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Major Ecosystems in China: Dynamics and Challenges for Sustainable Management

Yihe Lü · Bojie Fu · Wei Wei · Xiubo Yu · Ranhao Sun

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Abstract Ecosystems, though impacted by global environmental change, can also contribute to the adaptation and mitigation of such large scale changes. Therefore, sustainable ecosystem management is crucial in reaching a sustainable future for the biosphere. Based on the published literature and publicly accessible data, this paper discussed the status and trends of forest, grassland, and wetland ecosystems in China that play important roles in the ecological integrity and human welfare of the nation. Ecological degradation has been observed in these ecosystems at various levels and geographic locations. Biophysical (e.g., climate change) and socioeconomic factors (e.g., intensive human use) are the main reasons for ecosystem degradation with the latter factors serving as the dominant driving forces. The three broad categories of ecosystems in China have partially recovered from degradation thanks to large scale ecological restoration projects implemented in the last few decades. China, as the largest and most populated developing nation, still faces huge challenges regarding ecosystem management in a changing and globalizing world. To further improve ecosystem management in China, four recommendations were proposed, including: (1) advance ecosystem management towards an application-oriented, multidisciplinary science; (2) establish a well-functioning national ecological monitoring and data sharing mechanism; (3) develop impact and effectiveness assessment approaches for policies, plans, and ecological restoration projects; and (4) promote legal and institutional innovations to balance the intrinsic needs of ecological and socioeconomic systems. Any change in China's ecosystem management approach towards a more sustainable one will benefit the whole world. Therefore, international collaborations on ecological and environmental issues need to be expanded.

Keywords Ecosystem change · Ecosystem management science · Ecosystem-society interaction · Ecological restoration · Forest · Wetland · Grassland

Y. Lü · B. Fu (✉) · W. Wei · R. Sun
State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China
e-mail: bfu@rcees.ac.cn

X. Yu
Institute of Geographical Sciences and Natural Resources Research, CAS, Beijing, China

Introduction

China, as the largest developing country with a population of about 1.3 billion and a diverse natural environment, is suffering from heavy pressures on its natural ecosystems due to rapidly expanding economic growth and strong livelihood demands owing to a shortage of natural resources (Fu 2008). This combination of factors has resulted in structural and functional ecosystem degradations (Fu and others 2007). The traditional extensive management system with very low level inputs is far from being consistent with the stress that socioeconomic development places on ecosystem services. Therefore, it is of top priority for China to improve the ecosystem management system in order to enhance the capacity of major ecosystems to provide important services. It is thus necessary to explore a sustainable ecosystem management solution that meets the actual situation in China in order to optimize the provision of ecosystem services, and maintain the ecological integrity and sustainability of such services. The major ecosystems discussed here include three broad categories of forest ecosystems, grassland ecosystems, and wetland ecosystems. These three groups cover about 63.8% of the total territory of China, and about 74.4–81.5% of the total value [estimated on the basis of remote sensing and the procedures formulated by Costanza and others (1997)] of terrestrial ecosystem services in China (He and others 2005; Zhu and others 2007). These three types of ecosystems are crucial in providing ecosystem services and maintaining the ecological security of the nation.

To combat the ecological degradation problems, China has launched many large scale ecological restoration projects in sectors such as forestry, agriculture, and water resources (Zhao and others 2002; Li 2004; Wang and others 2007b; Liu and others 2008b; Yin and Yin 2010). However, the real world effectiveness of these efforts varies due to the impacts of various natural resources and socioeconomic factors. The objectives of this paper are to: (1) give an assessment on the status and trends of the major ecosystems based on the scientific knowledge available to date, (2) discuss the efforts and achievements of the major national scale ecological restoration projects, and (3) analyze the challenges and potential countermeasures for sustainable ecosystem management. These are believed to be beneficial in enhancing the understanding of the ecosystem management issues in China in a globalizing world. At the same time, the problems and potential solutions for ecosystem management may have implications for other countries facing similar socioeconomic development conditions and natural resources conservation.

Status and Trends of Major Ecosystems

Forest Ecosystems

Historically, China was a country rich in forest resources. During the Han Dynasty over 2,000 years ago, the forest coverage rate reached up to 50%, but that figure fell below 40% during the Tang and Song dynasties (Tao and Zhang 2002). Over the past 300 years, the forest resources in China exhibited a trend of declining before 1960 to growing after 1960 [Shi and others 2006; He and others 2008; Department of Forest Resources Management of the State Forestry Administration (DFRMSFA) 2010] (Fig. 1). Since 1980, the forested areas in China have been steadily increasing mainly due to the regeneration of woodland, shrubland, and plantation forests, with plantation forests contributing about 90% for the increase in the forest coverage rate (Fig. 2). At the same time, the old growth natural forests are declining in size (Fig. 2) [Peng and others 2008; Shi and Wang 2009; State Forestry Administration (SFA) 2010]. In terms of forest resources during the two periods since 1949 (1950–1962; 1999–2003), the percentages of plantation forest areas and stocks have increased substantially from 4.49 and 1.9 to 33.77 and 10.35%, respectively, while those of natural forest areas and stocks have declined from 95.51 and 98.1 to 66.23 and 89.65, respectively (Gao 2008). According to the seventh national forest resources inventory (2004–2008), China has a forest area of about 1.95×10^6 km^2 and a coverage rate of 20.36%, with natural forests contributing about 61.2% (SFA 2010). In spite

