical restoration technology can create a favorable water-soil environment for wetland health and promote self-repair processes in wetlands (Goodwin 1994). The water replenishment technology can eliminate the influence of water shortage and salinity by increasing the water supply (Gyuracz et al. 2011; Ahmed 2014). The sediment dredging can reduce the pollutant accumulation in sediment and the release into water (Sullivan and Aller 1996; Vellidis et al. 2003; Parkinson et al. 2006). However, the problems of high cost for construction and maintenance, large manpower and material resources consuming exist in the physical restoration technology (Goodwin 1994). The chemical restoration technology can improve wetland soil chemical properties by adding chemicals, fertilizing and soil conditioners to make wetland soil beneficial for the plant growth (Portnoy 1999). For example, the chemicals containing ions of aluminum, iron and calcium can rapidly remove the eutrophication pollutants in the sewage by chemical reaction of these ions with nitrogen, phosphorus and other substances in water. The disadvantages of chemical restoration technology include incomplete governance, high cost and secondary pollution (Portnoy 1999; Moreno-Mateos et al. 2015). Microbial use

**Table 1** The basic classification of wetland ecological restoration technology

Restoration technology	Classification	Description	Function
Physical restoration technology	Water-soil Engineering	Construction of water storage dams, drainage ditches and change land use to control wetland hydrology and land utilization	To create a favorable environment for the healthy development of wetlands
	Water replenishment	Water replenishment in water-shortage or saline alkali wetland through water conservancy facilities	To increase water supply, eliminating the impact of water scarcity and salinity
	Sediment dredging	Dredge sediment pollution in wetlands by artificial machinery	To reduce accumulation of pollutants in sediment and prevent releasing to water body
Chemical restoration technology	Chemicals adding	Adding algaecide and precipitating agent, ect.	To control eutrophication
	Fertilization and ameliorant application	Rational fertilization and adding chemical modifier	To improve physical and chemical properties of soil in wetlands
Bioremediation technology	Microbial restoration/Soil fauna restoration	Process of transforming toxic pollutants into non-toxic substance by using microorganisms/soil fauna naturally occurring or cultured under particular environment	To increase the degradation process of contaminants such as petroleum, pesticide and toxic organic pollutants, fixed heavy metals in wetlands and remove nitrogen, phosphorus and other nutrients from wetland.
	Phytoremediation	Utilization Plant functions of phytoextraction, phytovolatilization, roots filter and plant passivation	To absorb nutrients and heavy metals in the water and improve saline and alkaline land Aquatic using high plants

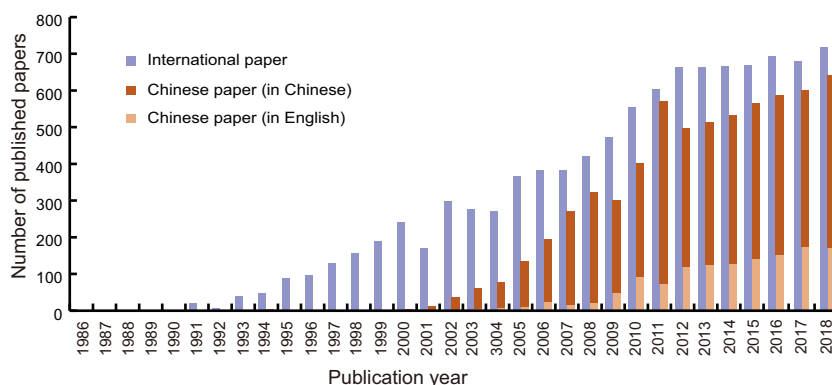
for polluted wetland restoration or wetland plant breeding is the main pathway of bioremediation (Land et al. 2011). Microbial restoration technology is mainly used for degradation of oil, pesticide, toxic and organic pollutants in wetland, as well as fixes the heavy metals and removing nutrients of nitrogen, phosphorus, etc. (DeMeester and Richter 2010; Land et al. 2011). The principle of fauna restoration which is necessary supplement for traditional bioremediation is that the miniature animal activities can promote the transference, transformation and degradation of pollutants in water (Hagerthey et al. 2014). The phytoremediation mainly utilizes the macrophyte to absorb nutrients, heavy metals and other pollutants in wetland. Up to now, the phytoremediation techniques have not been formed the bioremediation's own standards and system, and it implemented mainly on the basis of the different wetland types and pollution levels (Kentula 2000; Huang et al. 2016; Ivajnsic et al. 2016). Generally, the physical and the chemical methods are mainly used for urban wetlands restoration, while

the bioremediation is widely used for natural wetland restoration. The current practical results indicate that the combination of several techniques often gets a satisfied restoration effect. The leaching/extraction, which belong to physical-chemical restoration techniques, can be used to remove intractable organic pollutants in wetland soil. The plant-microbial combined restoration, which increases the wetland restoration effect by coordination of plant and microorganisms, can greatly improve water quality and maintain aquatic ecosystem balance by changing the plant community structure (Zhu et al. 2012).

