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Coupled effect of climate change and human activities on the restoration/degradation of the Qinghai-Tibet Plateau grassland

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Abstract: Climate change (CC) and human activities (HA) are the main reasons for the restoration/degradation of the Qinghai-Tibet Plateau (QTP) grassland. Many related studies have been conducted thus far, but the impact mechanism of CC coupled with HA on QTP remains unclear. We summarized the two main coupling factors in recent years (specifically, in the past five years) and obtained the following conclusions. (1) CC and HA have positive and negative effects on the QTP grassland ecosystem. CC primarily affects grassland ecology through temperature, humidification, and extreme climate, and HA mainly affects ecosystems through primary, secondary, and tertiary industries and restoration measures. (2) CC coupled with HA affects soil, plants, animals, and fungi/microbes. CC makes the snow line rise by increasing the temperature, which expands the zone for HA. CC also restricts HA through hydrological changes, extreme climate, and outbreak of pikas and pests. Simultaneously, measures are implemented through HA to control and adapt to CC. Hence, the grassland ecosystem is comprehensively influenced by CC and HA. (3) The grassland ecosystem dynamically adapts to the disturbance caused by CC and HA by changing its physiological characteristics, distribution range, diet structure, community structure, and physical state. Simultaneously, it responds to environmental changes through desertification, poisonous weeds, rodent outbreak, release of harmful gases, and other means. This work can be used as a reference for the sustainable development of the QTP grassland.

Keywords: Qinghai-Tibet Plateau; geochemistry; soil organic carbon; net primary productivity; pikas; pests; *Cordyceps sinensis*

1 Introduction

The Qinghai-Tibet Plateau (QTP) is an ecological security barrier for China, East Asia, and

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the world (Huang *et al*., 2017). It is located in Southwest China and has an average elevation of over 4,000 m and an area of approximately 2.5724×10^6 km^2; it is the highest and most extensive plateau in the world. QTP has a huge impact on the environment of China and even East Asia due to its extremely thermal and dynamic effects (Zhao *et al.*, 1995). With the exception of the north and south poles, QTP is the largest and the most complete natural ecology that is rarely disturbed by humans (Qiu, 2008). QTP is not only an important area for global carbon sequestration and biodiversity conservation (Mu *et al*., 2017), but also an indicator of world climate and ecological changes (Chen and zhu, 2015; Zhang *et al.*, 2015b).

Grassland is the main body of QTP, and it accounts for 60% of QTP, which is about 1.5×10^6 km^2 (Mo, 2020). The vast grassland ecosystem has many ecological functions, such as nitrogen and oxygen sequestration, water conservation, climate regulation, prevention of desertification, provision of living places for grassland organisms, provision of food and medicinal materials to humans, and husbandry basis (Fayiah *et al*., 2020). The alpine grassland ecosystem has important ecological and economic values. Research on the QTP grassland ecosystem is thus essential.

Grassland degradation has become a worldwide ecological problem in recent years. The QTP grassland ecosystem is considerably degraded under the combined effects of climate change (CC) and human activities (HA) (Harris, 2010; Fassnacht *et al*., 2015; Zhang, 2015d). Degradation causes pest and rodent outbreaks (Cao *et al*., 2016); decreases in biomass, biodiversity, soil nutrition, vegetation cover, and service function (Dong *et al*., 2013; Hao *et al*., 2020); and increases in greenhouse gases (Hu *et al*., 2017), soil erosion, and sandstorms (Hopping *et al*., 2018a). Therefore, grassland restoration has recently become an important topic of research on the sustainable development of QTP. Since the 1990s, the Chinese government has been focusing on restoring and protecting the QTP grassland ecosystem via agricultural technology (Dong *et al*., 2020), cultural education, economic methods, and policy measures (Han *et al*., 2016). Although these measures have exerted positive impacts on protecting the grassland ecosystem (Cai *et al*., 2015), several negative effects cannot be ignored; these include fencing (Dong *et al*, 2020), grazing and hunting exclusion (Lu *et al*., 2017a), economic compensation, establishment of nature reserves (Jiang *et al*., 2019), elimination of pests and plateau pikas (Tian *et al*., 2019), and privatization of grassland (Yeh *et al*., 2017). The negative effects of restoration measures have gradually attracted the attention of scientists. The reasons for QTP grassland restoration must be clarified, existing measures should be re-evaluated, and scientific and effective grassland restoration strategies based on different degradation reasons must be established.

The QTP grassland ecological restoration/degradation is driven by complex factors of CC and HA. Apart from CC (Lu *et al*., 2017b; Zheng *et al*., 2020) and HA (Zhang *et al*., 2017; Li *et al*., 2019d), which have been extensively studied, other factors, such as biological invasions (Wen *et al*., 2020), rodents (Yu *et al*., 2017), urbanization (Walt *et al*., 2015), land use change (Hopping *et al*., 2018a), railway construction (Luo *et al*., 2020), mining activities (Liu *et al*., 2020), tourism (Ding *et al*., 2018), digging and hunting (Xu *et al*., 2015), population migration (Wang *et al*., 2016c), and human restoration activities (Dong *et al*., 2020), play vital roles in the QTP grassland ecological restoration/degradation.

Previous researchers have focused on the impact of CC or HA on the QTP grassland restoration/degradation, but studies on the coupling relationship of CC and HA are insufficient. With this in mind, we discuss the following scientific issues through a review of previous studies: (1) the positive and negative effects of CC and HA on the restoration/degradation of the QTP grasslands; (2) the mechanisms and impacts of CC coupled with HA on grassland geochemical properties, soil organic carbon (SOC), net primary productivity (NPP), pikas, pests, and *Cordyceps sinensis*; and (3) how the grassland ecosystem dynamically adapts to the disturbance caused by CC and HA.

The data used for this review were from secondary sources, such as peer-reviewed articles on QTP and other grasslands. In total, 148 articles and other sources of materials were reviewed. Among them, 88% were from 2015 to 2020, 10% were from 2010 to 2014, and 3 were published before 2010.

2 Role of climate change in Qinghai-Tibet Plateau grassland restoration/degradation

Scientists generally believe that CC is an important driving factor for the restoration/degradation of the QTP grasslands, and many observations and experiments have been conducted on this matter. Numerous studies performed in the past five years (Table 1) have shown that CC is mainly affected by temperature and humidification. Scientists have tested the sensitivity of the QTP grassland ecosystems to CC through experiments, and the results showed that CC is a primary driving factor of the QTP grassland degradation (Wang *et al.*, 2016c; Che *et al.*, 2018). However, the driving factors of climate in alpine grasslands are spatially heterogeneous. Alpine grasslands in the south are sensitive to temperature. Alpine grasslands in the northeast show a strong response to precipitation, and those in the middle are mainly affected by the combined effects of radiation and temperature. Climate sensitivity increases considerably with altitude (Li *et al.*, 2019b). Han *et al.* (2019) used the normalized differential vegetation index (NDVI) of the mesoscale resolution imaging spectrum from 2000 to 2018 to combine the changes in temperature and precipitation and systematically study the characteristics of the QTP vegetation coverage and its driving factors. In general, the restored area is larger than the degraded area, and NDVI is significantly related to temperature and precipitation, of which temperature is dominant. The QTP grassland has spatial heterogeneity, and the increase in precipitation and temperature cannot explain the vegetation change characteristics in the entire QTP alpine grassland (Chen, 2020). However, given the warm and humid background, the degree of greening of the QTP grassland vegetation has increased significantly, and the overall habitat quality has become stable (Jiang and Zhang, 2016).

Relevant studies conducted in recent years have revealed the following spatial and temporal features. With regard to spatial features, many micro-scale studies were conducted in central and eastern QTP where monitoring and research stations, such as Nagqu, Bange, Beiluhe, Nam-MI, and Haibei, can be found. Meanwhile, many macro-scale studies were conducted in the Three Rivers Headwater Region, Qinghai province and Lhasa city, Himalayan Mountains, Tanggula Mountains, and entire QTP by using remote sensing technology, meteorological data, and literature reviews. With regard to temporal features, the time span was large in many studies, especially those on the effect of CC on the grassland ecosystem from 2000 to 2019. In addition, the growing season (April to September) is a hot period for many studies, and only a few scientists have paid attention to the ecological resilience in winter.

