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Qinghai–Tibetan Plateau peatland sustainable utilization under anthropogenic disturbances and climate change

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Abstract. Often referred to as the "Third Pole," China's Qinghai–Tibetan Plateau developed large amounts of peatland owing to its unique alpine environment. As a renewable resource, peat helps to regulate the climate as well as performing other important functions. However, in recent years, intensifying climate change and anthropogenic disturbances have resulted in peatland degradation and consequently made sustainable development of peatland more difficult. This review summarizes peatland ecological and economic functions, including carbon sequestration, biodiversity conservation, energy supplies, and ecotourism. It identifies climate change and anthropogenic disturbances as the two key factors attributing to peatland degradation and ecosystem carbon loss. Current problems in environmental degradation and future challenges in peatland management under the effects of global warming are also discussed and highlighted.

Key words: *climate change mitigation; peatland management; renewable resource; sustainable development.*

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Introduction

Sustainable development has been defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987). Since this report was published, "sustainable" has been widely used in government reports and research programs. However, most natural resources have become overused and peatlands are no exception. Overexploitation has degraded peatlands worldwide, greatly diminishing the ecological and socioeconomic benefits of the resource. The Chinese Government has also developed more sustainable management practices on peatlands to mitigate climate change.

Undisturbed peatlands have acted as persistent C sinks over thousands of years and play an important role in the global C cycle (Yu et al. 2010). They are considered as model ecosystems to conduct C cycle research due to their vulnerability to climate change and anthropogenic activity (Yu et al. 2010). Peatland formation and self-maintenance are dependent on climate, especially rainfall and temperature (Clarke and Rieley 2010). With continuing climate change and intensifying anthropogenic activity, carbon sequestration capacity of peatlands has been in large uncertainty, including those extensively located in China. Thus, increasing attention has been paid on the sustainable utilization and protection of peatland given its importance to China's economic development and the environmental benefit.

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Peatland regeneration is significantly slower than other sources of biofuels. Despite this, peatland has often been considered as a "renewable" resource (Schilstra 2001). In general, sustainable renewable resource usage practices should ensure that the exploitation rate of natural resources is lower than their regeneration rate (Daly 1990), but peatland usage has always exceeded its regeneration rate, which has resulted in vast areas of peatland degeneration. Furthermore, peatland degeneration has accelerated under climate warming and drought. It has been reported that the global peat C pool has decreased by 4.1 Pg (0.68% of total peatlands) over the past 200 yr (Roulet et al. 2007, Zhang 2009).

China's peatlands account for only 0.1% (104.41 × 10^4 hm^2) of the nation's land area. They store approximately 2.17 Pg C in total (Wang et al. 2014). Most of China's peatlands are located in Qinghai–Tibetan Plateau and northeast China. In the Qinghai–Tibetan Plateau, large areas of peatland developed owing to conditions of anoxia, low nutrients levels, low temperatures, and low pH (Fenner and Freeman 2011). It has been reported that the Qinghai–Tibetan Plateau, with 49% (5,086 km^2) of the total peatland area of China, has accumulated 1.49 Pg C, which is accounting for 68% of total peatland C storage in China. Most of these peatlands are distributed in Zoige Plateau (Fig. 1). This large area of peatland provides regional, ecological, and economic benefits, such as biodiversity protection, water conservation, and a source of biofuel. However, overexploitation has caused ecological issues and likely impacted its sustainability.

The objective of this paper was to provide an overview of Qinghai–Tibetan Plateau peatlands and its sustainable utilization under changing climate and anthropogenic disturbances. While focusing on ecological and economic benefits of peatlands, we also evaluated ecological issues and problems related to peatland degradation. Finally, we offer recommendations for the future development of peatland and suggestions for their sustainable utilization.

Ecological and Economic Benefits of Peatland in the Qinghai–Tibetan Plateau

Carbon sequestration

Peatlands are globally important terrestrial C pools with a worldwide area of approximately 4 million km^2, which

Fig. 1. Map of peatland distribution in Zoige Plateau. Black parts indicate the peatland retrieved from Landsat TM images.

have accumulated more than 600 Pg (1 Pg = 10^{15} g) C during the Holocene (Yu et al. 2010). Most of them are located in boreal, temperate, and tropical zones. In recent years, there has been growing recognition of their importance in C storage and their ecological role in changing global environmental processes.