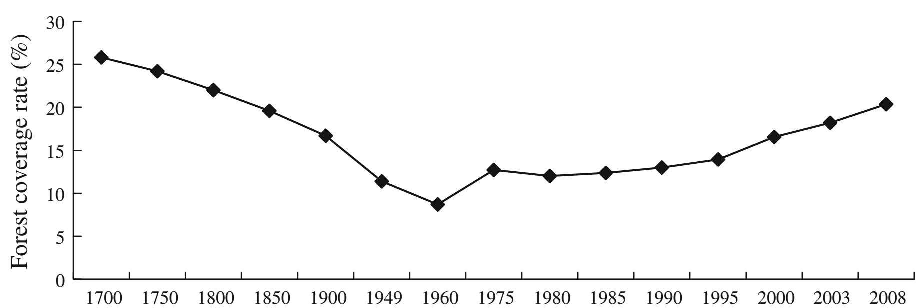


Fig. 1 Historical changes in China's forest coverage rate (*Data source*: Shi and others 2006; He and others 2008; DFRMSFA 2010)

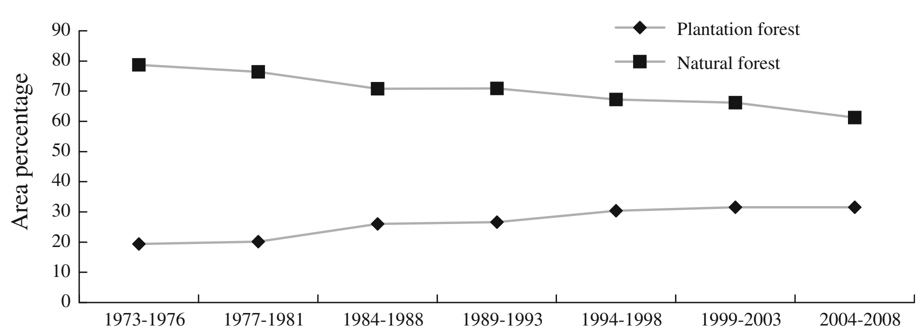


Fig. 2 The percentage change in natural and plantation forest area to forested land area in different periods of national forest inventory (*Data source*: Peng and others 2008; Shi and Wang 2009; SFA 2010)

of this, the forest resources in China are still low in quality and ecosystem service capacity in regards to the world context: (1) the forest coverage rate in China is only 2/3 of the world average ranking 139th globally; (2) the per capita forest area and stock are 1/4 and 1/7 of the world average, respectively; (3) the per unit area forest stock volume is 85.88 m^3/ha, which is similar to 78% of the world average; (4) plantation forests, dominated by young and middle aged stands, are characterized as low productivity with a stock of only 49 m^3/ha; (5) only 11.31% of the forest ecosystems in China have good ecological functions (DFRMSFA 2010).

Spatially, the forest ecosystem services vary greatly in different regions of China. For example, the major forest carbon pool is concentrated in the northeast and southwest regions of the nation, and the average carbon density is much larger in southwest, northeast and northwest regions (Xu and others 2007b). The forest ecosystems in northeast China cover 31.4% of the whole area of forest ecosystems in the nation, and the carbon stock in vegetation and soil accounts for 74.28 and 63.88% of those of the whole country, respectively, while the carbon densities of forest vegetation and soil are 2.7 and 1.22 times those of the national average, respectively (Zhao and others 2009).

However, with the reduction of natural forest areas and increase in plantation forest areas, the forest ecosystem functions are under the pressures of ecological degradation. Of the overall forest resources in China, plantation forests cover more than 30%. Nevertheless, the plantation forests are inferior to natural forests in ecological functions such as carbon sequestration, soil conservation, nutrient retention, and biodiversity conservation. Soil respiration in pine plantation was found to be significantly higher than that in the secondary oak forest of Jiangsu province, which is located in the southeast part of China (Shi and others 2009). However, the bulk soil organic carbon and nitrogen concentrations at the surface soil layer of 0–20 cm were significantly lower in Chinese fir plantation and regenerated forest than in natural forests at the study site of Sichuan province, which is located in southwest China (Luan and others 2010). Soil organic carbon, total nitrogen, and microbial populations and biomass in the surface soil layer (0–10 cm) from the *P. koraiensis* plantation were significantly lower compared to natural and regenerated forests in Liangshui Nature Reserve, which is located in northeast China (Shi and others 2008). Similarly, a study from southern China indicated that the contents of soil organic carbon, total nitrogen, and labile organic matter such as hot-water extractable organic carbon and total nitrogen, cold-water extractable organic carbon and total nitrogen, and microbial biomass were significantly lower in pure *C. lanceolata* plantation than the contents in native broadleaved forest (Wang and Wang 2007). Accordingly, the conversion of secondary forests to coniferous plantations can result in a decline in soil fertility (Wang and others 2010). This suggests that the scenario on expansion of plantation forests and shrinking of natural forests may lead to a loss in the ecological functioning of forest ecosystems. Therefore, simply seeking to increase the areas of plantation and recklessly expand the forest coverage rate cannot improve the overall service quality of forest resources.

With the implementation of ecological restoration projects in forestry and the improvement in ecosystem management skills, it is expected that by 2020 and 2050, the forest coverage rate in China will grow to 23.5 and 28% respectively (Dong and others 2008). Given the current extensive management style (e.g., dependent largely on tree plantations in reforestation or merely a logging ban strategy), the forest resources in China may fall short of supply in forest goods and services, even with the planned extent of forest coverage rates in the future, as compared with the increasing demands of urbanization, the population, and the economy (Dong and others 2008). This has raised serious concerns both domestically and internationally about the deficiency of forest resources and their management in China (Bull and Nilsson 2004; Démurger and others 2009). Understanding the diversity and complexity of forest ecosystem structure and processes, and enhancing the sustainable forest ecosystem management on the basis of forest ecosystem services should thus be utilized to address these challenges.

