Fundamental Research 1 (2021) 329–333

Contents lists available at ScienceDirect

Fundamental Research

journal homepage: http://www.keaipublishing.com/en/journals/fundamental-research/

Perspective

Priorities for the sustainable development of the ecological environment on the Tibetan Plateau

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The Tibetan Plateau is often referred to as the "roof of the world" because most of its area lies more than 4000 m above sea-level. As a result of this high altitude, the Tibetan Plateau stores the largest volume of glacier after the Arctic and Antarctic regions and is often called the Earth's third pole [1]. It has recently been estimated that the glacier reserves of the Tibetan Plateau contain more than eight trillion cubic meters of water, which could supply more than two billion people [2]. A number of large rivers originate from the Tibetan Plateau, including the Yangtze River, Yellow River, Brahmaputra and Ganges, leading to it being called the "water tower of Asia". The extreme environment and abundant water resources of the Tibetan Plateau mean that it forms a unique habitat for wildlife, and the genes of a large number of rare high-altitude plant and animal species are preserved in this important region.

Forests, grasslands, wetlands, permafrost and other ecosystems of Tibetan Plateau are vital carbon pools and are crucial to achieving global carbon neutrality. The role of the Tibetan Plateau as a natural barrier and its unique environment requires the development of a strategy for sustainable development to allow this region to meet the United Nations' (UN's) 17 Sustainable Development Goals (SDGs) [3].

The development of a strategy for the sustainable development of the Tibetan Plateau is not an easy task. The plateau is a sensitive, fragile and functionally vulnerable area in terms of the global environment and climate change and is comparable to the polar regions in importance [1]. The difference between this "third pole" and the Earth's actual polar regions is that the population and economy of Tibet are both developing rapidly. The population of Tibet increased from 2,580,000 to 3,510,000 from the year 2000 to 2019 [4], with most of this increase resulting from urbanization. The regional gross domestic product (GDP) of Tibet was up to 169.78 billion yuan (about US$ 26.20 billion) in 2019 [4], with a growth rate >12% in half of the years in the last two decades (Fig. 1). This growth rate ranked first in all provinces of China and was among the highest in the world.

Following this economic prosperity, can we say that the Tibetan environment is experiencing sustainable development? Eco-environmental deterioration and GDP growth simultaneously occur just as "twinborn sisters". This raised up the need for policy regulation to balance the population-resource-environment system on the Tibetan Plateau. Tibet's Ecological Security Barrier Protection and Construction Plan (hereafter referred to as "the Plan") entered into force in 2009 and a series of technological fixes was used to solve environmental problems. The ultimate goal of "the Plan" is to coordinate social, economic, environmental and ecological development.

1. Effectiveness of "the Plan" and the construction of environmental monitoring networks

Five key protection projects were adopted in "the Plan" to protect natural grasslands, forests, wildlife, wetlands and human health, with a total investment of 15.5 billion yuan. The first stage of "the Plan" ran from 2008 to 2015, which had improved the quality of the environment on the Tibetan Plateau [5]. The contribution of "the Plan" to improve the environment of the Tibetan Plateau has been summarized in supporting information (Table S1).

The area of forests, grasslands, wetlands and farmland remained constant during 2008–2015 and the structure of the ecosystem was stable, with an increase of 8.2% in the area with a high cover of vegetation. The control of desertification saw significant progress, with the area of degraded land decreasing by 107,100 hm^2 at a rate of 15,300 hm^2 per year. The proportion of clean energy, including electrical energy, solar energy and biogas, increased from 20.7% in 2008 to 65.6% in 2014, gradually transferring from a reliance on traditional biomass sources to clean, low-pollution energy. The establishment of 413,700 km^2 of national nature reserves provided state protection for the rare and endangered wildlife, such as black-necked crane and Tibetan antelope, highlighting the effectiveness of biodiversity conservation.