Qinghai–Tibetan Plateau soils, like soils in high latitudinal ecosystems in the Northern Hemisphere, are considered as a C sink for atmospheric carbon dioxide (CO_2; Yang et al. 2009). Total organic C storage in soils of the Qinghai–Tibetan Plateau is estimated at 19.23 Pg C including grassland and peatland (Wu et al. 2003, Fig. 2). Soil organic carbon stock in the top 30 cm depth in alpine grassland on the plateau amounts up to 4.4 Pg C (Yang et al. 2009). Peatland soil organic carbon (SOC) in the Qinghai–Tibetan Plateau accounts for 7% (1.49 Pg C) of total SOC in this region with a land area of only 0.2%, and the C accumulation rate was about 32.3 g $C{\cdot}m^2{\cdot}yr^{-1}$. The large C sink and accumulation rate in the Qinghai–Tibetan Plateau occurred in the early Holocene and were caused by high summer insolation and strong summer–winter climate seasonality (Wang et al. 2014). This considerably large carbon sequestration capacity may play a significant role in mitigating regional greenhouse gas emissions. It can also be used for C "trading" into the future. For example, under a potential value of 10 U.S. dollars per ton of C (Richards and Stokes 2004), it may cost 1.49×10^{10} U.S. dollars for Qinghai–Tibet Plateau peatland C stocks. Moreover, peatland in the Qinghai–Tibet Plateau accumulated 1.64×10^{11} g C/yr (Wang et al. 2014), which is equivalent to 1.64×10^{6} U.S. dollars per year. In this respect, peatlands are not only environment asset, but also a social and economic resource (Bullock et al. 2012). We can use these peatlands to develop regional carbon markets to fund peatland restoration research. However, this estimate should be used with caution since it is based on limited data from previous literatures and the C trade may be more complex. Thus, these data are a rough estimation and more reliable estimates of C trade will be required in the future research.

Biodiversity support

High ecosystem diversity (forest, grassland, wetland, peatland, etc.) accompanies with high species diversity in this region. As the largest peatland area in China, Zoigê peatlands are habitat for 162 species of swamp plants. They are living in lacustrine habitats and mountain valleys, most in the form of marsh plants. The dominant families are Cyperaceae (24 species) followed by Asteraceae (14 species), Ranunculaceae (14 species), Scrophulariaceae (12 species), and Poaceae (nine species). Zoigê Plateau peatlands are also rich in animal resources. There are 38 mammal species, 137 bird species, and 15 fish species (Xiang et al. 2009). Many endemic and highly endangered animal species also reside in Zoigê peatlands, including *Grus nigricollis*, *Ciconia ciconia*, and *Haliaetus leucoryphus* (He and Zhao 1998).

The biodiversity support of peatland was regulated by geology environmental and hydrological conditions. They are high intrinsic value and living unique and endanger species in peatland ecosystem. The peatland ecosystem also considered an entertainment place for bird watching due to its raising large species of birds.

Fuel supply

In the past, herders and their animals were generally scattered throughout grasslands, and cow dung was an important energy supply. Cow dung collection cannot meet the new demands due to fuel consumption increases associated with population growth, housing development,

Fig. 2. Profile of peatland (left) and grassland (right) in the Qinghai–Tibetan Plateau. The left picture was provided by Gang Yang, and the right picture provided by Dr. Yongheng Gao.

and urbanization. Thus, peat has become a major fuel due to a lack of other energy sources. A previous survey indicated that Zoigê Plateau peat storage was 19 Pg (comprising four counties: Zoigê, Hongyuan, Ngawa, and Maqu; Fei et al. 2006). There are 138 large peat mines and 82 medium-sized peat mines scattered throughout Zoigê County (Liu and Bai 2006). These peat mines could supply local people with energy resources for factories, schools, and apartment dwellings. Approximately 9,500 tons/yr of peat was consumed for heating and cooking in Hongyuan County alone (Fei et al. 2006). Moreover, it has been reported that the calorific value of peat in some areas is even greater, up to 3,500–4,000 kcal/kg, which could fully satisfy fuel requirements of local people (Chai et al. 1965). In a word, government policies and human activities have a profound effect on peatland resources. Nowadays, with the rapid development of transportation and electric industry, the energy structure has changed, and peatland resource is gradually replaced by coal and electric power.