Table 1 Impact of climate change on Qinghai-Tibet Plateau restoration/degradation

Effect	Factors	Mechanism	Study area	Research period (year)	Reference
Grassland restoration	Warming	Warming increases microbial residues, and this increase is conducive to SOC formation	Beiluhe Observation and Research Station of Chinese Academy of Sciences (34°51′N, 92°56′E) on QTP	2008–2010	Ding *et al*., 2019b
		Vegetation photosynthesis is strengthened, and the green area is expanded	R1 & R2: The Three Rivers Headwater Region	R1: 2000–2012; R2: 1982–2013	R1: Jiang and Zhang, 2016; R2: Gao *et al*., 2019
		Warming increases vegetation height	R2: Nagqu County (31°26′N, 92°11′E) and Bange County (31°23′N, 92°11′E)	2010–2013	Zhang *et al*., 2015d
	Wetting	Humid conditions help alleviate sandstorms, wind erosion, and desertification	165 random grass plots on the QTP	2000–2015	Huang *et al*., 2017
		In the short term, the amount of water is increasing, which is conducive to plant growth	Three Rivers Headwater Region	2000–2012	Jiang and Zhang, 2016
	Warm and wet conditions	Vegetation growth is promoted in warm and wet conditions	QTP (26°30′–39°30′N, 78°18′–103°60′E)	2001–2013	Wang *et al*., 2016c
		Vegetation activity is enhanced in warm and wet conditions	QTP (25°60′–39°12′N, 76°42′–105°30′E)	1982–2011	Cong *et al*., 2017
		NPP is enhanced in warm and wet conditions	QTP (26°30′–39°30′N, 78°54′–103°60′E)	2001–2015	Zheng *et al*., 2020
		Microbial activity increases as the temperature rises under warm and wet conditions	Nam Co Monitoring and Research Station for Multisphere Interactions (Nam-MI), which is located on central QTP (30°47′N, 90°58′E)	2012–2014	Chen *et al*., 2020a
		Microorganisms multiply and SOC increases under warm and wet conditions	R1: Nam Co Monitoring and Research Station for Multisphere Interactions (Nam-MI), which is located on central QTP (30°47′N, 90°58′E); R2: fenced alpine meadow located at Damxung Grassland Station, QTP (30°51′N, 91°05′E, 4333 m above sea level)	R1: 2012–2014 R2: 2015–2044	R1: Chen *et al*., 2020a; R2: Guan *et al*., 2018
Grassland degradation	Warming	The grassland ecological changes from carbon sinks to sources through the collapse of permafrost and increment in soil respiration	Eboling Mountain Region (38°00′N, 100°54′E)	2014–2016	Mu *et al*., 2017
		The oxidation capacities of carbon, nitrogen, and methane are affected by warming	QTP	2010–2019	Chen *et al*., 2013
		Large amounts of greenhouse gases are emitted into the atmosphere by warming	Boundary region between permafrost areas and seasonal frozen ground areas on southern QTP	September 2014	Wu *et al*., 2018
		Soil nutrients are lost because of SOC decomposition in warming condition	QTP	2010–2017	Liu *et al*., 2018
		Warming significantly increases the soil water-soluble organic carbon and affects the chemical composition of SOC	Qinghai Province (31°39′–39°19′N, 89°35′–103°04′E)	1985–2044	Zhang *et al*., 2017

(*To be continued on the next page*)

(*Continued*)

Effect	Factors	Mechanism	Study area	Research period (year)	Reference
Grassland degradation	Warming	Soil dryness is increased by warming	Administrative village in Namtso Township in the Tibet Autonomous Region of China	2006–2013	Hopping *et al*., 2018a
		Soil warming in early spring partially offsets productivity gains from the growing season	Haibei Grassland Ecological Monitoring Station (36°57′N, 100°51′E)	1997–2011	Guo *et al*., 2018a
		Plant diversity is reduced by warming	Nagqu County (31°26′N, 92°11′E) and Bange County (31°23′N, 92°17′E)	July to August 2013	Zhang *et al*., 2015d
		The adaptation of weeds and pests is increased by warming	Haibei Alpine Meadow Ecosystem Research Station (37°37′N, 101°12′E)	2010–2011	Cao *et al*., 2015
		Soil microbial diversity is significantly reduced by warming in cultivated grasslands	Nagqu County (31°26′N, 92°11′E) and Bange County (31°23′N, 92°16′E)	2013–2016	Zhang *et al*., 2016a
		Soil microorganisms convert into poor nutrient content and low active state in warming condition	Haibei Alpine Meadow Ecosystem Research Station (37°37′N, 101°12′E)	2006–2012	Che *et al*., 2018
		In the long run, the amount of water will decrease because of glacier retreat and permafrost thawing	Tanggula Mountains over central QTP	1976–2013	Ke *et al*., 2017
	Wetting	The soil's capacity for water conservation is decreasing because of the increase in rain erosion	Tibet	2000–2019	Chen *et al*., 2020b
		Excessive humidity is not conducive to vegetation growth in humid areas	Nam Co Monitoring and Research Station for Multisphere Interactions (30°47′N, 90°58′E)	Every April to September from 2012 to 2014	Chen *et al*., 2020a
		Soil microbial diversity is greatly reduced by concentrated heavy rain in natural alpine grasslands	Nagqu County (31°26′N, 92°11′E) and Bange County (31°23′N, 92°17′E)	2013–2016	Zhang *et al*., 2016a
	Extreme climate	Alpine animals and plants are covered and frozen to death, and the soil is eroded by extreme climate disasters, such as snowstorm, rainstorm, and thunderstorm	R1: Three Rivers Headwater Region (31°39′–36°12′N, 89°45′–102°23′E) R2: About 2946 km long from east to west, west from the Pamirs and east to the Hengduan Mountains; about 1532 km wide from south to north, south from the Himalayan Mountains and north to the Kunlun-Qilian Mountains R3: QTP	R1: 1960–2010 R2: 1949–2015 R3: 1961–2008	R1: Wang *et al*., 2014; R2: Wang *et al*., 2019b; R3: He *et al*., 2016

2.1 Role of climate change in Qinghai-Tibet Plateau grassland restoration

2.1.1 "Warm and wet" trend

The "warm and wet" trend of CC has been recognized by most scientists (Schuur *et al*., 2015; Hoham and Remias, 2020). Therefore, most studies on QTP grassland ecosystems are based on the background of "warm and wet." However, a few scientists have proven through experiments that the warm and humid trend is conditional. Wen's eight-year (2011–2018) warming experiment showed that short-term warming (three years) brings about a "dry and hot" trend, and long-term warming (>three years) brings about a "warm and humid" trend (Wen *et al*., 2020). Therefore, warming and wetting are conducive to the restoration of the QTP grasslands within a certain range (Chen *et al*., 2015).

2.1.2 Role of warming in Qinghai-Tibet Plateau grassland restoration

Solar radiation and temperature are the dominant factors in alpine meadows for the restoration of grassland (Zheng *et al*., 2020). NPP increases in warm conditions, and warming has increased the photosynthesis of vegetation, extended plant growth seasons, expanded grassland areas, and increased grassland NPP (Zhang *et al*., 2014; Mao *et al*., 2015). Glacier retreat and permafrost thawing are caused by increasing temperature (Wu *et al*., 2012; Ke *et al*., 2017). Hence, the altitude that can be covered by vegetation increases, and grassland expands. Warming has significantly increased the overall NPP of grassland, but due to the regional imbalance of driving factors, the NPP of several areas has weakened. In detail, the western region of QTP has become relatively dry, and its NPP has decreased. The eastern region has become warmer and wetter than before, and its NPP has increased gradually from the east to the west (Yuan *et al*., 2017). Moreover, a certain correlation exists among temperature increase, permafrost thawing, and vegetation cover. Yuan's experiments showed that a slight increase in soil temperature and vegetation cover caused by a temperature increase can offset the impact of CC on permafrost (Yuan *et al*., 2020).

2.1.3 Role of wetting in Qinghai-Tibet Plateau grassland restoration

Microorganisms multiply in humid conditions, which is beneficial to plant growth (Wang *et al*., 2018a). Ding reported that humid conditions contribute to microbial residues (Ding *et al*., 2019b). Chen showed that microbial activity increases in moderately wet conditions (Chen, 2020). In addition, wind speed is subject to humidity, and the frequency of wind erosion and sandstorms is reduced in wet conditions (Jiang and Zhang, 2016), which is conducive to the restoration of QTP grasslands. Altogether, humid conditions are conducive to the restoration of QTP grasslands within a certain range.

2.2 Role of climate change in Qinghai-Tibet Plateau grassland degradation

CC leads to QTP grassland degradation directly and indirectly. Warming, wetting, drought, and extreme weather affect the grassland ecosystem directly, and ecological participants, such as soil, vegetation, animals, and atmospheric composition, lead to indirect degradation of the QTP grasslands.