Since 2013, the Environmental Protection Department of Tibet, in association with the Chinese Academy of Sciences (CAS), has constructed a series of ecological and environmental monitoring networks on the Tibetan Plateau [5]. The networks include both remote sensing and ground monitoring stations. A database of information on glaciers,

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https://doi.org/10.1016/j.fmre.2021.03.006

Available online 2 April 2021

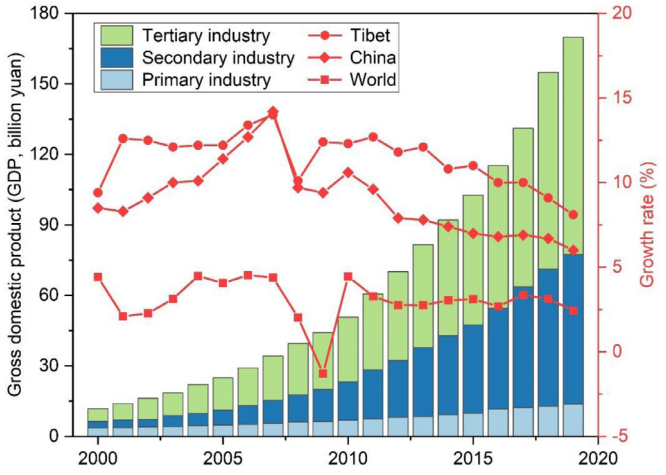

Fig. 1. Rapid development of the gross domestic product (GDP) in the Tibet during 2000–2019, compared with China and the world.

lakes, soil, biota and climate has been recorded in the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/en/). The collection and sharing of scientific data about the Tibetan Plateau are important for both scientists trying to understand the mechanisms of environmental change and policy-makers aiming to monitor the dynamics and trends of socioeconomic-environmental development over time.

2. Overarching environmental issues

Despite the above achievements, we aim to clarify the limitations on the protection of the environment and to identify the priorities for an environmental policy that can accommodate both economic changes and sustainable development on the Tibetan Plateau.

Climate warming, droughts in winter, intense evaporation, flooding and frequent winds still adversely affect some regions of the Tibetan Plateau. A combination of the harsh climate and grazing pressures means that there are still sporadic deteriorations in the grasslands of the northern Tibetan Plateau, illustrating the problems in balancing the supply and demand of livestock with their weakening effect on the functioning of the ecological environment [6].

There has been extensive collapse and melting of glaciers in southern Tibetan Plateau under the influence of the current global climate crisis [7]. The amount of precipitation has increased during the last two decades, associated with an increase in local temperatures, leading to the expansion of lakes on the central Tibetan Plateau [5], for example, the number of lakes >1000 m^2 has increased by 14% in the last 50 years. Lake Selin Co has grown by 40% during the last 20 years and is now the largest lake in Tibet [8]. The collapse of glaciers and outbreaks of water from glacial lakes have destroyed roads and farmhouses. The risk of environmental/climate disasters on the Tibetan Plateau had increased in recent years and has led to stress in local residents.

In the Tibetan Plateau, water and soil quality have generally remained good; however local contaminations also need attention. As the Tibetan Plateau is characterized by widely distributed hydrothermal systems, discharging of geothermal waters contains extremely high arsenic, fluorine and mercury, which are toxic to human health [9]. The water quality of some ground waters/rivers passing through geothermal areas has therefore deteriorated. The soils have inherited the features of the Tibetan rocks (shales and arc-related rocks) and are enriched in arsenic and fluorine [10]. Soil erosion and flooding from melting glaciers or lakes, can also release these toxic elements to aquatic ecosystems [11], and lead to geological hazard.

In addition to changes in the local environment, trans-boundary pollution transport becomes more important. The Tibetan Plateau is located adjacent to the south Asian subcontinent, which is a heavily polluted region. The northward passage of the Indian monsoon results in the incursion of polluted air over the Tibetan Plateau (Fig. 2). Dichlorodiphenyltrichloroethane (DDT), currently used in India for the control of malaria, and other pesticides have contaminated the air in southern Tibetan Plateau [12]. Black carbon generated by biofuel, coal and petroleum combustion in South Asia also follow the air mass entering the Tibetan Plateau [13]. It has been shown that around 2–100 tones persistent organic pollutants enter the Tibetan Plateau via air flows through valleys and even across the Himalayan ridges [14]. These contaminants may then be stored in glaciers after dry and wet deposition.