Ecotourism and economics

It has been widely accepted that the major barrier for tourism development in the Qinghai–Tibetan Plateau is accessibility and the harsh environment. However, the developing highway infrastructure is providing new tourism opportunities. The increase in tourism income has a positive linear relationship with the length of the railway and highway. Data from the China Statistical Yearbook (1995–2013) show that income from overseas and nationwide tourism dramatically increased in Qinghai Province and the Tibet Autonomous Region after the Qinghai–Tibetan Railway was established in 2006 (Fig. 3). Increasing human population is a prerequisite for the development of tourism. It is reported that human has been living for 5,200 yr in the Tibetan Plateau and agriculture facilitated permanent human occupation subsequently (Chen et al. 2015). We take Zoigê County as a case study; in the 1920s, most of the Zoigê Plateau region was much less populated (Li 2008). Recently, the number of residents in this region has grown to 70,000. Owing to its unique natural and cultural landscapes, local communities have developed ecotourism over the past several decades. Most favorite visit places in this region include the following: (1) the natural landscapes comprising grasslands, rivers, and snowcapped mountains. For tourists who travel in the upper reaches of the Yellow River, they can see endangered species, such as the Black-necked crane (*G. nigricollis*); (2) landscapes in the region notably exhibiting Tibetan culture, such as folk costumes, cultural cuisine, and famous temples like the Maiwa Temple, which is the biggest Tibetan Buddhist temple in northwestern Sichuan Province, as well as the history of the Long March (Mei 2003). Tourism can make the better use of land resources, but it is also a driving force behind environmental degradation if the number of visitors is not controlled (Petrosillo et al. 2006). Thus, China must develop a sustainable development plan that needs to consider the assessment of environmental impacts, ecological restoration implementation, and the protection and improvement of legislation, education, and publicity (Lei and Liu 2006).

Ecological Issues and Problems Related to Qinghai–Tibetan Plateau Peatlands

Peatland degradation

Over the past four decades, typical alpine wetlands in the Qinghai–Tibet Plateau are shrinking; the area of wetland in the Qinghai–Tibet Plateau has been reduced over by 10% (Wang et al. 2007). Zoigê County is an example of such degradation. In Zoigê County, peatland area shrank from 612 to 430 km^2 from 1974 to 2007 (Jiang et al. 2012) and up to 1,426 km^2 when taking into account the degradation area as a whole (Zoigê Plateau, Chen et al. 2014). The main reasons for the peatland degradation in the Zoige Plateau are overgrazing and drainage which can regulate soil nutrient cycles and to some extent influence alpine ecosystem structure and function (Han et al. 2011, Zhao et al. 2014).

This degradation is also largely attributed to increasing population, human demand as well as climate change. According to statistical reviews and county annals, the population of Zoigê County increased from 4.7×10^4 to 7.0×10^4 during 1970 to 2006 and the sheep increased from 19.4×10^4 to 36.1×10^4 in the 18 yr after 1970 (Fig. 4). Increasing population is accelerating the rate of peatland degradation through urbanization. Increased livestock-induced overgrazing will promote the peatland degradation process (Du et al. 2004). Climate change is another main factor that leads to peatland degradation. It is reported that climate warming and rainfall reduction may accelerate the carbon decomposition and loss of soil carbon in peatland (Dorrepaal et al. 2009, Fenner and Freeman 2011). All of these two processes can make peatland degradation. In our study area, Zoigê Plateau also experienced significant warming and rainfall reduction over the last several decades (Yang et al. 2014). The processes in this region will accelerate peatlands degradation.