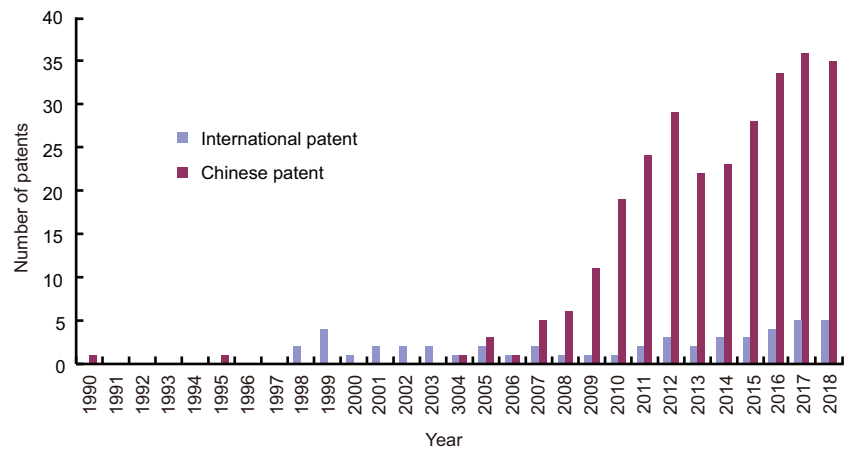
### Comparison of Degraded Wetland Restoration Techniques in China and International Nations

Since the 1990s, international funds have been increasingly used to establish protection and recovery of endangered

**Fig. 1** Comparative analysis of publication related wetland restoration



**Fig. 2** Comparative analysis of patent on wetland restoration technology (Due to the access limitation, the number of international patents is limited)



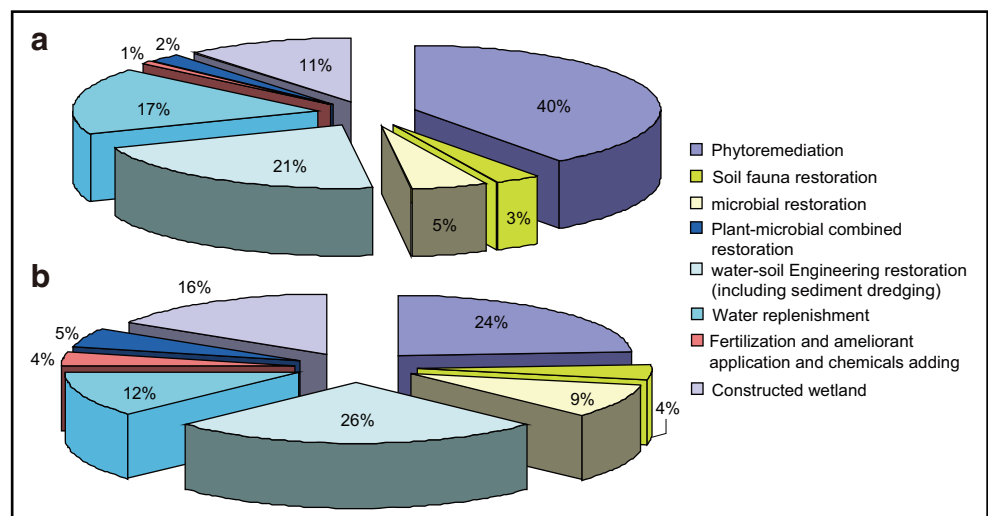
wetlands and enhance global awareness of biodiversity conservation (Bartels and Anderson 1993; Meli et al. 2014). The number of research studies related to vegetation restoration in degraded wetlands was reported in a series of books, monographs, and papers related to wetland restoration, which were published in succession. The retrieved results from the Science Citation Index Expand database of ISI Web of Science and the CNKI Chinese literature retrieval database showed that the numbers of publications related to wetland ecological restoration present an increasing trend year by year both in China and international states (Fig. 1).