Grassland Ecosystems

Grasslands are the dominant land cover or ecosystem type, accounting for 13% of the global grassland area and over 40% of the total land area in China, with 84.4% of that distributed in western and northern China (Kang and others 2007). As an important gene bank for wild animals and plants, the grassland in China is home to over 6,700 known species of forage plants, including 320 endemic species, and more than 2,000 species of wild animals, including over 40 species with the highest ranking of priority for national protection. However, the grassland ecosystem in the country is affected by severe degradation. The grassland ecosystems most affected by degradation are mainly found in the arid and semi-arid areas of northern China and in the Qinghai-Tibetan Plateau. In the headwater areas of the Yangtze and Yellow Rivers, there is approximately 357.13×10^4 ha of degraded grassland, of which about 21% is heavily degraded (Zhou and others 2005). In Guinan County of Qinghai Province, there has been a 12.6% reduction of grassland over the last three decades (1976–2006) with particularly severe grassland degradation in high density grasslands, which showed a net reduction of

28.87% (Feng and others 2009a). Grassland degradation has caused great losses in ecosystem services. According to research based on MODIS remote-sensing data, the potential economic losses due to grassland degradation on a national scale amounted to 6.66 billion USD from 2003–2005, 78.41% of which occurred in the seven western and northern provinces/autonomous regions including Inner Mongolia, Xinjiang, Tibet, Qinghai, Gansu, Yunnan, and Sichuan with Inner Mongolia as the biggest loser (Wang and others 2007c). Along with grassland degradation, ecosystem functions were significantly reduced, including vegetation cover and composition, species richness and diversity, the proportion of fine forage, aboveground and underground biomass, litter, soil organic carbon, soil microbial biomass carbon, total nitrogen, total phosphorus, and the fertility level (Wang and others 2009a; Zuo and others 2009). Compared with the 1950s, present grass production has decreased by 30–50% and grasslands have been turned into barren land and desert in some severely degraded areas with the ecological functions and productivity of the grassland totally lost (Wang 2005).

The grassland ecological conditions in some areas have improved since the implementation of grassland conservation projects and enhanced grazing management. For example, vegetation growth has improved due to reduced grazing intensity in eastern Inner Mongolia and the eastern region of the Qinghai-Tibet Plateau (Xu and others 2007a). However, the current grassland ecological monitoring and resource inventory system is not sufficient, and large uncertainties are prevalent in reporting the ecosystem status and trends on both a regional and national level (Harris 2010; Liu 2009a).

Wetland Ecosystems

The wetlands in China covers an area of 38.48 million hectares (excluding paddy fields), ranking the fourth in size worldwide, and about 94% of the wetland ecosystems are natural. About 84% of China's natural wetlands are palustrine, lacustrine and riverine wetlands with the palustrine wetlands being the largest. These are the most widely publicized data on Chinese wetlands. However, the latest published paper on wetland changes in China showed that the wetlands in China covered an area of 304, 849 km^2 in 2000, with 50, 360 km^2 lost in the 1990–2000 period (Gong and others 2010). A general trend of an overall reduction but a partial expansion in specific locations is evident on national, regional, and local scales (Yan and others 2006; Li and others 2007b; Wang and others 2007a; Tong and others 2008; Zong and others 2009; Zhang and others 2009c; Gong and others 2010; Xie and others 2010). Another major threat to the wetland ecosystem health is water pollution [Han and others 2006; Fu and others 2007; Yang and others 2008; Ministry of Environmental protection (MEP) 2008]. Although water pollution will not lead to the shrinkage of wetland resources, it can significantly weaken the capability of wetlands to provide ecosystem services, posing serious risks to food production, the water supply, and biodiversity resources.

Ecological degradation and water pollution in wetland ecosystems have led to a loss of ecosystem services. Over the past 50 years, 1.5 Pg (petagrams or billion tons) of soil organic carbon in the surface soil of wetland ecosystems, 1/7–1/6 of the total wetland soil carbon stock, has been lost mainly due to cropland encroachment and overgrazing (Zhang and others 2008b). The provisioning service value accounts for only a small part of the total ecosystem service value of wetland ecosystem in China (Zhang and others 2008a, d, 2009b). Temporal decreases in wetland ecosystem values have also been detected in different wetland areas (Zhang and others 2008c, 2009c). Usually, a small increase of provisioning service value results from increased human use intensity is at the cost of many times decreases of other ecosystem service values, which entails the conservation of wetland ecosystems in their natural states.

Driving Mechanisms of Ecosystem Changes

On a national scale, China's forest ecosystems are more fragmented than those of the United States (U.S.), which resulted mainly from anthropogenic disturbances such as agricultural expansion and poor forest management practices (Li and others 2010). Most of China's forest resources are distributed in the mountainous areas, where the economy is underdeveloped and the local people still depend highly on forest resources for their livelihoods. Human activities, together with the needs of the local people for timber and fuelwood resources, have caused ongoing deforestation, and eventually resulted in the degenerative land cover transition series of "forest to woodland to grassland to cropland" or "shrubland to grassland to cropland" (Zou and others 2006). In addition to human-induced factors, natural factors (e.g., altitude, landform, climate, and hydrology) have also impacted forest ecosystems (Xu and others 2006b). With a rise in altitude, the combined effects of natural and anthropogenic factors will reduce the disturbance and pressure on the forest when the forest ecosystem is gradually stabilizing. Climate change is also a driver of forest ecosystem change. The results of 22 years of data showed that reduced rainfall and rising temperatures have led to a decline in the forest coverage rate in northwestern China (Guo and others 2008b). The importance of natural factors seems to be scale dependent. For example, in northeast China, climate factors accounted for 34–76% of the variation in forest species richness on a regional scale, but explained only 0–44% of variation on a local scale (Wang and others 2009c). National macro-socioeconomic conditions and forestry policies often have significant effects on forest resources. For example, during the 1958–1962 period, following the Great Leap Forward policy and the establishment of the People's Commune, the forest resources in the Nujiang River basin were severely destroyed. More than 70% of the deforestation came from the 'making iron and steel' and 'running public communal dinning halls' campaigns, which became major drivers of the sharp decline in forest resources in this area (Feng and others 2008). National policies also have a lag effect on forest ecosystem change. The increase in the forest coverage rate in China over the last decade can be attributed largely to the ecological benefits brought about by key national ecological restoration projects such as returning farmland to forest (or Grain to Green) and natural forest conservation.