Despite the outdoor quality, the indoor air quality should be of great concern, as the toxic metals and carcinogenic organic pollutants were found in the atmosphere of the nomadic tents in the Tibetan residents, which can be attributed to the combustion of solid biomass fuels, especially yak dung [15]. The household heating/cooking emissions, having a notable impact on both air quality and human health, however, are conventionally ignored [16].

3. Data and policy limitations

The environmental monitoring networks on the Tibetan Plateau have produced a database for grazing, grassland deterioration and soil erosion in this region [17]. These data are essential for policy-makers examining the benefits of different environmental protection projects and evaluating the effects of sustainable development policies on the ecology of the Tibetan Plateau.

However, recent changes in the global climate have increased the melting of glaciers and ice collapse, causing glacier debris flows and other disasters [7]. Data on the climate, the hydrology of glaciers and their mass balance are essential in deciding how to prevent such disasters and to protect lives and property. More unified and interconnected field science monitoring stations (FSMSs) need to be built. The targets of current monitoring stations are often different and their geographical distribution is not uniform [17]. These shortcomings impair the continuity and integrity of the collected data and make it difficult to understand complex changes in the environment of the Tibetan Plateau.

A few challenges make the existing data insufficient for evaluating the status of pollutants on the Tibetan Plateau. First, the concentration data of contaminants in air, water, soil and the biota are limited as a result of the large spatial coverage of the plateau, which hinders our understanding of their regional distribution and concentration and, in particular, their influence by land surface processes. Second, there is no systematic monitoring data for residential areas, which leads to uncertainties in estimating the impact of local activities on the human health. Third, the contaminant types fall into broad classes. Although inorganic contaminants have raised concern, organic and biological (i.e., bacteria and viruses) contaminants are not taken into consideration.

The pollutants deposited in glaciers can be released into rivers and lakes downstream; flooding and hydrothermal eruption can release toxic elements from soil into water. Given that the pollution and natural disasters often simultaneously happen, however, comprehensive monitoring activities are very limited. It is difficult to obtain a systematic understanding regarding environmental changes or establishment of an early warning system [18].

Unlike in the Arctic and Antarctic, plastic products have been widely used in the Tibetan Plateau [19]. The high levels of solar radiation and weathering on the Tibetan Plateau lead to the rapid break-up of plastics to form microplastic particles. Microplastics circulating in the ecosystem will eventually find their way into both wildlife and humans and may cause adverse health problems [20]. Data and monitoring are essential for tracking the transport and circulation pathways of microplastic particles in the Tibetan environment.