2.2.1 Grassland degradation caused by climate change directly

First, many scientists believe that the drought brought about by CC exacerbates the degradation of the QTP grasslands because warming increases evaporation, which is not conducive to the growth of the grassland vegetation. A short-term temperature increase (three years) makes air and soil dry and hot (Wen *et al*., 2020), thereby limiting the growth of grassland vegetation (Fu *et al*., 2013; Hopping *et al*., 2018a).

Second, grassland is degraded in over-wet areas. Glacier retreat and permafrost melting, which are caused by CC, lead to an over-humid condition in the atmosphere and soil, and NDVI is negatively correlated with precipitation in humid areas (Han *et al*., 2019). Precipitation increases plant productivity, leading to an increase in nutrient consumption and a decrease in the content of SOC. SOC is lost under excessive humid conditions in alpine meadows (Yang *et al.*, 2017). McCarthy reported that plants allocate a relatively small proportion of their body out of surface to conduct photosynthesis, thereby reducing the carbon input from vegetation to roots under a condition of relatively sufficient moisture (Mccarthy and Enquist, 2007).

Third, as the amount of water increases, rain erosion intensifies, and the risk of being eroded by wind and water in grasslands increases (Chen *et al.*, 2020a).

Fourth, warming in the non-growing season is not conducive to grasslands. Guo found that warming before the growing season (March to April) in winter and spring reduces soil water use efficiency and decreases grassland productivity (Guo *et al.*, 2018a).

Fifth, extreme weather also causes grassland degradation (Chi *et al.*, 2016). He analyzed the spatial pattern and trend of extreme weather in QTP alpine meadows by using meteorological data from 1961 to 2008. His results showed that climate experiences many warm extremes and few cold extremes (He *et al.*, 2016). In addition, extreme weather affects the physiological and biochemical processes of plants (Han *et al.*, 2019). Heavy rains, hail, snowstorms, mudslides, ice avalanches, and thunderstorms are the main extreme weather disasters in QTP (Wang *et al.*, 2014; Bai *et al.*, 2019). The monitoring of the QTP snow disasters indicates that 238 large-scale snow disasters have occurred in the past 50 years. A high-risk zone of snow disasters from northeast to southwest was identified in space (Wang *et al.*, 2019b). The grassland here was covered by severe ice avalanches and blizzards, and the animals and plants were covered or froze to death. Meanwhile, heavy rainfall and hail aggravate soil erosion (He and Richards, 2017). Frequent extreme weather is another reason for the degradation of the QTP grasslands.

2.2.2 Grassland degradation caused by climate change indirectly

Grassland degradation can be caused by soil changes under CC. An increase in temperature causes permafrost thawing; the water seeps, and the soil surface becomes dry, which is not conducive to vegetation growth (You *et al.*, 2017). Moreover, warming increases evaporation and significantly reduces the average soil moisture in the growing season (Fu *et al.*, 2013). Although warming has increased the amount of water via glacier retreat and permafrost thawing, the water volume is expected to decrease in the long run, eventually leading to soil water shortage and grassland degradation (Wang *et al.*, 2016b; Ke *et al.*, 2017). Moreover, warming accelerates the decomposition of organic matter and strengthens soil respiration, thereby changing the soil carbon cycle (Ding *et al.*, 2019b). Carbon flux measurements have shown that QTP grassland is an important carbon sink (Doetterl *et al.*, 2015). In warm and wet conditions, the carbon sink function of the QTP grassland ecology is significantly strengthened (Mu *et al.*, 2017), and the increasing temperature causes soil and grassland degradation under CC.

Furthermore, grassland degradation can be caused by changes in species relationships in grassland ecosystems under CC. The eight-year warming experiment of Wen showed that warming has increased the drought on the surface soil layer, and this increment is conducive to the growth of pikas and poisonous weeds. The adaptation to CC of weeds, pests, and pikas is increasing, thereby reducing grassland biodiversity (Wen *et al.*, 2020). Dorji conducted a five-year (2009–2015) study on the relationship among warming, grazing, spring melting, and grassland organisms in the central part of QTP and discovered that warming reduces species richness and promotes the proportion of shrubs in total vegetation (Dorji *et al.*, 2018).

At the same time, the living environments of vegetation and animals are changed by the increasing soil temperature, and the grassland ecosystem is disturbed (Guan *et al*., 2018). Chen *et al.*’s (2020a)six-year warming experiment showed that under warming conditions, the DNA replication, transcription, translation, and signal transduction of soil microorganisms are significantly inhibited, and the soil protozoan community shifts to a less nutritious and less active state. Overall, the increase in pests, decline in biomass and biodiversity, and suppression of microorganisms lead to grassland degradation under CC.

3 Role of human activities in Qinghai-Tibet Plateau grassland restoration/degradation

HA plays an important role in the restoration/degradation of the QTP grasslands. In addition to husbandry and agriculture, which have been widely studied, changes in lifestyle brought about by urbanization, changes in economic growth patterns, and changes in land use brought about by tourism and industries are new factors that influence the QTP grasslands. Furthermore, the disturbance of the biological chain caused by mining and hunting and the ecological restoration measures implemented by humans affect the ecological restoration/degradation of the QTP grasslands. As a result, people are looking for new restoration measures. For example, several scientists believe that artificial grassland is a good replacement for degraded grassland (Li *et al*., 2017; Li *et al*., 2018a). Others think that we do not need to carry out any restoration. Li *et al.*’s (2019a) research on aeolian desertification in the northeast of QTP for nearly a thousand years predicted that as long as moderate HA is maintained, the grassland ecology of QTP will recover naturally even if no restoration is carried out.

Recent relevant studies have revealed the following spatial and temporal features. With regard to spatial features, many studies have adopted typical counties, such as Nagqu, Damzhung, Xihai, Gonghe, Tiebujia, Hongyuan, Maqu, Damxun, and Lhasa, as samples to examine HA effects on grassland. Other studies have focused on the region along the Qinghai-Tibet Railway. In this region, the ecologically fragile areas, such as permafrost and the agro-pastoral zone, are popular research subjects. With regard to temporal features, several management and restoration measures have been implemented since 1984, and these include the privatization of pastures, fencing, and setting of reserve areas. In sum, relevant studies were mainly from the 1990s to the 21st century, and most of them have been conducted for more than 10 years.

3.1 Role of human activities in Qinghai-Tibet Plateau grassland restoration

3.1.1 Moderate grazing is beneficial to grassland restoration

The positive effects of moderate grazing have been widely recognized (Li *et al*., 2018b; Dong *et al*., 2020). Experiments have shown that the above-ground biomass, vegetation coverage, SOC, and total soil nitrogen of grassland ecosystems have a slight linear growth relationship with changes in grazing intensity. Furthermore, light and moderate grazing activities exert a positive impact on vegetation diversity and soil respiration. Mu evaluated nectar (fodder) and plant diversity in areas with non-, light, moderate, and heavy grazing. The results showed that the nectar and plant diversity of light and moderate grazing grasslands is higher than that of severe and non-grazing areas (Mu *et al.*, 2016). Cui compared the grazing situation in warm and cold seasons. They found that moderate grazing significantly increases the production of alpine grassland plants in both seasons (Cui *et al.*, 2014). Miehe reported that traditional migratory grazing is the best strategy for protecting QTP grasslands because people have been living with this lifestyle for thousands of years, proving that grasslands are sustainable in this moderate grazing condition (Miehe *et al.*, 2019). Altogether, moderate grazing is beneficial to the ecological health of QTP grasslands.

3.1.2 Urbanization is conducive to grassland restoration to a certain extent

Urbanization is conducive to popularizing education and changing the diet structure in QTP. With the introduction of rice and flour, the demand for beef and lamb declines (Wang *et al.*, 2016a). Several scientists believe that population growth does not necessarily lead to a growth in husbandry. In addition, certain herders move to urban locations to improve their life and educational resources; afterward, they rent out or abandon their ranches (Cao *et al.*, 2018a). Therefore, the problem of overgrazing is alleviated by urbanization, which is beneficial to QTP grasslands.

3.1.3 Tourism is conducive to grassland restoration to a certain extent

Scientists have found that practitioners in the tourism industry are inclined to protect the environment (Li *et al.*, 2019c). Tourism brings income to the local government so that they will have funds for grassland restoration and construction. Furthermore, tourism is a new means to make a living for several residents (Yang *et al.*, 2019); hence, the problem of overgrazing is alleviated to a certain extent. The direction of the future development of QTP is how to manage the tourism in QTP so that it can improve the economic conditions of local residents and local governments and contribute to the protection of grassland ecosystems.