International papers on wetland restoration began to be published in large numbers from 1990 and increased rapidly. Wetland restoration wasn't paid widespread attention in China until 2000, which was about 10 years after most international developed nations. Although the wetland restoration study in China fell behind of international countries, the numbers of published papers in China were gradually close to the international publications, indicating that the development speed of wetland restoration research in China are much fast.

The check results of international patents from the ISI Derwent Innovations Index, Sopotat patent database and CAS patent analysis system (<http://patent.casip.ac.cn/pat2/view/m05/A0500.xhtml>) showed that the international patent related to wetland restoration appeared at 1998 and kept a stable number each year. The first patent related to wetland restoration in China was authorized in 1990, and then the annual number of patents increased rapidly after 2006 (Fig. 2), which was much more than that of international patent number because of the access limitation of international patent. From the view of patent types, the physical restoration technique and combined restoration technique were advanced, while the chemical restoration technique and bioremediation technique lagged the international states. The wetland restoration method has been developed gradually from the single and simple technique to combined and complex treatment method, reflecting that the degraded wetland restoration received more and more attention.

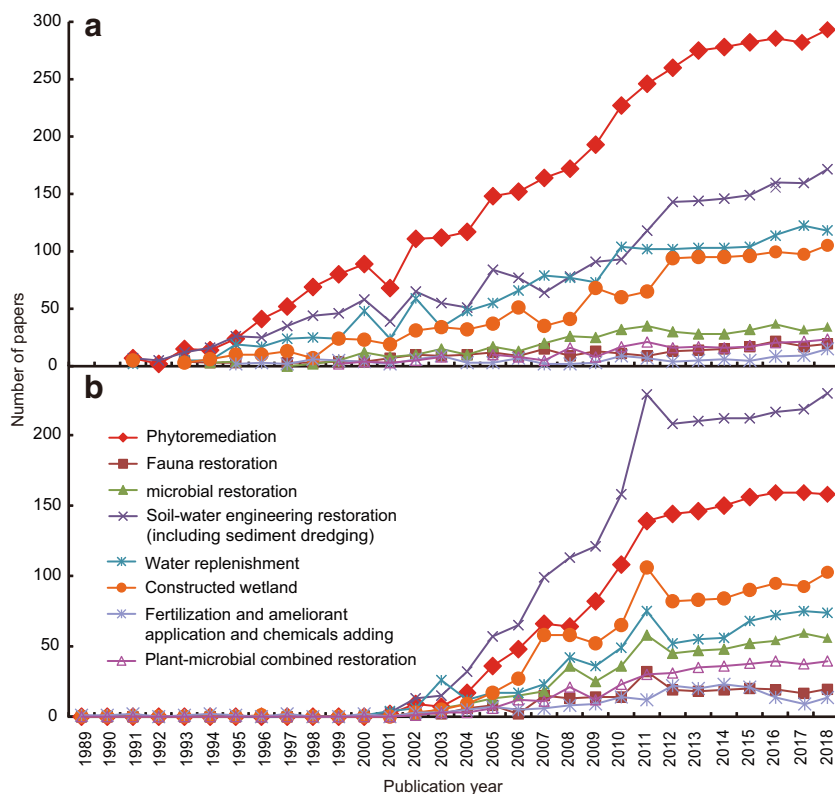
The phytoremediation and engineering restoration are regarded as the key point both in China and international nations (Fig. 3). The proportions of international publications

**Fig. 3** The proportion of mainstream technologies of international papers (A) and Chinese papers (B) related wetland restoration





**Fig. 4** Numbers of international paper (A) and Chinese paper (B) related the mainstream restoration technologies during 1989–2018



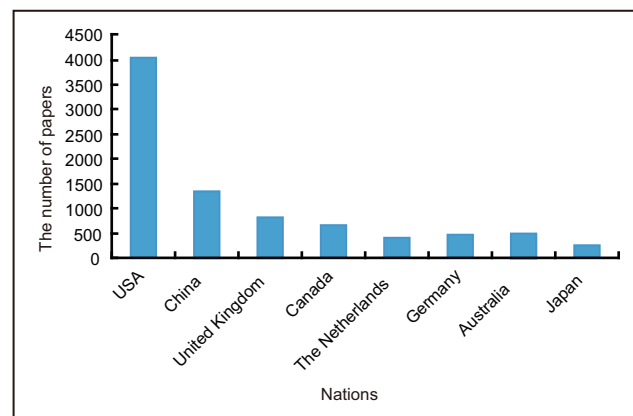
related to phytoremediation and water-soil engineering restoration of total international papers of wetland restoration were 40% and 21%, respectively (Fig. 3A), and those proportions in China were 26% and 24%, respectively (Fig. 3B).