The influence of population growth and lifestyle changes on peatland ecological functions and services

According to the Millennium Ecosystem Assessment (2005), peatland provides four main ecosystem services, namely provisioning services, regulating services, cultural services, and supporting services (MEA 2005). All of these ecosystem services changed in Qinghai–Tibetan Plateau peatlands under conditions of climate change and anthropogenic activity (Fig. 5). Population growth in this region has required more land for agriculture, more

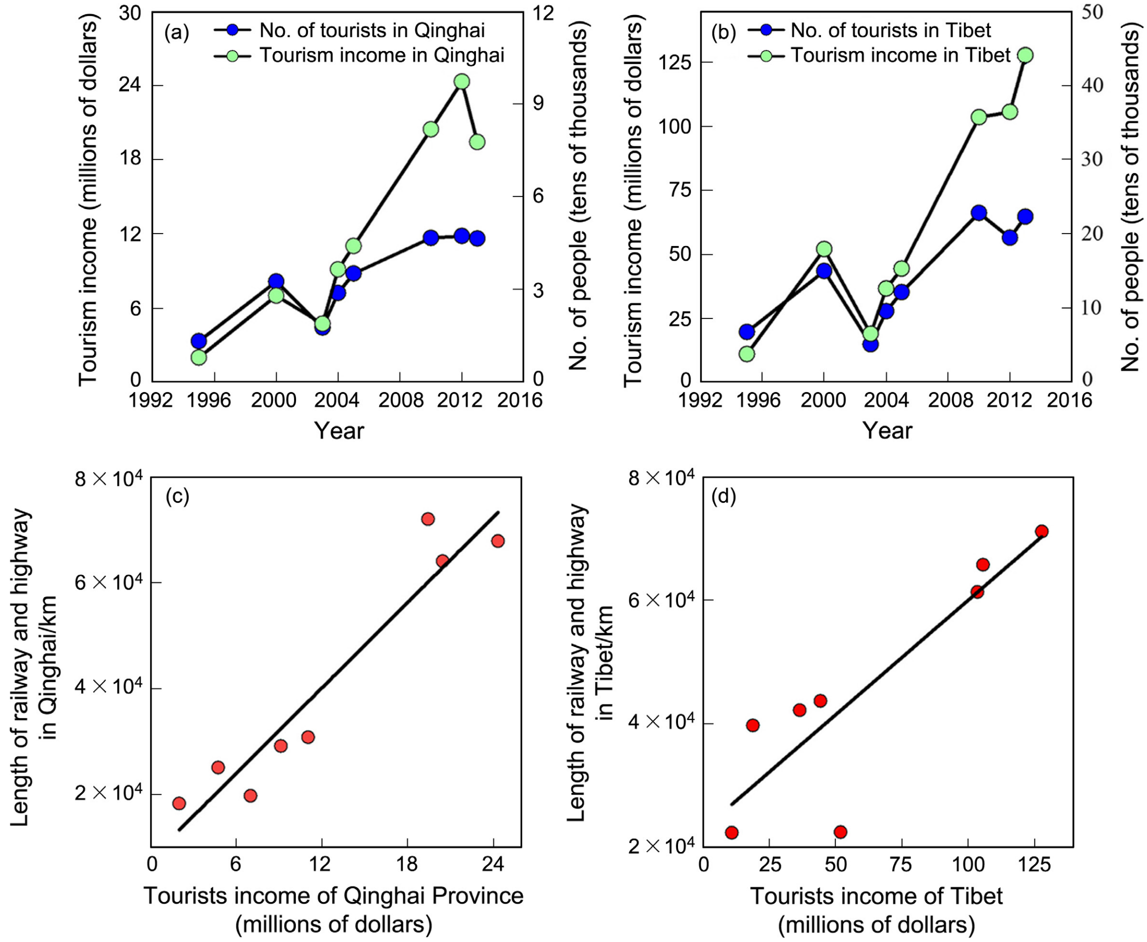

Fig. 3. The relationship between road construction, tourism income, and the increasing numbers of tourists traveling to Qinghai Province and Tibet. (a, b) Scatter plots related to the number of tourists and tourism income in Qinghai and Tibet, respectively. (c, d) Regression lines of tourism income and the length of railways and highways in Qinghai and Tibet, respectively.