Human activities and climate change are believed to be the two major drivers of grassland ecosystem degradation. The present institutional arrangement, taking the property rights arrangement called "Household Production Responsibility System" as an example, does not promote the sustainable use of grassland ecosystems because it does not avoid over-grazing problems and exacerbates "the tragedy of the commons" in grassland degradation (Li and others 2007a). Overuse of grassland ecosystem resources leading directly to grassland degradation, and climate change exacerbates the degradation problem (Han and others 2008). An analysis of the factors of desertification in the Hulunbeier Grassland over the last 50 years (1953–2004) indicated that the intensity of human activities (including population density, grassland cultivation, and grazing intensity) and climate warming contributed about 89% of the grassland ecological degradation (Chen and others 2008). In regards to the desertification of alpine grassland in the headwater area of the Yellow River, human-induced and natural drivers contributed 61.6 and 38.4% respectively (Wang and others 2006a). In the western and southern forest areas of China, deforestation and/or cropland abandonment are the major drivers behind the increase in grassland areas at decadal time scales (Yan and others 2005; Xu and others 2006b; Zou and others 2006; Liu and others 2008a). This kind of grassland is in a successional stage, and may experience a natural succession towards a shrub and forest ecosystem (without human disturbance) in the long-term.

The driving mechanisms behind wetland ecosystem change vary according to the wetland type. For example, terrestrial water bodies like rivers and lakes are largely affected by rainfall and hydrological conditions, and these areas are directly influenced by water quantity (Li and others 2008b). The change in the area of the estuarine wetlands, such as the Yellow River Delta, is intimately associated with the sediment quantity and water quantity from the upper reaches (Tian 2008). The human activities of development and use have a significant impact on the coastal and palustrine wetlands. For instance, between 1954 and 2005, the marshes of Sanjiang Plains (located in northeastern China) were reduced at an annual rate of over 50,000 ha, resulting mainly from agricultural development (Song and others 2008). Thus, agricultural reclamation is the direct driver and the change in hydrological regime is the indirect driver of wetland change (Zhang and others 2009a; Zhou and others 2009). Agricultural development tends to exert more impact on the quantity of wetlands than on their distribution patterns (Zhang and others 2010b). In densely populated areas, urbanization is one of the main factors behind wetland loss (Xu and others 2009; Xie and others 2010). From 2000–2006, the coastal wetlands in Dalian City, which is in northeastern China, declined by nearly 100 km^2, with the human activities (e.g., expansion of industrial parks by means of filling the sea and the growth of aquaculture) being the major drivers (Jiang and others 2008). Regarding the change in the water quality of wetlands, non-point sources of nitrogen and phosphorous from agricultural and urban areas have been attributed as the main triggers for lake water eutrophication (Le and others 2010). Heavy metals in water have mainly resulted from industrial wastewater discharge (Zhang and others 2010a). The major human-induced factors of wetland ecosystem change found in a national wetland resources survey include reckless agricultural cultivation and conversion, pollution, over-exploitation of biological resources, water and soil loss and siltation, and unwise use of water resources, which contribute to 30.3, 26.1, 24.2, 8, and 6.6%, respectively, to the threats of key wetland areas, with lacustrine wetland being the most severely affected wetland type due to a combined impacts of these factors (Lei and Zhang 2005).

The driving mechanisms behind the changes in forest, grassland, and wetland ecosystems are complex and involve various factors. The natural and socioeconomic factors interact with one another, although the importance of each driver and the combination of various factors may change according to the ecosystem type, geographical location, and spatiotemporal scale. Natural factors (e.g., climate) constitute the macro controller of ecosystem change, but their intensity of change is generally considered moderate, with significant effects only in the long term. In contrast, the driving roles of the human-induced factors are more prominent. These factors, including population growth, livelihood needs, and socio-economic development needs, are often regarded as the most important direct drivers of ecosystem change. As human beings are not well-positioned to regulate natural factors on large temporal and spatial scales, the major approaches in sustainable ecosystem management are leveraging legal, administrative, institutional, and policy measures to regulate human behaviors on the use of natural resources in a scientific manner.

Efforts and Achievements of National Ecological Restoration Projects

To address the growing ecological and environmental problems, the Chinese government has launched a series of key projects on ecological restoration, such as the Natural Forest Conservation Project, the Program of Returning Farmland to Forest/Grassland or Grain to Green Project, and the Wildlife Conservation and Nature Reserve Development Program (Bennett 2008). The ecological restoration projects discussed in this paper are those formulated and promoted by the Chinese central government on a large spatial scale with a top-down approach in decision making and implementation. Therefore, the funding for these projects is provided mainly by the central government. Statistics from the National Development and Reform Commission of China indicated that over 700 billion RMB (about 100 billion USD) has been invested in key ecological restoration projects on forest, grassland, and wetland conservation and restoration (http://english.gov.cn/2009-09/06/content_1410525.htm).