3.1.4 Restoration measures are effective

Beginning in the 1990s, a series of protection and restoration measures were implemented by humans in the QTP grassland ecosystem, and these included agriculture, economy, culture, and policy (Table 2). Han *et al.* (2016) conducted a sensitivity analysis of the response of ecological service value to land use change. The results showed that the average sensitivity index of ecological service in Qinghai Province was 0.693 and 1.137, respectively from 1988 to 2000 and from 2000 to 2008, which means that for every 1% increase in land use change, the value of ecological services fluctuates by 0.693% and 1.137%, respectively. Monitoring of the ecological status of the QTP grassland from 2000 to 2008 and 2008 to 2015 shows that the grassland degradation trend has weakened significantly, and the restoration trend has strengthened. In particular, the proportions of degraded grassland have decreased by 19.9%, and restored grassland has increased by 33%. Vegetation coverage, especially alpine meadows, has also increased by an average of 1.9%. Furthermore, the pressure of grazing on grassland has decreased, the supply of forage has improved, and the contradiction between forage and livestock has eased (Huang *et al.*, 2017). Evidently, the restoration measures are effective (Shao *et al.*, 2017).

3.2 Role of human activities in Qinghai-Tibet Plateau grassland degradation

Several scientists believe that HA is the dominant factor affecting the QTP grassland degradation. Pan estimated that non-climatic drivers account for 66.1% of the QTP grassland changes (Pan *et al*., 2017). Among them, farming, grazing, hunting, mining, tourism, urban construction, and railway construction contribute to the degradation of the QTP grassland to varying degrees.

Table 2 Protection and restoration measures being implemented in Qinghai-Tibet Plateau since the 1990s

Methods		Reference
Agricultural	Reduce livestock Seasonal grazing Collective grazing Fencing Fertilization Increase seeding rate Replanting Improve grassland quality Control rodents and pests Reduce rain erosion by technology	Dong *et al*., 2013; Yeh *et al*., 2017; Hopping *et al*., 2018b; Wang *et al*., 2018b; Miehe *et al*., 2019; Dong *et al*., 2020; Cao *et al*., 2011; Cao *et al*., 2018c; Chen *et al*., 2016a; Wu *et al*., 2019
Economic	Financial compensation Ecological protection reward Compensation for animal accidents	Yang *et al*., 2019; Chen and Zhu, 2015
Cultural	Law education Environmental education Popularize knowledge/skills of ranch management	Han *et al*., 2016
Policy	Seasonal fallow Grazing exclusion Establish administrator management system Return ranch to grass Return construction to grass Nature reserves Biodiversity conservation	Cai *et al*., 2015; Lu *et al*., 2017a; Lu *et al*., 2017b; Jiang and Zhang, 2016; Fu *et al*., 2019; Zhang *et al*., 2016b

3.2.1 Overgrazing aggravates grassland degradation

Overgrazing is one of the main causes of QTP grassland degradation. In the past 30–50 years, overgrazing in QTP has led to severe degradation in the vegetation and soil of alpine grassland. SOC has decreased by 42% relative to that in non-degraded grassland (Liu *et al*., 2018). Zhang’s warming and cattle grazing experiments showed that overgrazing reduces the height and quantity of plants, and it is the main driving force for vegetation changes in alpine grasslands (Zhang *et al*., 2015d). Li *et al*. (2019d) selected five sections along 1100 km from east to west of the Three Rivers Headwater Region to analyze the soil erosion data in the past 50 and 100 years. The results showed that in the past 100 years, almost no soil erosion occurred, but soil accumulation did occur. However, soil erosion has intensified in the past 50 years, and soil erosion is closely related to the number of livestock and intensity of grazing. In addition, many experiments have attempted to quantify the difference between grazing and non-grazing grasslands. Lu analyzed and summarized the average data of 61 related studies (Lu *et al*., 2017b). The SOC, soil total nitrogen, NH_4^+–N, microbial carbon, above-ground biomass, underground biomass, vegetation coverage, and vegetation height of grazing grassland decreased by 1185.19 g/m^2, 97.4 g/m^2, 2.56 mg/kg, 66.70 g/m^2, 88.92 g/m^2, 197.30 g/m^2, 16.92 g/m^2, and 5.53 cm, respectively, compared with the values for non-grazing grassland. Notably, if no appropriate and effective restoration methods are implemented, some grassland in QTP may disappear within a few decades due to the rapid loss of SOC and the slow recovery (Zhang *et al*., 2015c).

3.2.2 Over-digging and over-hunting aggravate grassland degradation

QTP has many well-known medicine resources, such as *Cordyceps sinensis*, saffron, and snow lotuses (Sun *et al.*, 2020b). People on QTP have a thousand-year tradition of digging for natural medicines, and this approach has been proven to be environment friendly. However, the demand for these medicines has increased in recent years (Shrestha and Bawa, 2014). Excessive digging disrupts the alpine grassland ecosystem. Take *cordyceps*, a traditional Chinese herbal medicine, as an example. Given that *Cordyceps sinensis* only emerges 2–3 cm above the ground, digging activities require crawling or creeping on the grass to explore them inch by inch. Furthermore, the time of digging for natural medicines coincides with the season of plant growth, which is from May to June; hence, digging and trampling activities cause serious disturbance to soil, plants, and organisms in QTP. Xu's quantitative research showed that digging and trampling activities have reduced the biodiversity in grassland ecosystems by 10%–13%, vegetation coverage by 11%–19%, and above-ground biomass by 21%–40% (Xu *et al.*, 2015).

In addition, QTP has many well-known wild animal resources, such as Tibetan antelopes, wild donkeys, and wild yaks. Over-hunting has reduced the number of wild animals greatly and has even made certain species extinct. The carnivores in the food chain are hunted, which destroys the biodiversity and causes herbivores to multiply; this situation intensifies the damage on grassland vegetation. Although the Chinese government has excluded several areas from hunting and digging activities, poaching is still common. One reason is that local residents have low awareness of legal and environmental protection. Another reason is that the prohibition of digging and hunting affects their livelihood (Cui *et al.*, 2017). In summary, over-digging and over-hunting cause grassland degradation and disturb the living habitat of other organisms. Thus, they deserve our attention.

3.2.3 Secondary and tertiary industries accelerate grassland degradation

City construction damages the grassland ecosystem. The speed of urbanization in the QTP region accelerates with the increase in population. As a result, cities invade grasslands, impervious surfaces change the reflectance and groundwater flow in cities, and artificial structures break the original grassland landscape into fragments; consequently, the native grassland habitat is lost (Gong *et al.*, 2017).

Moreover, the Qinghai-Tibet Railway is causing interference to the environment. It crosses vast grasslands and permafrost areas, causing serious interference to the environment along the line. Researchers have found that the impact of the Qinghai-Tibet Railway includes a 30-km range along the line (Luo *et al.*, 2020). Specifically, in addition to the destruction caused by railway construction and operation (Shang *et al.*, 2015), the interception of the railway has disrupted the migration paths of animals, leading to species extinction and destruction of the grassland biological chain, which are unfavorable for the grassland ecosystem.

Furthermore, mining on QTP has attracted widespread attention in recent years (Liu *et al.*, 2020). The development of mining has brought about changes in land use and damaged the ecology of the QTP grassland. Qian conducted research on six open-pit coal mines on the south side of Qilian Mountain (Qian *et al.*, 2018). The results showed that the capacity for soil water conservation and the value of ecological services are decreasing in these places.

Lastly, the influence of tourism cannot be ignored. QTP is a famous destination for its unique natural scenery and mysterious Tibetan Buddhist culture. In 2008, the tourist population of Lhasa (the capital city of Tibet) was 1.5 times larger than the permanent population. By 2014, the tourist population was 14.1 times larger than the permanent population and produced 174.8 tons of garbage daily in Lhasa. Estimations indicate that Lhasa will have 9,260,000 tourists in 2025 and will produce 960 tons of garbage per day (Ding and Wang, 2018). Apart from garbage, Le believes that tourism can also lead to soil and vegetation degradation by reducing plant height, species diversity, and above-ground biomass (Le *et al.*, 2014). Furthermore, tourism-related services, such as catering, accommodation, transportation, shopping, and entertainment, have developed accordingly. Horse riding, bull riding, grass sliding, hunting, vehicle rolling, and other play activities have also further aggravated the degradation of the QTP grassland.

3.2.4 Negative effects of improper restoration measures

First, "grazing exclusion" involves removing the important participant in the original stable grassland ecosystem quickly; then, the regular pattern is broken, which is not conducive to the health of the grassland ecosystem. In addition, the "grazing exclusion" policy has been rejected by several residents for the reason that they must give up their basic income, which is from grazing (Cui *et al.*, 2017).

Second, "fencing" has protected the grassland in several severely degraded areas for a certain period. As the grassland recovers, "fencing" will have negative effects. For example, the "no-fencing" zone will become a seriously degraded area. Moreover, "fencing" disturbs animal migration and will destroy the grassland ecosystem ultimately (Dong *et al.*, 2020).