Both the international and Chinese scientific papers related to all concern types of wetland restoration techniques showed increasing trends with time increased (Fig. 4A, B). The annual international publications, especially those about phytoremediation, water-soil engineering restoration and water replenishment studies increased quickly since 1990, among which the published paper numbers of phytoremediation occupied a dominant position with the most rapid growth rate, followed by water-soil engineering restoration and water replenishment (Fig. 4A). There were very few published papers related to wetland restorations in China before 2000. Since then, the wetland restoration studies were widespread gradually. The annual increase number of scientific papers about water-soil engineering restoration was highest and those about phytoremediation and artificial wetlands ranked second and third, respectively (Fig. 4B).

The comparative analysis results of publication number on wetland restoration in mainstream countries during 2000–2018 showed that the maximum of 4044 papers were published by United States, while China ranked second with 1335 English papers, which were much lower than that of the United States (Fig. 5). The development of mainstream restoration techniques of phytoremediation and water-soil

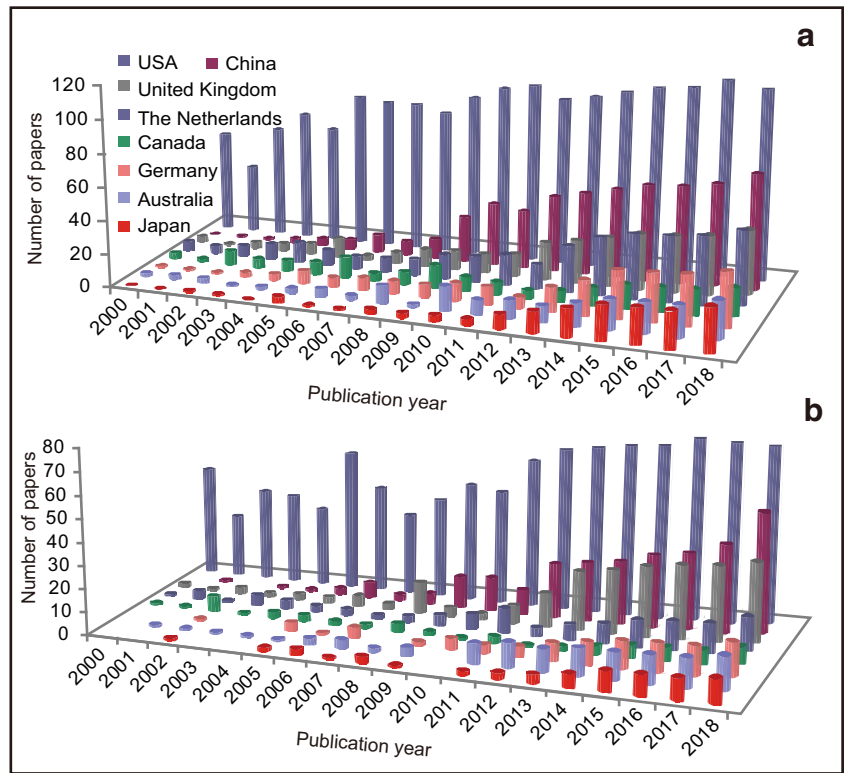
engineering restoration in the United States showed a fluctuation growth trend during 2000–2018 and those development trends in China, UK, Canada and other mainstream countries appeared a fast-growing trend since 2004, among which China achieved a great increase rate (Fig. 6A, B).

Regardless of phytoremediation and water-soil engineering restoration, the highest publishing percentage of related papers was published by the Louisiana State University during 2000–2008, the United States Geological Survey ranked second (Fig. 7A, B). The publications related to the phytoremediation and water-soil engineering restoration