Generally, the results of these key projects have been encouraging. The implementation of these projects has, to some degree, improved the functioning of various ecosystems. Meanwhile, large scale campaigns have greatly increased public environmental awareness and generated favorable social benefits (Zhuang 2003; Zhang 2007). Typical large scale ecological restoration projects are shown in Fig. 3. Under the Grain to Green project, 0.27 million km^2 of land were reforested from 1999 to 2008, with 1/3 of reforested land coming from cropland (Li 2009). In the region enacting the Three-North Shelter Forest project, the average forest coverage rate increased from 5.05 to 10.51% between 1978 and 2008 (Liu and others 2009). The implementation of Natural Forest Conservation Project and Green to Green Project has greatly accelerated the national ecological restoration process of forest ecosystems, resulting in the effective protection of key natural and noncommercial forest, improved soil ecological functionality, less water and soil loss, and reduced disasters due to sandstorm and desertification (Lei and others 2008; Cao and others 2009; Xu and others 2010).

Through the implementation of grassland restoration projects, the grassland vegetation has improved in quality, leading to greatly enhanced capacity of grassland in sand fixation and soil and water conservation, and ultimately a significant improvement in ecological conditions at the project sites, such as those for the protection of grassland from grazing (Fig. 3). Grassland conservation and restoration measures increased the average vegetation coverage rate, height of plant community, and productivity by 16, 63, and 80%, respectively, according to the national grassland monitoring report of 2008 by the Ministry of Agriculture of

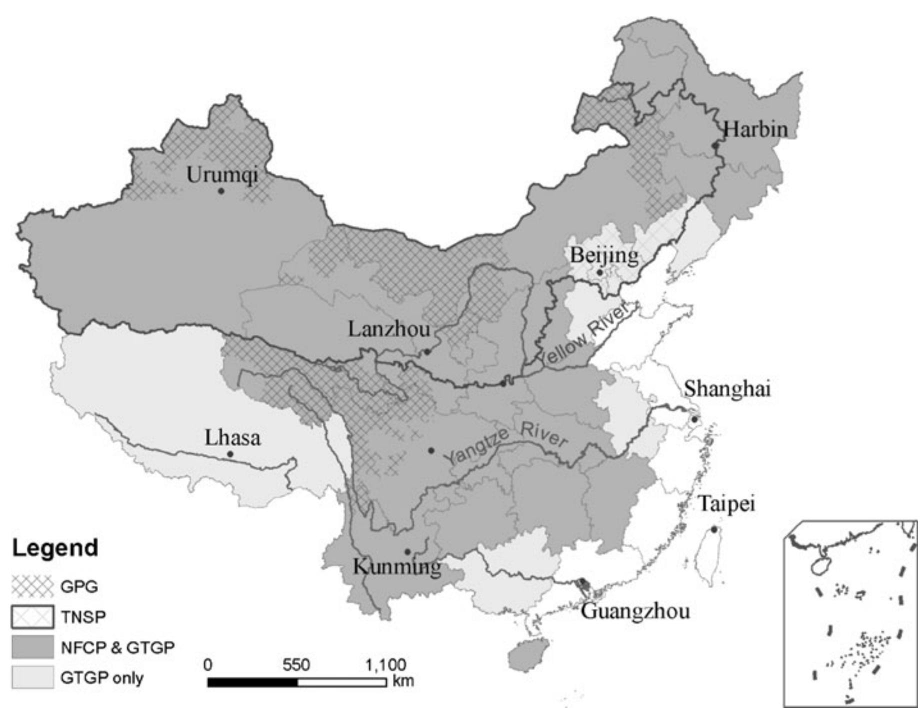


Fig. 3 The geographical extent of four typical large scale ecological restoration projects for forest and grassland ecosystems in China. *GPG* grassland protection from grazing, *TNSP* three-north shelter forest project, *NFCP* natural forest conservation project, *GTGP* grain to green project

the People's Republic of China. Local and regional research also supports the trend of ecological improvement of grassland ecosystems driven by the effective implementation of ecological restoration projects. In the ecological restoration sites of Maqu County of Gansu Province, the average grass vegetation coverage rate and forage production increased by 9 and 22.5%, respectively, compared to the adjacent grasslands (Wang and others 2008a). The average yield of alpine grassland increased by 40% because of improved pest and poisonous forage control in northern Tibet, and nearly 18% of the severely degraded grassland has shown significant recovery in recent years (Gao and others 2010). In grasslands of northern China, biomass carbon stock increased at an average rate of 0.2 Tg (teragram = 1 trillion grams) per year during the 1982–2006 period resulted from ecological restoration (Ma and others 2010).

Typical cases for effective wetland restoration have also been reported in the literature since 1998 when the Chinese government called for the ecological restoration of wetlands. Natural restoration was effective in habitat creation for rare waterfowl conservation in the Yancheng Biosphere Reserve (Wan and others 2001). The Tarim River restoration project successfully improved the hydrological situation of the riparian wetlands and showed positive effects on the conservation of endangered plant species and rare migrating bird species (Li and others 2009). Wetland restoration in the Yellow River Delta has shown increasing efficiency in water pollution control, soil quality improvement, carbon sequestration, and habitat expansion (Cui and others 2009). Large areas of cropland and other land cover types were converted to lake in the Dongting Lake area in order to enhance its ecological functionalities of flood control, biodiversity conservation, and water pollution mitigation (Pan and Yu 2010; Xiong and Wang 2010). Data from State Forestry Administration also indicated that more than 550 wetland nature reserves were established across China by the end of 2008, in addition to 36 Ramsar sites (wetlands of international importance) and 80 wetland parks (MEP 2008). As a result, about 49% of natural wetlands in China have been legally protected. From 2003 to 2008, the total number of nature reserves in China increased from 1,999 to 2,538, with over 90% of the nature reserves serving for the protection of typical natural ecosystems and important wildlife species (He 2009). Subsequently, about 15% of the terrestrial land surface in China has been designated as nature reserves.