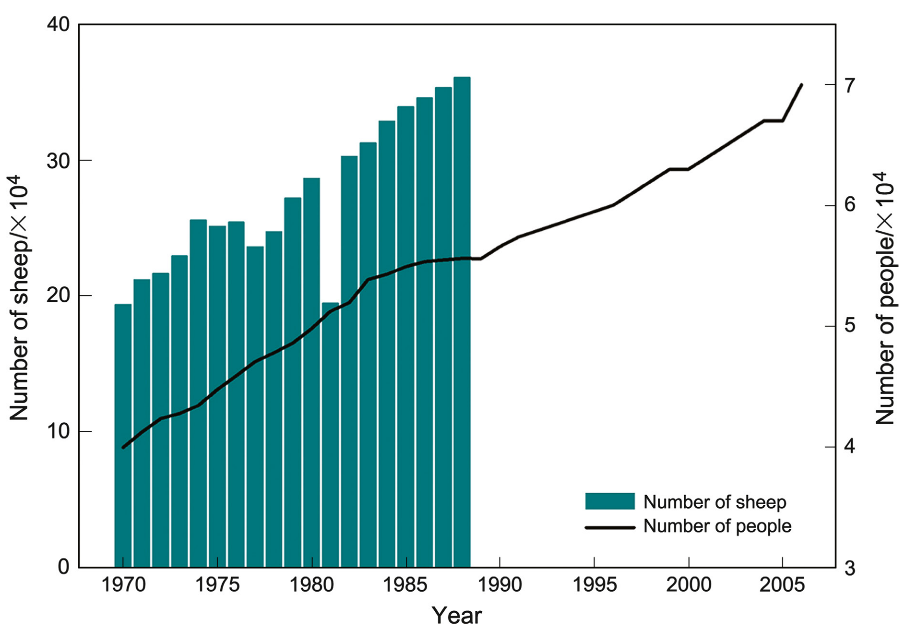

Fig. 4. Yearly increases in the population of people and sheep in Zoigê County. The insert in the upper left corner is a combined scatter plot and fitted regression line for temperature in the Zoigê Plateau. The data come from China Statistical Yearbook.

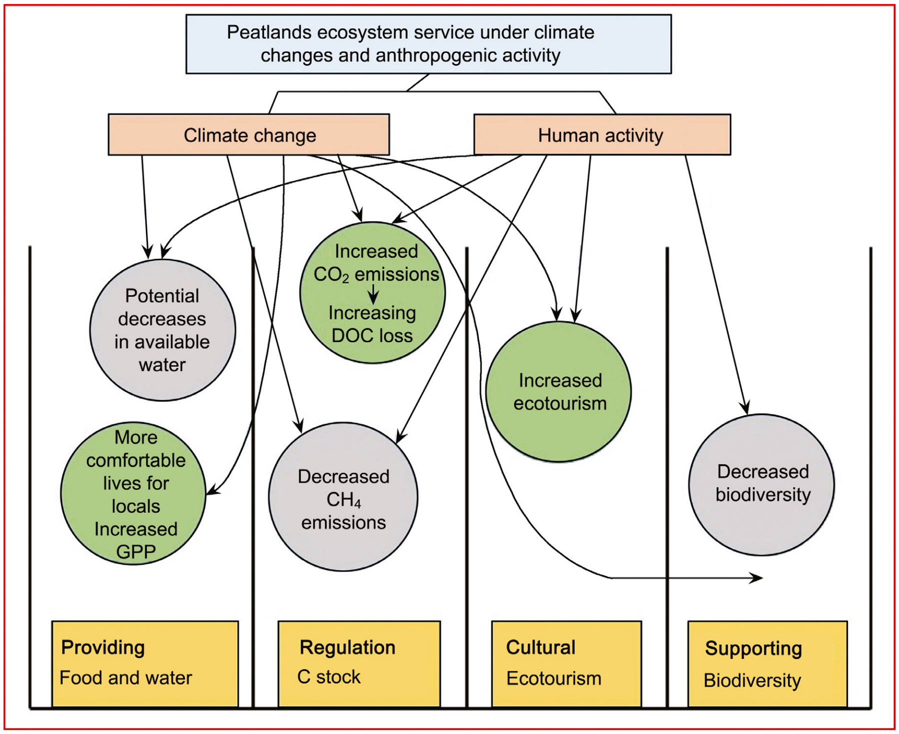

Fig. 5. Zoigê Plateau peatland ecosystem services under climate change and anthropogenic activity. Green and gray circles indicate overall positive and negative effects on peatland ecosystem services, respectively.

animals for meat product, and more peat for fuel. All these changes require the reclamation of more peatland to be turned to grassland, which consequently altered peatland ecosystems. It has been reported that peatland area decreased by 183 km^2 and the area of grassland increased by 135 km^2 between 1974 and 2007 (Jiang et al. 2012). Consequently, peatland structure and function are altered considerably, from a carbon sink and area of high biodiversity to a food supply base. The degradation of wetland and peatland also changed the value of ecosystem services (Li et al. 2010). For example, compared to intact swamps, primary changes observed in degraded swamp vegetation were an increase in species abundance and a decrease in vegetation succession rates (Li et al. 2011).