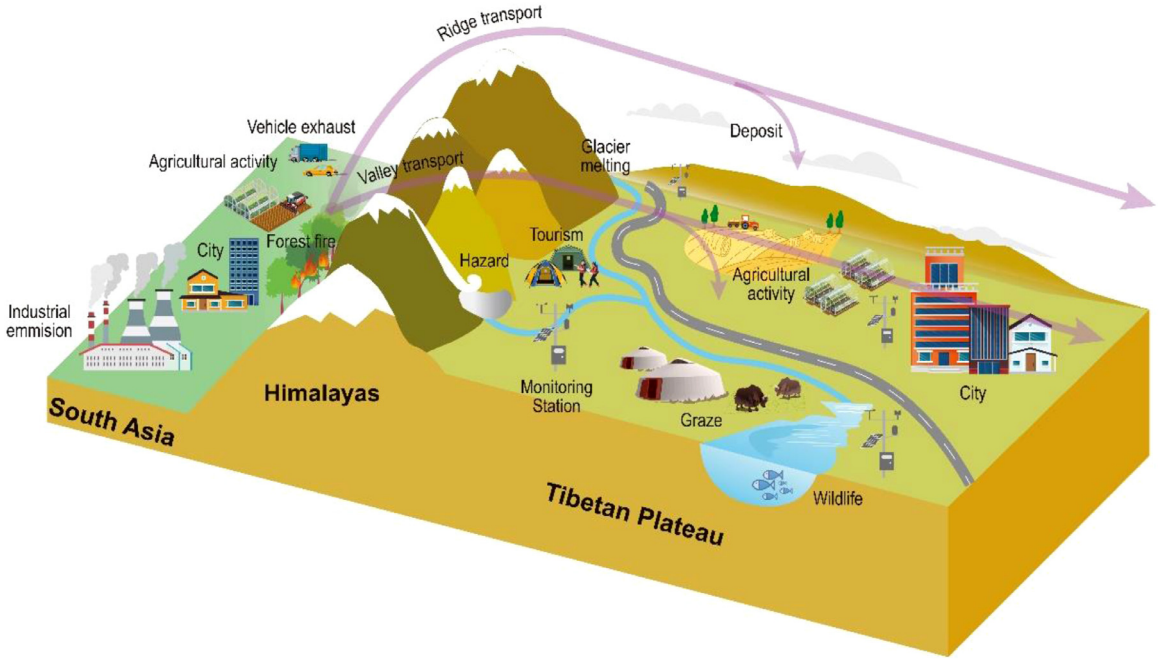

Fig. 2. Transport of contaminants from South Asia across the Himalayas and land surface processes affecting pollution on the Tibetan Plateau.

There is also a lack of regional, targeted guidelines for environmental monitoring. The current evaluation guidelines are the national unified quality standards, but these standards cannot exactly assess the environment on the Tibetan Plateau. Some of the experimental methods used by the national standard are unsuitable for high-altitude environments where the low atmospheric pressure can affect measuring instruments. Guidelines should be developed that update standards and improve experimental methods.

New policies are also needed to protect the function of the Tibetan Plateau as a carbon pool. Tibetan ecosystems (e.g., forests, alpine grasslands, wetlands, shrublands and permafrost) that store large amounts of carbon are crucial in regulating the global climate and balancing carbon emissions [21], which is important for China to achieve the goal of carbon neutrality. Despite calls for the protection for the carbon pool of the Tibetan Plateau, the value of this ecosystem service is unknown due to a lack of policy support.

In addition to the shortage of regional policies, there is also a lack of international policies covering the Tibetan Plateau and neighboring countries in South Asia. Although scientists from many countries have identified transport processes for both inorganic and organic pollutants from South Asia to the Tibetan Plateau, there is still no consensus about how to control their emission and transport. Consultations and negotiations by multinational governments (e.g., industrial negotiations, technological upgrades and ecological compensation) are required to fully address the impact of the trans-boundary transport of contaminants to the Tibetan Plateau from South Asia. China needs to formulate and negotiate international policies for cooperation with adjacent countries in South Asia to achieve the SDGs of the Tibetan Plateau.

Education about environmental protection is also relatively weak. The local population does not understand that grazing can lead to the degradation of grasslands and that their traditional lifestyles (yak dung burning) can release pollutants. There is a need to improve public knowledge about the balance between lifestyles and environmental risk.

The lack of monitoring data and relevant policies still limits the sustainable development of the Tibetan Plateau. Overcoming these challenges requires the combined efforts of scientists, government officials and the local population.

4. Proposed priorities for sustainable development on the Tibetan Plateau

Five priorities that need to be addressed in the future sustainable development of the Tibetan Plateau are listed in Fig. 3. These priorities, driven from the current achievements and challenges, aiming to meet the goals of global SDGs [22], are discussed in the following text.

- **Establishing an early warning system for environmental change.** The current global climate crisis has significantly changed the environment of the Tibetan Plateau, causing a series of disasters such as desertification and glacier collapse. Scientific researchers, government officials and businesses need to work together to build an early warning system to monitor environmental changes on the Tibetan Plateau. This system could determine the potential adverse impact of environmental changes and remove hidden dangers. This is closely linked to the UN's SDGs 3, 11 and 13.
- **Accelerating the construction and reform of FSMSs.** More remote sensors and passive samplers should be placed in areas that are not currently monitored to enhance the integrity of data and improve data sharing. Uniform and distinct observational targets are set at different FSMSs. Aircraft, helicopters and satellites should be used to obtain data to provide a good foundation for achieving the UN's SDGs 1, 3 and 13.
- **Formulating highly targeted environmental monitoring guidelines.** The environment of the Tibetan Plateau is fragile and emerging pollutants may damage both ecosystems and human health. Contaminants need to be monitored to protect the local water, soil and atmosphere. National standards need to be adjusted according to the regional characteristics of the environment to provide better protection and to control local emissions. Such guidelines would enhance the achievements of the UN's SDGs 12, 13, 14 and 15.
- **Constructing the ecological functional area of the carbon pool.** Ecological functional zones of carbon pools should be constructed in specific regions of the Tibetan Plateau to provide a basis for carbon trading and cross-domain ecological compensation. We need to estimate the baselines of the carbon storage capacity (carbon pool) and