The effectiveness of large scale ecological conservation and restoration efforts can also be represented by the improvement of ecosystem functionality. In the red soil region of southern China, ecological restoration using various vegetation types showed positive effects on soil ecological functions with carbon sequestration as the most significantly improved (Lü and others 2008). The mixed forest restoration approach has exhibited the most positive effects on biodiversity conservation and other ecological functions such as soil conservation (Ren and others 2007; Lü and others 2008). Regarding the semiarid grassland ecosystem in China, grazing exclusion can increase carbon sequestration logarithmically, and the carbon sequestration effect is most prominent on a decadal time scale (He and others 2009). For the alpine meadow in the Qinghai-Tibetan Plateau region, the grazing exclusion has enhanced aboveground live biomass, root biomass, litter accumulation, and soil functionality (Shi and others 2010). Monitoring of the effectiveness of wetland restoration in the Yellow River Delta over seven years indicated significant improvements in the ecological integrity of the wetland ecosystems, as represented by indicators including water quality, soil salinity, soil organic matter, plant community, and bird species (Cui and others 2009).

The achievements in ecological conservation and restoration in China during recent years would not be possible without the strong, top-down policy implementation and large input of monetary funds and other resources. However, several problems are still prevalent, such as insufficient monitoring and assessment, heavy reliance on state financing and a lack of public contribution, rigidity and inconsistency in policy measures, inadequate inter-agency cooperation and planning, insufficient consideration of local interests, and neglect of appropriate technical practices (Yin and Yin 2010). These factors and their interactions make the situation of ecosystems and their management more complex than ever before, posing huge challenges to the ecological conservation and restoration efforts in China.

Challenges and Recommendations for Sustainable Ecosystem Management

Major Challenges

Many challenges remain in the sustainable management of ecosystems in China, including the limited availability of natural resources, the already tense human-nature relationships, and the strong momentum for economic development and urbanization (Shao and others 2006). About 23.4 and 41.7% of the land area in China are marginally suitable and unsuitable for human settlement, respectively (Feng and others 2009b). The remaining land area is thus heavily populated with an ever-increasing rate of urbanization (Fang and Lin 2009), which may bring about profound impacts on the natural environment (Güneralp and Seto 2008). For example, the scale of human settlement had significantly negative impacts on the net primary productivity (NPP) of ecosystems in highly populated and economically productive southeastern China (Lu and others 2010). At the same time, China is ambitious in its economic growth, with the goal of quadrupling the gross domestic product between 2000 and 2020 (Hicks and Dietmar 2007). This implies inevitable large scale increases in the human use pressures on natural ecosystems.

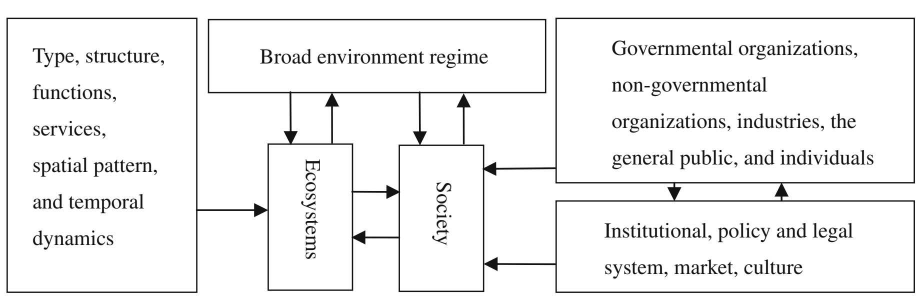
Another fundamental challenge is the insufficiency of institutions, legislation, and enforcement. In the institutional arrangement point of view, there is a lack of coordination among governmental agencies as well as unclear responsibilities (Ongley and Wang 2004; Wang and others 2008b). Generally, there are also several drawbacks in the current Chinese legal system regarding ecosystem management, including the lack of sound ecological and socioeconomic science bases in balancing the interests of various actors, weak legal liabilities, neglect of important issues (e.g., rights and duties of social entities or stakeholders over the sustainable utilization and management of natural resources; joint duty of care for ecological conservation and restoration; sustainable resources utilization or zoning and planning for ecological conservation and restoration), and low executive ability and performance of legal provisions because of lenient penalties for violations of laws and regulations on ecosystems (Zhou and others 2008). Bureaucratic politics between environmental and nonenvironmental ministries has limited the legislation and effective implementation of environment and natural resource conservation laws (Zhu and Jiang 2008). Furthermore, local governments have also been a major reason for failures in enforcing environmental laws (Ongley and Wang 2004) for their overemphasis on local economic growth and benefits. The most difficult challenge, however, may be to find effective approaches to regulating the behaviors and relationships of the various stakeholders (e.g., different levels of government, the industrial sector, and the public), who often have different, sometimes conflicting, objectives and expectations. In a more technical sense, there is a lack of an updated, publicly accessible monitoring system for the ecosystem status and trends. In a practical sense, the success of ecosystem management practices depends on their effectiveness in generating alternative livelihoods to mitigate and transfer the human pressures on ecosystems and formulating incentive mechanisms to stimulate ecosystem conservation and restoration. Therefore, capacity building should be enhanced in fields such as multi- and transdisciplinary scientific research, technological innovation, ecological monitoring and data sharing, policy and institutional design, and environmental legislation and enforcement on the ecology and human dimension of the dynamics and management of ecosystems (Tao and others 2007; Gu and Sheate 2005; Xu and others 2006a; Wang and others 2006b, Lo and others 2006).