Third, the privatization strategy of pastures implemented by China has had little positive effect because herders camp in fixed areas and the grassland around the camps is trampled on seriously (Yeh *et al.*, 2017; Cao *et al.*, 2018a).

Fourth, although the establishment of the Nature Reserve Zone has a certain protective effect on ecological restoration (Jiang *et al.*, 2019), the conflict of interest between the protected area and local residents is prominent. For example, residents are not satisfied with the compensation because it is too small to make up for the loss of grazing and hunting in the Nature Reserve Zone. In addition, the Nature Reserve Zone was set up by the government suddenly and directly, which means the local residents must change their lifestyle, which they have had for thousands of years, quickly. This change is understandably difficult (Shrestha and Bawa, 2014). Furthermore, several local residents have low environmental and legal awareness; they still enter the reserve for grazing and hunting, thinking that doing so is not a serious matter. Lastly, certain restoration measures are short-lived and discontinuous. Overall, the negative effects of improper restoration methods have been widely identified gradually (Lu *et al.*, 2017a).

4 Coupled effect of climate change and human activities on Qinghai-Tibet Plateau grassland restoration/degradation

We summarized the effects of CC and HA on the restoration/degradation of the QTP grasslands in the past five years (Tables 1 and 3) in Sections 2 and 3, respectively, but the effects of CC and HA are not independent, and many coupling relationships exist (Xiong *et al.*, 2019). CC expands the zone for humans, plants, and animals. It restricts HA by increasing the adaptability of plateau pikas and pests and the occurrence frequency of extreme weather conditions, such as snow storms, thunderstorms, and extremely cold or hot weather. Meanwhile, HA directly affects the grassland ecosystem through grazing, digging, mining, traveling, trampling, and fertilization and indirectly aggravates CC by changing the surface reflectance and atmospheric composition (Figure 1).

Table 3 Impact of human activities on Qinghai-Tibet Plateau grassland restoration/degradation

Effect	Impact	Mechanism	Study area	Research period	Reference
Grassland restoration	Urbanization	Changing from grazing to purchasing food, which is conducive to grazing management and restoration measures	Nagqu County in northern Tibet (30°31′–31°55′N, 91°12′–93°02′E)	1991–2011	Wang *et al*., 2016a
		Change the food structure with rice and noodles, and the demand of grazing will decline	Maqu County on eastern QTP (33°99′N, 102°07′E)	1996–2016	Cao *et al*., 2018a
		Improving and popularizing the knowledge of grazing management and environment protection	Damzhung County in Tibet Autonomous Region of China	1990–2012	Hopping *et al*., 2016
	Grazing	Plant diversity can be increased by grazing	Nagqu County (30°31′–31°55′N, 91°12′–93°02′E) and Bange County (31°23′N, 90°17′E)	July–August of 2013	Zhang *et al*., 2015d
		Plant photosynthesis can be enhanced by grazing directly and indirectly	Xihai Town of Haiyan County (36°56′N, 100°57′E) and Tiebujia Town of Gonghe County (99°35′N, 37°02′E)	2012–2017	Shen *et al*., 2019
		Grazing can increase the nitrogen content in soil and promote nitrogen uptake by plants	Xihai Town of Haiyan County (36°56′N, 100°57′E) and Tiebujia Town of Gonghe County (99°35′N, 37°02′E)	2012–2017	
		Plant production in alpine grassland is significantly increased by moderate grazing	QTP	2010–2020	Dong *et al*., 2020
		Plant diversity and nectar (forage) sustainable production are promoted by light and moderate grazing	Hongyuan County (32°48′–32°52′N, 102°01′–102°33′E)	2004–2014	Mu *et al*., 2016
		Traditional migratory pastures are conducive to sustainable pasture development	Kobresia pastures in eastern Tibetan highlands	1984–2016	Miehe *et al*., 2019
		Multi-family grazing management can maintain better soil fertility and support grassland sustainable use	Magqu County on eastern QTP	1996–2016	Cao *et al*., 2018b
		Nitrogen adding (fertilization) can significantly increase the coverage of grassland	Damxung, northern Tibet	2012–2014	Zong *et al*., 2016
	Restoration	Restoration methods, such as nature reserve, return farmland to grass, and the Three North Shelter Belt Project, are effective	R1: QTP; R2: Qinghai Province (31°09′–39°19′N, 89°35′–103°04′E); R3: QTP; R4: China; R5: Water Tower region of China	R1: 2000–2100, 2030–2050, and 2080–2100; R2: 1988–2008; R3: 2000–2015; R4: 2001–2010; R5: 2000–2010	Zhang *et al*., 2015c; Han *et al*., 2016; Huang *et al*., 2017; Lu *et al*., 2018; Wang *et al*., 2015

(*To be continued on the next page*)

(***Continued***)

Effect	Impact	Mechanism	Study area	Research period	Reference
	Urbanization	Population growth has a negative impact on grassland	QTP	2002–2019	Fayiah *et al*., 2020
	Secondary industry	The quality of soil along the railway is declining	Continuous permafrost regions along the Qinghai-Tibet Highway in the north of Kunlun Mountains	2013	Shang *et al*., 2015; Sun *et al*., 2020b
		Grassland ecology is destroyed by mining	Southern slope of Qilian Mountains	1975–2016	Qian *et al*., 2018
	Tertiary industry	Tourism has a negative impact on plant height, vegetation coverage, species diversity, and above-ground biomass in grassland	Lhasa	2015–2025	Le *et al*., 2014; Ding and Wang, 2018
Grassland degradation	Grazing	SOC is reduced by grazing	QTP	The past 100 years	Li *et al*., 2019d
		The height, coverage, and living conditions of vegetation are reduced by grazing	R1: Nagqu County (30°31′–31°55′N, 91°12′–93°02′E); R2: Haibei Alpine Meadow Ecosystem Research Station (37°37′N, 101°12′E)	R1: 2010–2013; R2: 2010–2011	R1: Zhang *et al*., 2015d; R2: Cao *et al*., 2015
		Biomass is reduced by grazing	R1: Qinghai Province (31°39′–39°19′N, 89°35′–103°04′E) R2: Northern Tibetan Plateau	R1: 1985–2044; R2: 2010–2013	R1: Zhang *et al*., 2017; R2: Zeng *et al*., 2015
		The uptake of nitrogen by plants and microorganisms is reduced strongly by grazing	Nagqu County on the Tibetan Plateau (30°31′–31°55′N, 91°12′–93°02′E)	Growing season	Jiang *et al*., 2017b
		The size and reproduction of pests are significantly increased by grazing	Haibei Alpine Meadow Ecosystem Research Station (37°37′N, 101°12′E)	2010–2011	Cao *et al*., 2015
		Soil erosion is accelerated by livestock	R1: Qinghai Province; R2: across 1100-km East–West transect in the Three-River Headwaters Region	R1: 2009–2012; R2: 1919–2019	R1: Harris *et al*., 2016; R2: Li *et al*., 2019d
	Restoration	Several improper restoration methods, such as grazing exclusion and fencing, are harmful to the health of grasslands to a certain degree	R1: Damzhung County in Tibet Autonomous Region of China R2: QTP	R1: 1990–2012; R2: 2010–2020	R1: Hopping *et al*., 2016; R2: Dong *et al*., 2020

4.1 Coupled effect on soil organic carbon

Researchers have attempted to determine whether HA or CC dominates SOC. In terms of leading factors, Wang's warming–grazing experiment evaluated the coupling relationship between CC and grazing in SOC change. The experiment showed that CC dominated by temperature rise directly reduces the SOC content, and the factor of grazing only results in a small variation in SOC concentration (Zhang *et al*., 2017). In terms of propelling factors, soil and plants are trampled by grazing, thereby reducing soil carbon uptake from vegetation to roots, which has a negative impact on SOC. However, grazing can also have a positive impact on SOC through trampling, falling leaves, and manure return. In summary, no significant correlation exists between grazing and SOC (Wang *et al.*, 2019a).

Moreover, complex relationships exist among CC, HA and grassland. HA further aggravates CC, such as increasing the amount of greenhouse gas, which affects the change in SOC. Grazing exclusion experiments have shown that grazing exclusion reduces the soil respiration of QTP meadows and grasslands but increases their sensitivity to temperature; in addition, grazing areas have a higher potential to release carbon than non-grazing areas under future warming conditions (Zhang *et al.*, 2017; Guo *et al.*, 2018b). Notably, although CC is generally recognized as the main controlling factor of SOC, Doetterl discovered that SOC is controlled by the interaction between geochemistry and climate. After the relationship between geochemical factors is removed, the relationship between CC and carbon flux is significantly reduced (Doetterl *et al.*, 2015) (Figure 2).