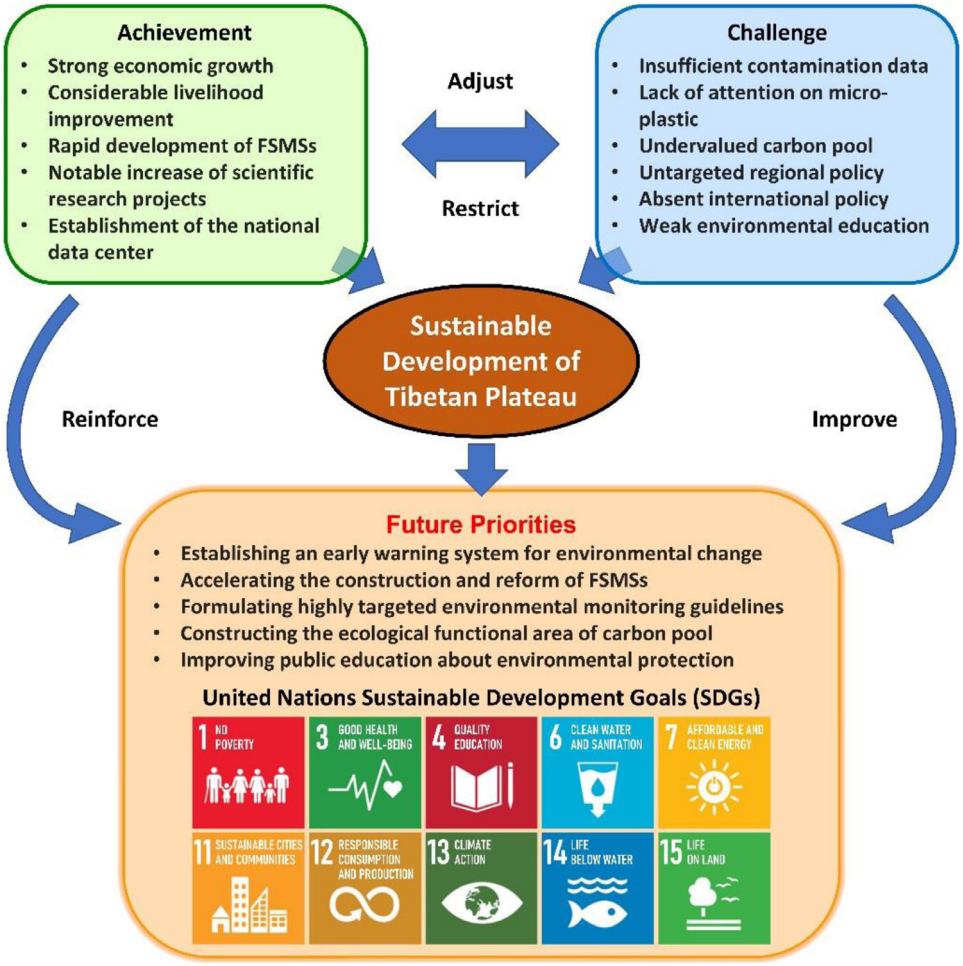

Fig. 3. Achievements, challenges and future priorities for the sustainable development of the ecological environment of the Tibetan Plateau.

then extrapolate our experience to other regions of the plateau. The implementation of the relevant policies will help improve the UN's SDGs 6, 13 and 15.

- **Improving public education about environmental protection.** Education and publicity about environmental protection could help the local population to change their lifestyles and help them to monitor, and perhaps even supervise, targets for environmental protection. The changes could help to improve the UN's SDGs 4, 6, 7 and 13.

Declaration of Competing Interest

The authors declare they have no conflict of interest.

Acknowledgements

This study was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences, the Pan-Third Pole Environment Study for a Green Silk Road (Pan-TPE) (XDA2004050202), the National Natural Science Foundation of China (41925032 and 41872100), and the China Postdoctoral Science Foundation (2020M680696) .

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fmre.2021.03.006.

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