Some Recommendations

Firstly, it is urgent to advance a science-based and application-oriented ecosystem management system in China. Based on the findings in the analysis of the major ecosystems and their management in China, a conceptual framework can be formulated to deal with various issues concerning ecosystem management (Fig. 4). A multidisciplinary science is required to inform ecosystem management decisions and applications via disentangling the complexity, interactions, and co-evolution of ecosystems and society across spatiotemporal scales. Ecosystems provide support for the development and welfare of human society, and at the same time, human society uses, modifies, and takes care of ecosystems as valuable resources. Society and ecosystems are components of, and are adaptable to, the broad environmental regime that exerts macro controls (such as climate change across spatiotemporal scales or geomorphological differentiation). Therefore, ecosystem management needs support from the two pillar fields of ecosystem science and socioeconomic science.

Ecosystem science deals mainly with the type, structure, function, service, spatial pattern, and temporal dynamics of ecosystems under anthropogenic disturbances and interventions. Socioeconomic science mainly considers the mechanisms for establishing and applying of institutional, legal, cultural, policy-based, and market-based instruments to regulate interrelationships among the various social actors as well as between social actors and ecosystems in the sustainable use, conservation, and restoration of ecosystems. This kind of socioeconomic science provides a

Fig. 4 A conceptual framework for the analysis of ecosystem management issues



sound base for the establishment and optimization of incentive and disincentive mechanisms to shift the behaviors of various social entities (from individuals, communities, and industries, to governmental agencies) towards the sustainable use, conservation, and restoration of ecosystems. The multidisciplinary science on ecosystem management is thus qualified as the intersection and very forefront of newly advocated scientific fields such as the study of coupled human and natural systems (Liu and others 2007), ecosystem service science (Armsworth and others 2007), land change science (Turner and others 2007), and sustainability science (Kauffman 2009). Technical innovations in the fields such as ecological monitoring, ecological engineering, and ecologically friendly use of ecosystem services (Mitsch and Jørgensen 2003; McShane and others 2007; Wikelski and others 2007) are crucial for bridging science with the real world effectiveness and sustainability of ecological restoration and conservation efforts. Therefore, science-based technological advancements are urgently needed in the fields such as water pollution control (Qu and Fan 2010) and ecosystem rehabilitation (Xu and others 2008).

A second recommendation, in order to develop an updated and sound database for ecosystem management, is an urgent need to integrate or coordinate the existing ecological monitoring resources to establish a well-functioning national ecological monitoring and data sharing mechanism. China already has some ecological monitoring and research systems affiliated with different central governmental agencies. The Chinese Ecosystem Research Network, comprised of 40 ecosystem monitoring and research stations on different ecosystem types across China, is managed by the Chinese Academy of Sciences (Fu and others 2010). The SFA is responsible for the monitoring of forest and wetland ecosystems. Under the supervision of SFA, the Chinese Forest Ecosystem Research Network has also been established (Guo and others 2008a). The monitoring and management of grassland ecosystems fall under the supervision of the Ministry of Agriculture. The monitoring facilities on the quantity and quality of water resources are supported and supervised by the Ministry of Water Resources and MEP. Based on these existing ecological monitoring and research systems, it is crucial to establish a national ecological monitoring and data sharing mechanism to facilitate and implement data-driven, science-based sustainable ecosystem management policies.

Public access to ecological and environmental monitoring data is necessary to fuel wide participation and ecological and environmental democracy in ecosystem and environmental management, which will improve the quality of decision-making in ecosystem and environmental management (Li and others 2008a). Regional and national internet-based geo-data sharing frameworks have been established and shown to be applicable for public use (Li and others 2008c; Zhu and others 2010). This suggests that China has the technological capability to share data, and the establishment and effective functioning of an ecological and environmental data sharing mechanism is possible with a strong political push.

Thirdly, an impact and effectiveness assessment on policies, plans, and ecological restoration projects is needed. The strategic environmental impact assessment (SEIA), a procedure for evaluating the environmental implications of government policies, plans, and programs in decision-making processes (Noble and Storey 2001), needs to be strengthened as a useful tool to prevent ecological destruction on a broad scale. The SEIA concept was introduced into China in the early 1990s and gained legal status when the Environmental Impact Assessment (EIA) Law went into effect on September 1, 2003. However, real world applications of SEIA usually fail to perform the provisions in the EIA law and need to be improved (Zhu and Jiang 2008). To improve the effectiveness of SEIA, ecological impacts (e.g. ecosystem change and the change of social-ecological relations) need to be incorporated into the assessment process for governmental policy and plans of regional development (e.g., urbanization), infrastructure development (e.g., large dam, railway or highway) and even large scale ecological rehabilitation projects (Shen and others 2004; Kittinger and others 2009; Wang and others 2009b). Developing a scientific evaluation mechanism and improving the efficiency of ecological restoration and conservation projects should be taken as a core strategy of national ecological conservation, restoration, and development efforts (Lü and others 2006). More specifically, a system for the evaluation of the effectiveness on SEIA implementation need to be established technically and institutionally (Wu and others 2011).

As a fourth recommendation, legal and institutional innovations are needed to guarantee effective ecosystem management. In regards to the legal system on ecosystem management, concrete efforts should be made to effectively coordinate the relations between/among different laws and regulations, improve the quality and efficiency of legislation and law amendment, and strengthen the capability and practicality of the laws in regulating the rights, obligations, and responsibilities of the stakeholders in ecosystem management under the context of legislation based on different central governmental agencies. This is necessitated by the present contradictions and deficiencies existing in different laws and regulations as well as their execution processes in ecosystem management (Chen and Tang 2007). The deficiencies are characterized by a lack of coherent, consistent and responsive laws and regulations, which have indulgenced overuse and ecological degradation of natural ecosystems, while, the contradictions are resulted from the dissected administrative management of ecosystem components (i.e., land, water, and organisms) by different governmental sectors such as the ministries at the central government level (Zhou and others 2008).