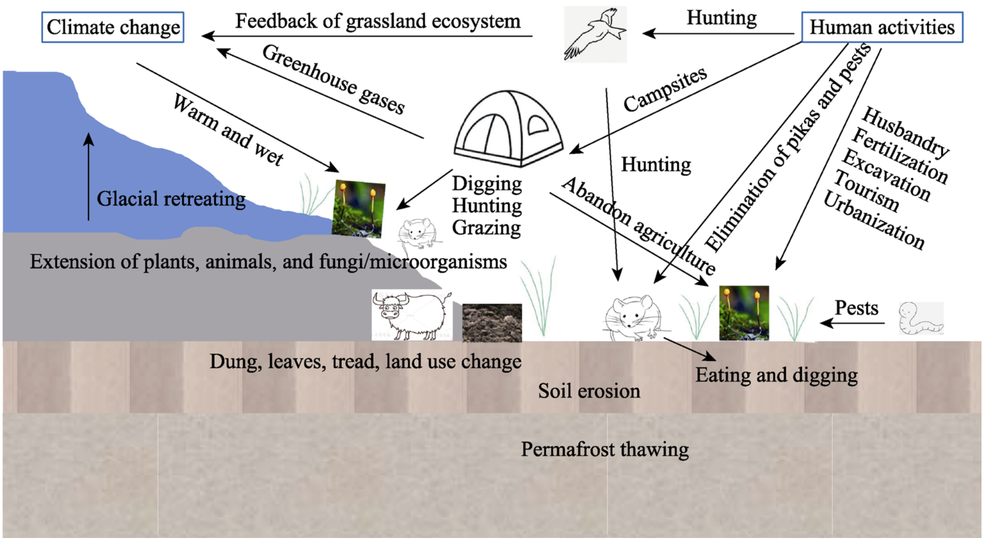

Figure 1 Coupled effect of climate change and human activities on Qinghai-Tibet Plateau grassland restoration/degradation

4.2 Coupled effect on the production of the grassland ecosystem

NPP is affected by CC and HA. Although the green area of alpine vegetation has been proven to increase in warm and wet climate conditions (Jiang and Zhang, 2016), in areas with high human pressure, especially in grazing and traveling areas around Lhasa, the decline of alpine vegetation is strong (Luo *et al.*, 2020), and grassland degradation is obvious.

Furthermore, glacier retreat forms new pastures at high altitudes, and the impact of HA expands as a result. Digging, grazing, and tourism activities have expanded to high elevations with the expansion of grasslands. The grassland degradation caused by HA in high-altitude zones aggravates soil erosion by wind and water and brings about soil nutrient loss (He and Richards, 2017). In turn, soil nutrient loss causes the degradation of grassland again at high elevations (Liu *et al.*, 2018).

With regard to the total NPP, Wang calculated the contribution of the interaction between CC and HA to the total NPP of QTP vegetation through a quantitative assessment using the CASA model and the results showed that CC plays a leading role in the total NPP(Wang *et al.*, 2016c). Zhang obtained similar results, but he clarified that air temperature is the main cause of grassland changes in biomass and total NPP, and precipitation and grazing are the secondary causes (Zhang *et al*., 2017). However, several scientists hold the opposite view. They believe that overgrazing instead of CC is the main cause of vegetation changes in QTP. Grazing offsets the increase in vegetation height and surface biomass caused by warming (Zhang *et al*., 2015d). Zhang's scenario simulation results showed that in the past 30 years, biomass in grassland and grazing intensity has been negatively correlated, and biomass has declined at all grazing degrees against the background of warming (Zhang *et al*., 2017) (Figure 3).

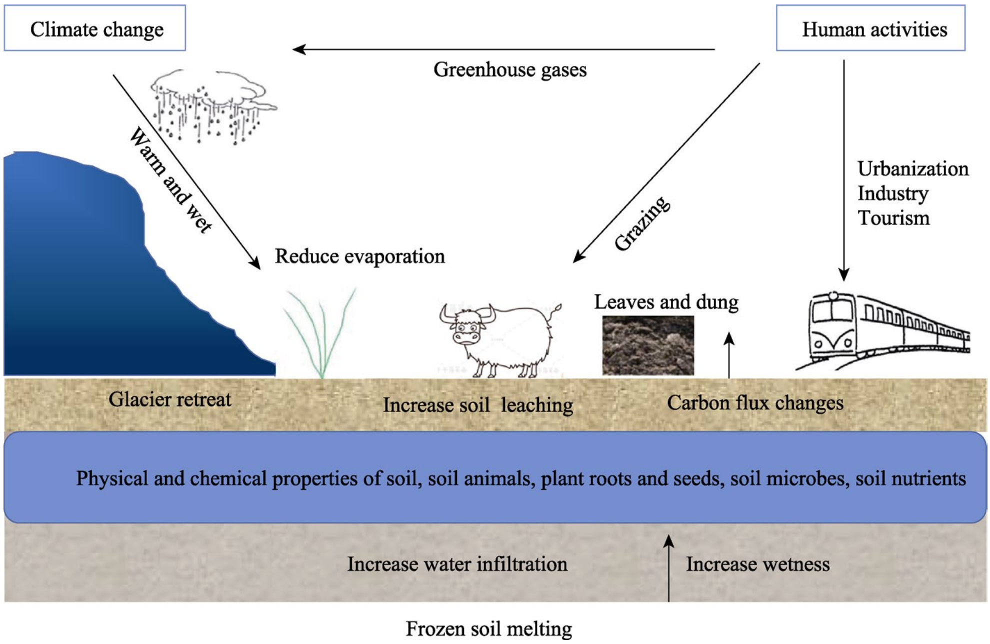

Figure 2 Coupled effect on soil organic carbon

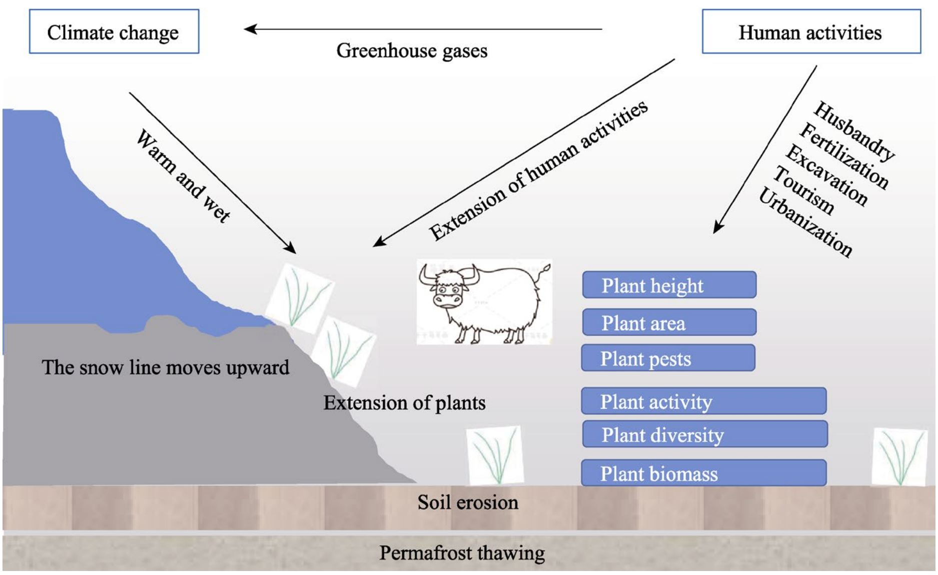

Figure 3 Coupled effect on the production of the grassland ecosystem

4.3 Coupled effect on pikas and pests

Primarily, pikas on QTP grassland cannot be ignored (Yu *et al.*, 2017). Pikas are important participants in the grassland ecosystem, and the burrowing and gnawing activities of pikas reduce the soil moisture, hardness, organic carbon, and nitrogen, thereby changing the vegetation cover, soil nutrient content, microbial community, physical structure, and porosity (Ding *et al.*, 2019a). Pikas also increase the top soil gravel, which is not conducive to vegetation restoration and excavate large pores to form many bald spots, mounds, and pores, which change the soil structure in such a way that air and water flow only in the shallow pores created by them. Thus, the connectivity of soil pores is destroyed and soil erosion is aggravated (Hu *et al.*, 2020). Furthermore, the adaptability of pikas to CC is increasing, and the prediction results of the food chain model show that the number of pikas on the QTP is between 70 and 288 per hectare without external interference, which is a relatively high number (Sun *et al.*, 2015). To improve the pasture economy, humans have carried out various interventions to limit or eliminate pikas on QTP. Examples include the use of pesticides to eliminate pikas or the adoption of eagles to hunt them; both measures have been in vain. Experiments have shown that in 80% of the areas subjected to drug elimination, the number of pikas can be restored to 70% of the original number within four years, and the number of pikas is much greater than the demand for food for eagles (Tian *et al.*, 2019). Meanwhile, the methods of grass improvement and replanting have produced better results. Experiments have shown that the height of plants is negatively correlated with the density of pikas. Therefore, ecologists have proposed a biological control model of "increasing the proportion of grasses in the plant community to control the hazards of pikas". Notably, pikas are important participants in the grassland ecosystem of QTP, and they can provide homes for plateau lizards and birds, form habitats for creatures, and become the staple food of eagles and other animals (Zhao *et al.*, 2020). Appropriate human interference can help improve the habitat of pikas and promote the quality of alpine grassland, but transitional intervention would lead to reverse succession of the ecosystem. Hence, the pika exclusion strategy is inappropriate, and ecological measures should consider the comprehensive influence of CC and HA.