In addition to unsustainable management practices that follow peatland ecosystem function and service degradation, lifestyle changes of herdsmen also had an impact on peatland ecosystem services (Fig. 5). People living in the Qinghai–Tibetan Plateau would historically migrate to wherever water and grassland were available. This way of life gradually changed, especially since the "herdsmen housing plan" (an effective way to guide herdsmen to get out of primitive living condition and feel the modern civilization which was started at 2006) was implemented by the Chinese Government. The government report (Office of Housing Plan at Tibet Autonomous Region 2014) shows that this project has established 56,000 households until 2013 in Tibet Autonomous Region. We take Zoigê Plateau as an example. This project has established 608 settlements and helped resettle 210,677 people to the Ngawa Tibetan and Qiang Autonomous Prefecture (Fan 2012). The project provided greater convenience to the local population including providing them safety drinking water, improving medical conditions, and raising the average income levels of the herdsman. However, it has also changed the lifestyle in this region (Fig. 6).

Today, Tibetan nomadic tents have been replaced by community housing. All grasslands and peatlands have been allocated to individual herdsmen and enclosed by families. As a result of this enforced convenience, traditional livestock husbandry was replaced by the modern farm. Motorcycles, trucks, and cars are typically used to manage these new types of farms. These changing lifestyle will increase cultural ecology service including accelerating the development of ecotourism industry and promoting the widespread of national culture. However, the urbanization and modernization lifestyle will also decrease supporting service (Fig. 5), especially for biodiversity, which will be decreasing due to the increase in population size and growth rate (Liu et al. 2003). As mentioned above, a new age of urbanization has arrived in the Zoigê Plateau. But how to face the challenges of such opportunities and consequences has yet to be identified.

The vulnerability of carbon stocks to climate change and anthropogenic activity

Increasing temperatures (Chen et al. 2013), fluctuations in water tables and dramatically increased human