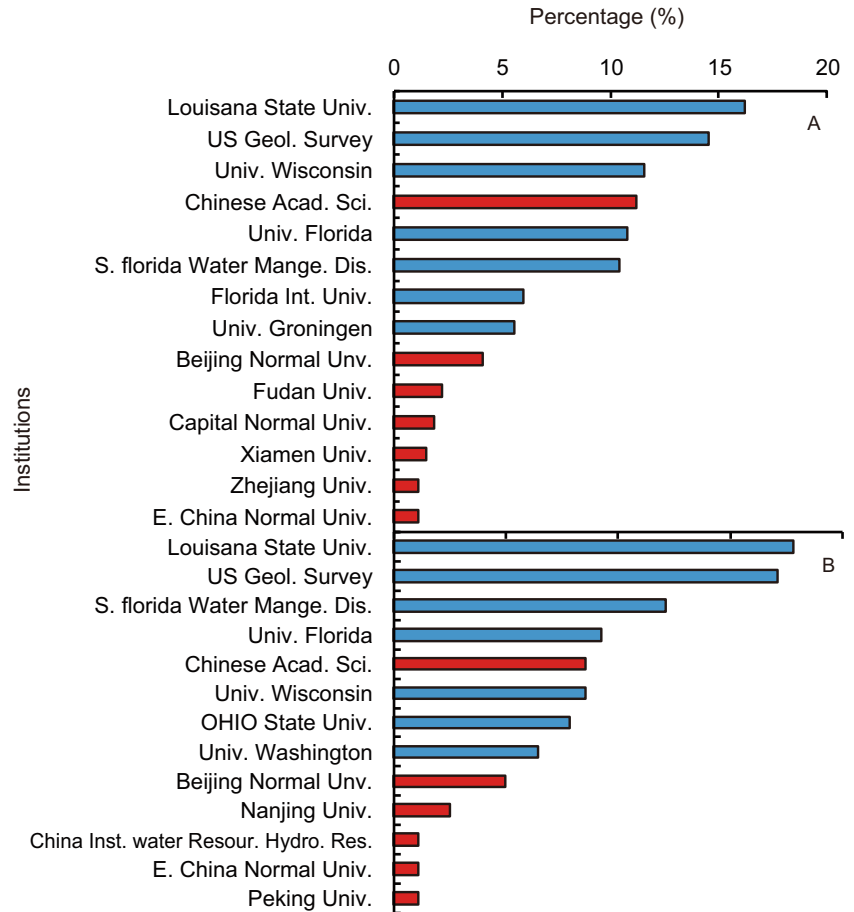


**Fig. 5** The total number of English papers related wetland restoration in the mainstream nations during 2000–2018

**Fig. 6** The numbers of international papers on phytoremediation (A) and engineering restoration (B) for wetlands in the mainstream nations from 2000 to 2018



**Fig. 7** The percentage of scientific papers on phytoremediation (A) and engineering restoration (B) for wetlands published by the mainstream institutions of international nations (in blue) and China (in red) during 2000–2018



techniques which published by Chinese Academy of Sciences ranked fourth and fifth, respectively, in the world and first in China. The Beijing Normal University became a major research institution only behind of CAS in China on wetland ecological restoration (Fig. 7A, B).

## Trends in the Development of Degraded Wetland Restoration in China

Based on the wetland ecological restoration practices in China and international states, the bioremediation technology received a great attention in developed countries and great deal of fund was invested on bioremediation research and practice. In accordance with principles of substrate design, biological population selection, community structure design and landscape design, the eight wetland ecological restoration techniques of lakeside wetland engineering technique, aquatic vegetation remediation technique, artificial floating island technique, natural-imitated dam engineering technique, artificial medium purification engineering technique, grass and forest combined ecosystem engineering technique, river corridor bioremediation technique and lakeside zone sewage and wastewater treatment engineering technique were summarized currently in China (Peng et al. 2003; Liao and Huang 2013; Ren et al. 2015; Liu and Mou 2016; Shang et al. 2016; Cui et al. 2018). Those techniques have greatly promoted the development of ecological restoration protection of China. Based on the international development trend of ecological restoration, the study and practice of biological combined restoration technology will get more and more attention on future wetland restoration research in China. In the process of wetland bioremediation technology research, the one hand is that the indigenous species with high purification capacity should be actively selected and used, the other hand is that the species with high capabilities of pollution-tolerance and decontamination should be introduced based on results of enough tests and risk assessments. Because of different functions and interrelation of plants and microorganisms in bioremediation, combination of phytoremediation and microbial restoration can get a preferable effect for damaged wetlands restoration. Meanwhile, the application of gene engineering technology in bioremediation field to breed wetland plants and microorganisms with high salt-tolerance, decontamination and high biomass will greatly promote the application of bioremediation technology in wetland restoration.

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## Compliance with Ethical Standards

**Conflict of Interests** The authors declare that there is no conflict of interests regarding the publication of this paper.

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