Additionally, grassland caterpillars are important participants in the QTP grassland ecosystem and essential indicators of the extreme ecological environment of alpine hypoxia grassland. An example is the grassland caterpillar *Gynaephora menyuanensis*, which is one of the main pests in the alpine meadow in the northeast of QTP. An outbreak of *G. menyuanensis* causes a shortage in livestock production by causing sickness and death among livestock, but it also causes pest interaction in forage (Zhang and Yuan, 2013). Thus, the community development of caterpillars is crucial for the ecology of pastures and grasslands. Previous warming–grazing experiments have shown that the growth rate of grassland caterpillars increases by 9%, and the weight of females increases by 26% in warming–grazing treatment (Cao *et al.*, 2016). Specifically, CC and HA significantly increase the body size, potential reproductive capacity, and density of caterpillars, which is unfavorable for grasslands (Cao *et al.*, 2015). In addition, the distribution of caterpillars is mainly restricted by the degree of grazing. Comparative tests conducted on non-, light, moderate, and heavy grazing have revealed that heavy grazing increases the density of caterpillars in grasslands, and moderate grazing inhibits the increase in species density (Chen *et al.*, 2016b). Furthermore, the environmental adaptability of caterpillars increases under conditions of grazing and warming, and caterpillars exacerbate grassland degradation by reducing the biomass of sedge and plants (Cao *et al*., 2015). Notably, spring melting and moderate grazing can offset several of the impacts of warming on plant communities (Dorji *et al*., 2018) (Figure 4).

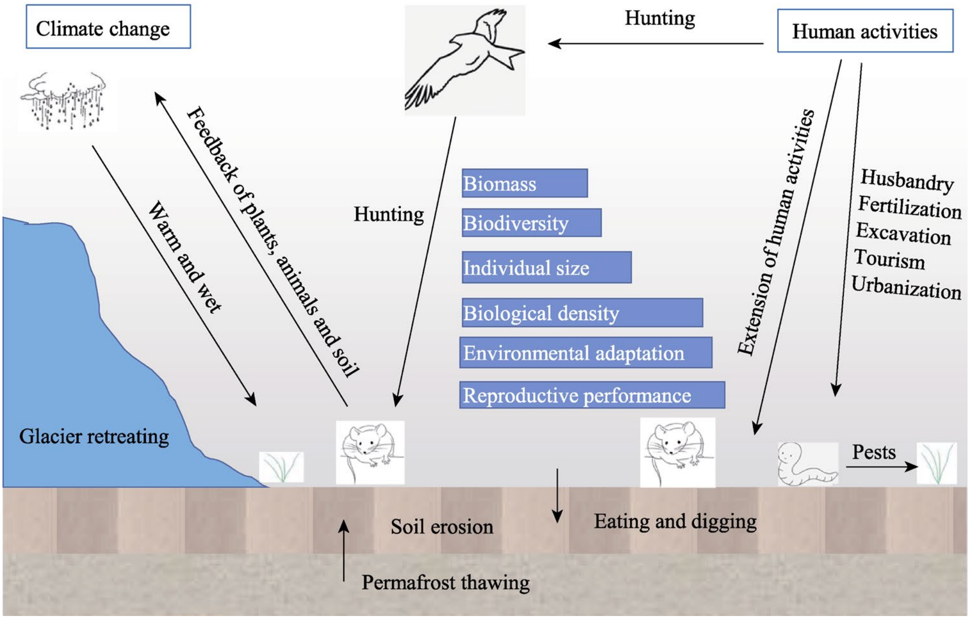

Figure 4 Coupled effect on pikas and pests

4.4 Coupled effect on *Cordyceps sinensis*

The coupled effect of CC and HA exerts a significant influence on the fungi/microbes in QTP grassland. An example is *Cordyceps sinensis*, a valuable medicine with a good reputation worldwide (Xu *et al*., 2019). Glacier retreat makes the snow line move up (Ke *et al*., 2017; Cao *et al*., 2017), and the *C. sinensis* produced near the snow line moves along the snow line (Li *et al*., 2014). To obtain high-quality *C. sinensis*, diggers dig at high altitudes, increasing the damage to the fragile environment. During the two-month digging period, diggers need to build fires for heating, cooking, and setting up tents. Service industries, such as supply stations, movie theaters, and hotels, are also available near the camps. Furthermore, new tools have resulted in increased vehicle crushing and oil burning waste and litter, which increase the temperature and CO_2 content and further aggravate the glacier retreat at high-altitude zones. Consequently, the snow line moves up further, and diggers need to constantly move their camps to even higher altitudes in the two months of digging. A vicious circle is therefore formed (Yan *et al*., 2019).

Furthermore, the excavation of *C. sinensis* has increased the amount of bare ground and the number of poisonous weeds on the surface, thus providing an enlarged habitat for the settlement of pikas and voles. The local people of QTP do not kill creatures because of their religious belief (Sangji, 2015), and this situation creates suitable conditions for the outbreak of rodents; rodent outbreaks destroy the grassland seriously (Danjiu, 2019).

Furthermore, the income obtained from digging for *C. sinensis* for two months is equivalent to the income from farming for one year. Therefore, excavators are unwilling to engage in agriculture and husbandry. The phenomenon of "abandoning agriculture and husbandry" has spread in these zones, thus affecting CC and HA (Fan, 2016; Danjiu, 2019) because excavation activities and husbandry are important to the changes in the alpine grassland ecosystem (Figure 5).

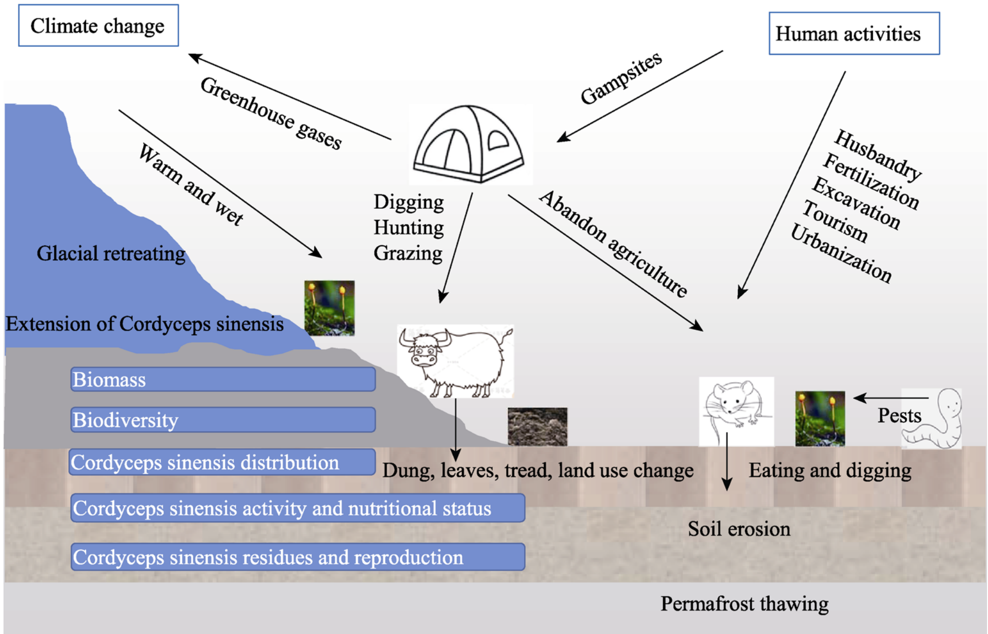

Figure 5 Coupled effect on *Cordyceps sinensis*

4.5 Dynamic adaptation to climate change and human activities

CC and HA cause grassland degradation and reduce the ecological service functions of the QTP grasslands; for example, they can change pasture growth, carbon sequestration, biodiversity, above-ground/underground biomass, vegetation coverage, soil physical/chemical properties, and seed banks (Hopping *et al.*, 2018b; Li *et al.*, 2020). Simultaneously, the participants in the QTP grasslands adapt to these changes dynamically by changing the community structure, diet structure, morphology, and distribution range. The grassland ecological environment also responds to CC and HA disturbance through soil nutrient loss, desertification, sandstorms, drought, downstream floods, poisonous weeds, rodents, and harmful gases, such as N_2O and CO_2 (Harris, 2010; Fayiah *et al.*, 2020; Guo *et al.*, 2020b). They are summarized in Table 4.