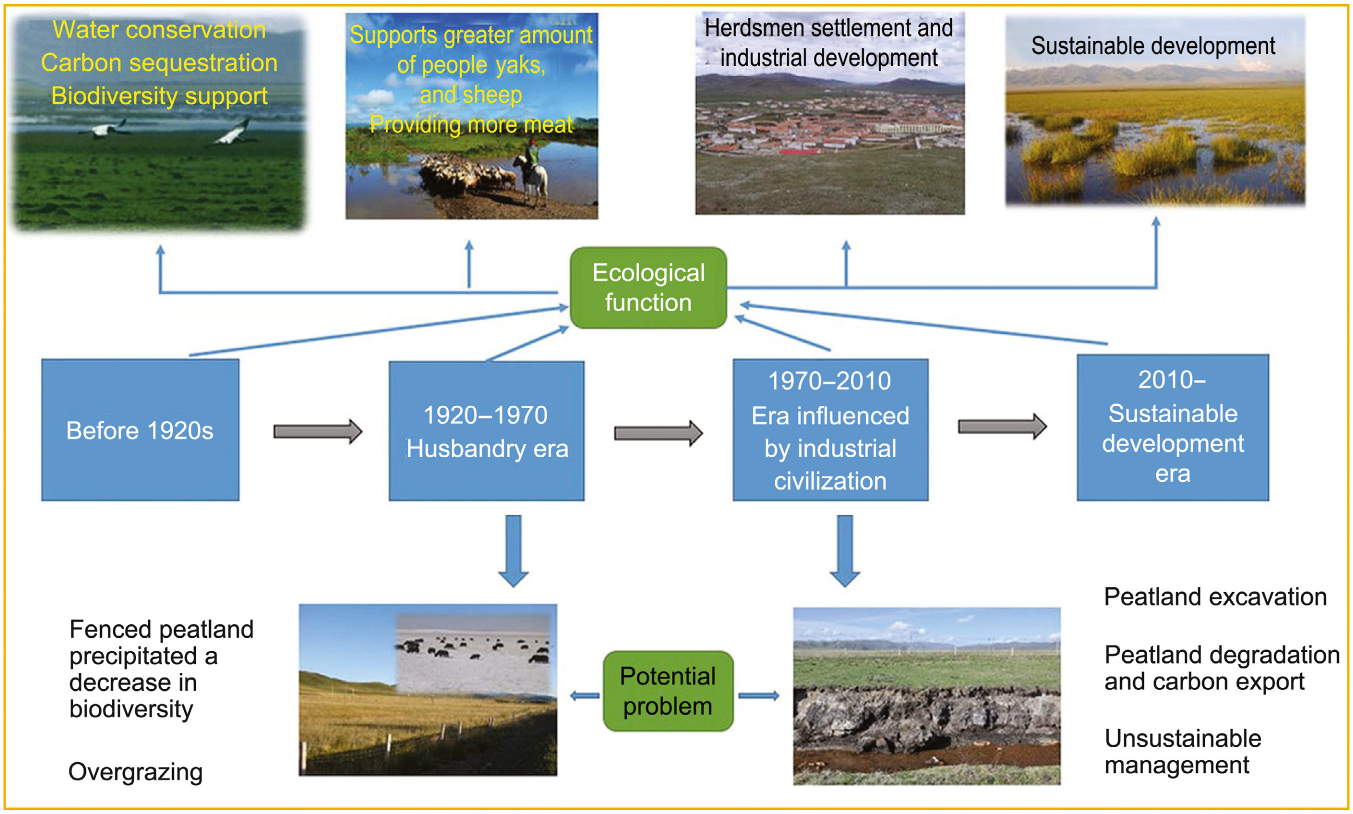

Fig. 6. Zoigê peatland utilization history.

activity changes to peat drainage, and fuel excavation are the primary factors that alter peatland C cycles and even could change the C sink into a C source in the future, making peatland more critically vulnerable. More and more research has shown that global warming-induced drought accelerates C exports from peatland because warming increases microbial growth, causing a breakdown in organic C (Fenner and Freeman 2011, Abbott et al. 2014). The approximate twofold observed rate of global warming in this region could lead to drought, the thawing of permafrost, the breakdown of organic matter, and the release of carbon (Fenner and Freeman 2011, Chen et al. 2013). In addition, warming has a significant effect on methane (CH_4) fluxes due to consistent temperature dependence across microbial to ecosystem scales (Yvon-Durocher et al. 2014). Our previous research found that CH_4 emissions increased by 28% after a short-term soil warming (Yang et al. 2014). Warming can also increase microbial communities to use older soil organic C stores (Abbott et al. 2014, Streit et al. 2014). Water table fluctuations have significant effects on peatland CH_4 dynamics (Yang et al. 2014). Our previous study found a positive relationship between water table levels and CH_4 emissions. Average CH_4 emissions increased by approximately 82% as water drawdown varied from −50 to 0 cm (Yang et al. 2014). Peat drainage is the primary anthropogenic disturbance of peatland ecosystems. As soon as peat soil is drained, peat starts to degrade (Regina et al. 2015). CH_4 emissions decreased when peatland is drained, but CO_2 and nitrous oxide (N_2O) emissions increased. It has been reported that approximately 10–20% of peatland has been drained for agricultural and livestock production worldwide (Frolking et al. 2011), and this peatland reclamation emits 6% of total global CO_2 emissions. It has been reported that CO_2 emissions reached 77 Mt/yr by degenerate peat in our study site (Wang et al. 2006, Joosten 2009). Accordingly, sound land-use planning is key to reducing negative effects of peatland drainage, and peat soil could be protected by land-use restrictions and restored by disabling unsound drainage and cultivation practices (Regina et al. 2015). However, there remain many uncertainties related to such biogeochemical cycles under climate change in combination with anthropogenic activity. With continued climate change, the future of biogeochemical cycling will be complex, and more detailed research must be conducted on climate change and its feedback to soil C dynamics.