For example, the Law on Water Pollution Control and the Law on Fishing Industry have inconsistent definitions on water body for aquaculture and fishing, which makes the administrative responsibilities of these water areas difficult to define (Song 2007). For the same resource use activity, different laws provide different judgments on the violation or non-violation of the laws. These contradictions result from legislation at the central governmental level with very limited consideration on the dynamics and integrity of ecosystems and insufficient coordination among different governmental departments in charge of different ecosystem components. Therefore, a public service collaborative platform needs to be established with a standard functional coordination and public service collaboration mechanism at the national level. This mechanism can be realized by a committee with key members from all government departments closely related to ecosystem and environmental management in order to promote collaboration on ecosystem management and environmental protection issues at the central government level.

County level governments are the 'grassroots and battlefront' in ecosystem management because the county is a basic management and action unit for ecological conservation, restoration, and development in China. Therefore, it is of critical importance to strengthen and integrate the functions of the various county government departments on ecological issues, and to enhance accountability in the integrated ecosystem management of the county level government. This has been shown to be applicable and effective in the implementation of soil and water conservation and the Grain to Green projects in Shanxi province, northern China (Yuan 2009). The administrative (e.g., command and control policies or regulations), legal (e.g., legislation and law enforcement), and market approaches (e.g., ecological and environmental taxation and payment for ecosystem services) (Zhang and Wen 2008) need to be balanced and integrated to create a more flexible and effective ecosystem management system. This can be brought about through a paradigm shift from "command and control" to the "rule of law", public participation, and market-based incentives in ecosystem management routines. For example, when non-state actors such as private companies and citizens are given and taking more responsibilities and tasks in environmental governance, new relations between state, market, and civil society in environmental governance will emerge to potentially improve efficiency, accountability, and legitimacy in ecosystem management (Mol 2009). Market-based incentives from supply chain, customers, and communities were found to play positive roles in engaging firms to improve environmental management performance (Zhang and others 2008e). Public disclosure of the environmental performance information on firms is effective in urging firms to comply with environmental regulations (Wang and others 2004). The environmental information disclosure approach can be used similarly to improve environmental performance of local governments.

To date, the ecological conservation, restoration, and development projects have been largely financed by the Chinese central government and have caused financial hardships for some local governments to provide logistics supports. Therefore, a diversified funding mechanism should be fostered for the sake of the sustainability of ecological projects with a wide participation of stakeholders at the local, national, and international levels (Liu and others 2008b). Positive signs have been reported at the local level in diversified funding represented as household- and company-based ecological rehabilitation (Liu 2009b; Zhao 2009). This also implied the potential of the stakeholder participation and diversified funding approach.

Finally, besides the above points regarding the improvement of ecosystem management in general, some specific recommendations on the management of forests, grasslands, and wetlands can also be provided. For forest ecosystems, the focus of management should be directed toward quality advancement, including: (1) the conservation of natural and ecological forests to enhance ecological services such as biodiversity maintenance, carbon sequestration, hydrological regulation, and erosion control, which can be implemented as forest parks and nature reserves where non-timber forest products, cultural services (e.g., ecotourism), and payment for ecosystem services could be used as tools for economic profits; and (2) ecologically friendly plantation forest management, which involves improving the ecological services of plantation forests, while simultaneously promoting the productivity of economic goods such as timber, with best management practices evaluated and rewarded by governmental subsidies or tax abatement. For grassland ecosystems in China, stopping the trend of ecological degradation by strictly prohibiting agricultural cultivation and implementing effective grazing intensity control is still urgently needed because overgrazing and over-cultivation are the most important anthropogenic drivers for grassland degradation (Han and others 2008). For wetland ecosystems, "a no net loss" strategy on maintaining the acreage of wetlands, environmental flow management (i.e., the hydrological regime required for wetland health), and water pollution control need to be integrated.

Concluding Remarks

Under immense human pressure, major ecosystems, such as forest, grassland, and wetland ecosystems, have experienced ecological degradation. With great efforts in ecological conservation, restoration, and development, the degraded ecosystems have begun to recover. However, ecosystem management in China still faces many challenges that call for concrete actions.

The basic facts of major ecosystems and their management in China are as follows: (1) weak ecological monitoring systems and lack of data sharing mechanism, which has provided marginal support for decision-making and public participation in ecosystem management; large uncertainty still remains on the status and trends of the major ecosystems at the national level; (2) Ecosystems have been managed mainly on the basis of their components rather than on their integrity; (3) weak institutional and market systems to regulate the behaviors of governmental actors, non-governmental actors, and the public in safeguarding sustainable ecosystem use and management.

Sustainable ecosystem management is urgently needed both as a multidisciplinary or trans-disciplinary science and as a practical approach in balancing and optimizing the use, conservation, and restoration of ecosystems. Ecosystem management can also be considered as a multiplayer game with government agencies, enterprises, non-governmental organizations, individual ecosystem users, and the ecosystems themselves as key players. To facilitate the sustainability of this game, the basic condition is no net benefit or welfare loss for all the players in the long term and, ideally, every player should be able to gain net profits from the game. Under this multiplayer game metaphor, the Chinese government should take the leading role in environmental responsibilities and harmonize the relationships among all players in the sustainable management of major ecosystems. Three pillars or priorities are urgently needed to facilitate sustainable ecosystem management in China, including: (1) improved legislation and law enforcement performance, (2) the establishment of coordination mechanism within the governmental hierarchy, and (3) capacity building through the development of alternative livelihoods for local stakeholders to divert their use pressures on ecosystems and simultaneously promote the welfare of the stakeholders. The lessons learned and the achievements made in China during the ecological degradation and restoration process could benefit the whole world. Therefore, international collaborations on ecological and environmental issues need to be expanded on a broad scale. The recommendations raised here may be applicable to other nations, especially developing nations with similar physical and socioeconomic contexts.

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