Other issues of Qinghai–Tibetan Plateau peatlands

Besides above-mentioned issues and problems in peatlands, Qinghai–Tibetan peatlands also experienced biological invasion, active rodents, and even soil desertification. Alpine meadows in Qinghai–Tibetan

Plateau are suffering serious invasion of *Stellera. Stellera* is a toxic perennial weed, which has become one of the most serious weed threatening a wind range of grasslands. The outcome of *Stellera* in this region is displacement of the dominant species, and its toxicity prevents it from being eaten by yaks (Liu et al. 2004). The outbreak of this invasion species is also an indicator for soil degradation. There is a typical mode of soil degradation in this region: peat soil → mire soil → meadow soil → aeolian sandy soil (Xiang et al. 2009). The spread of *Stellera* is accelerating soil desertification. Grassland rodents were also considered one of the main factors of soil desertification. As the key species, plateau pika and zokor play an important role in energy flow and nutrient circle of alpine meadow ecosystem. With a higher density, plateau pika and zokor activities degraded vegetation and soil by increasing unpalatable plants; reducing plant height, cover, and biomass; accelerating soil erosion; and reducing nutrients. The effective method to control plateau pika and zokor activity is to determine the causing hazard (Zhou et al. 2010).

Balance Between Peatland Conservation and Development

There is a growing recognition that regulating the exploitation and utilization of natural resources is the foundation for sustainable development. Peatland is a unique ecosystem that fixes atmospheric CO_2 through photosynthesis and locks it into the subsurface. However, the sequestration rate of peatland is very slow compared to utilization rates. Moreover, peatland is a particularly fragile ecosystem. Its existence is strongly determined by regional hydrology. When a waterlogged environment is changed or peatland is drained for development of agriculture and animal husbandry, large amounts of organic C are released. During 1960–1970, more than 700 ditches were dug and approximately 20×10^4 km^2 of peatland was drained, which emit large amount of carbon. The government has now realized the important role of peatland in mitigating global warming and instigated strategies for peatland restoration. Peatland restoration is an efficient way to reduce carbon losses from drained peatland (Kim et al. 2012). To date, more than 200 km of ditches within the Zoigê Marsh have been refilled for restoration, allowing 50,000 hm^2 of marshes to be recovered (Wang et al. 2006).

Besides agricultural drainage, grazing, especially when peatland is frozen or not waterlogged in winter, is another important factor affecting peatland conservation and sustainability utilization. It has been reported that 80% of peatland in the Tibetan Plateau are grazed or browsed by animals in winter and early summer (Joosten et al. 2012). Overgrazing led to the Zoigê Plateau to be involved in long-term conflicts between nature conservationists and livestock grazing. Wetland conservation regulations that prohibited the drainage, mining, and reclamation of peatland have been approved by the People's Congress of Gansu and Sichuan protect biodiversity conservation as well as the livelihood of local people (Joosten et al. 2012). They allocated 0.3% of their yearly budgets to peatland restoration and encouraged local people to protect peatland by reducing the number of livestock.

Recommendations and Suggestions for Sustainable Utilization of Peatland on the Plateau

Peatland offer potentially huge ecological and economic benefits. As one of the largest plateau peatlands in the world, peatland in the Qinghai–Tibetan Plateau are receiving increasing attention. As a renewable resource, knowing about peatland sustainable utilization in this specific region will provide a good experience to other peatland managers. The peatland ecosystem in this region is very sensitive and fragile to climate change and human activities. Government policies, the changing lifestyles of herdsmen, and rapidly changing climates are the main factors influencing peatland loss. There is urgent need to take countermeasures to keep the peatland sustainable utilization in Qinghai–Tibetan Plateau. Based on this review, we make four recommendations. First, the government and the general population should pay more attention to peatland conservation. We need to develop more sustainable management practices including providing more economic compensation for herdsmen who are willing to control the quantity of livestock. Second, we need to refill the peat excavation ditches for natural restoration and protect them from further degradation. Third, more researches should be conducted on sampling and conservation peat stratigraphy for future scientists before peatland degrade, because future scientists will gain much more information from the analysis of peat stratigraphy for peatland restoration. Fourth, we should better control the human population in this region and raise their awareness of peatland protection.

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