The invasion of woody plants has become a global problem in grasslands. Given that grassland degradation has become severe, resulting in reduced groundwater height and soil water retention, grasslands have changed to shrubs. Scientists predict that alpine meadows will gradually be replaced by shrubs, and the distribution area of alpine grasslands will expand and occupy the west and north areas in the warmer and wetter future (Adam *et al.*, 2020). Although the presence of woody plants in alpine hypoxia places is unsuitable at present (Zhang *et al.*, 2015a), the invasion of woody plants in QTP is still worthy of further research.

Table 4 Dynamic adaptation of Qinghai-Tibet Plateau's grassland ecology to climate change and human activities

Participants	Dynamic adaptation	References
Animals	Change the distribution range (e.g., *C. sinensis* distribution changes with the snow line)	Li *et al*., 2014
	Change the diet structure (e.g., the diet structure of caterpillars changes with altitude)	Zhang *et al*., 2016a
	Change the physical characteristics	Cao *et al*., 2016
Plants	Change the state of existence	Mccarthy and Enquist, 2007; Yuan *et al*., 2017
	Change the community structure (e.g., increase the number of poisonous weeds)	Li and Liu., 2017; Hao *et al*., 2020; Chu *et al*., 2019; Wen *et al*., 2020
	Phenology changes	Guo *et al*., 2020a
	Change the distribution range	Wang *et al*., 2016a
Soil	Change the physical state (e.g., water conservation)	Miehe *et al*., 2019; Guo *et al*., 2020b; Li *et al*., 2020
	Change the chemical properties (e.g., acidity and alkalinity)	Yang *et al*., 2017; Li *et al*., 2020
	Change the respiration rate	Chen *et al*., 2017; Qiao *et al*., 2015
Water	Change the physical state (e.g., glacier melting)	Jiang and Zhang, 2016; Jiang *et al*., 2017a; Hoham and Remias, 2020; Lei *et al*., 2012
Atmosphere	Changes in composition (e.g., CO_2 and N_2O)	Hu *et al*., 2017; Leng *et al*., 2020; Sun *et al*., 2020a; Zhao *et al*., 2017

5 Conclusion

5.1 Effect of climate change

CC is one of the main reasons for grassland restoration/degradation. Warm and wet climate conditions are the primary influencing factors. QTP has high spatial heterogeneity, and warm and wet conditions have different effects on different regions and times. The positive effects of warm and wet conditions are as follows: (1) enhanced photosynthesis of vegetation; (2) increased NPP; (3) expansion of the greening area; (4) increase in microbial activity; and (5) decrease in wind erosion and sandstorms. The negative effects of warm and wet conditions are as follows: (1) soil erosion is aggravated in over-humid areas; (2) evaporation intensifies in arid areas, resulting in soil water shortage; (3) the proportion of shrubs is increasing; (4) the interaction between pests is intensified; (5) the microorganisms in grasslands are inhibited because of the increasing adaptability of pests and pikas; (6) the warming in winter and spring causes a decrease in soil water use efficiency; and (7) extreme climate affects the physiological process of plants and creatures in the alpine grassland ecosystem.

5.2 Effect of human activities

HA is one of the main reasons for grassland restoration/degradation in QTP. The positive effects of HA are as follows: (1) moderate grazing is beneficial to grassland ecological health; (2) urbanization is conducive to population education and change in residents' diet structure and lifestyle; (3) restoration measures are effective; and (4) tourism is a new means to make a living, and it provides funds for local environmental protection. The negative effects of HA are as follows: (1) over-grazing, over-hunting, and over-digging are widespread; (2) urban construction, railway construction, mining, and tourism activities destroy the grassland ecosystem; and (3) grazing exclusion, fencing, grassland privatization, and nature reserves have certain drawbacks. In sum, apart from husbandry and agriculture, which have been widely studied, changes in lifestyle, economic growth patterns, and land use brought about by tourism and industries are new factors that deserve our attention.

5.3 Coupled effects of climate change and human activities

CC, HA, and grassland in QTP exert many coupled effects. First, SOC is significantly affected by the coupled effect of these factors. CC increases plant respiration, but HA decreases it. HA is affected and restricted by CC, and HA intensifies the change in CC and then changes SOC. Second, NPP is significantly affected by the coupled effects of CC and HA. CC enlarges the grassland area and increases NPP, and HA can offset the effect of CC on vegetation; in turn, changes in vegetation affect CC and HA again. Third, the population structure and environmental adaptability of creatures are changed under the coupled effect of CC and HA. Then changes in creatures affect HA and CC again. For example, *C. sinensis* growing along the snow line moves to a high altitude because of CC. Then, HA moves too, which increases CC again.

5.4 Dynamic adaptation to climate change and human activities

The grassland ecosystem mainly adapts to the coupled effects of CC and HA through the following: (1) changing the population structure; (2) changing the food structure; (3) changing the physical state; (4) changing the physical and chemical properties; (5) changing the distribution range; (6) causing outbreak of pests and poisonous weeds; (6) causing outbreaks of pikas; (7) desertification; (8) invasion of woody plants; and (9) changing the reproductive status.

6 Outlook

6.1 Comprehensive understanding of grassland degradation

Although the restoration/degradation of QTP grassland ecosystems has been extensively studied, no standard for degradation exists at present. Several scientists regard the reduction in soil nutrients and NPP in grasslands as the standard (Su *et al.*, 2015; Wang *et al.*, 2016c; Gu *et al.*, 2019). Meanwhile, other scientists view dominant populations, biomass, grass mass, caterpillars, animal caves, number of herders' camps, distance between camps, and time of fencing as degradation standards. Scientists obviously have different assessments of QTP grassland degradation. Several of them believe that the degradation of QTP grassland ecology has reached about 90%, 50%, and 30% (Dong and Sherman, 2015; Fayiah *et al.*, 2020). Thus, scientists suggest that apart from focusing on vegetation cover, biomass, and biodiversity, attention should also be paid to the characteristics of plant communities and ecosystem resilience (Cao *et al*., 2019). Presently, comprehensive evaluation of the degradation of QTP grassland is lacking. Thus, decision makers cannot formulate suitable strategies for the sustainable development of QTP grassland. Related studies should incorporate HA into the grassland ecosystem and conduct a comprehensive evaluation from the perspective of ecology in the future. Attention must be devoted to the ecological service function and the adaptation and feedback of soil, plants, animals, and humans in QTP grassland.

6.2 Comprehensive understanding of climate change

At present, studies on the impact of CC mainly focus on warming, glacier retreat, permafrost thawing, and hydration changes. Specifically, warming methods are used to obtain research results in many experiments. However, apart from overall warming, the definition of global warming also includes local cooling and increased frequency of extreme weather conditions. In recent years, a few scientists have used models to predict the impact of cooling on the QTP grassland ecosystem. Although the warm and wet phenomenon is already recognized as a CC trend, studies under cold conditions are also forward-looking, especially in the QTP area because QTP is characterized by widespread glaciers and permafrost, and warming makes glaciers melt. Then, the icy-cold water flows to low-altitude areas, bringing low-temperature water to QTP grassland and cooling the air and soil. Will it bring about cool zones in the background of increasing temperature?

Another feature of global warming is the exacerbation of climate extremes (He *et al*., 2016), such as snowstorms, thunderstorms, extremely cold and hot weather, extreme droughts, and floods. Relevant literature on the impact of extreme climate is still lacking, which inspires us to focus on the overall perspective of global change in the future.

6.3 Coupled relationship among climate change, human activities, and grassland ecology needs further discussion

Although we focused on the coupled relationship among CC, HA, and grassland ecology, our work is still at the phenomenon description stage and lacks a quantitative analysis. Therefore, a comprehensive evaluation is yet to be systematically summarized. We recommend using a certain species as a clue to explore the coupled impact of CC and HA and then expanding the results to populations and communities to establish the coupling relationship between them gradually.

Basing on the summary provided by this review, we advise future studies in this field to focus on the following aspects: (1) tracking the status of the QTP grassland restoration/degradation; (2) studying the impact of glacier retreat and permafrost thawing the QTP grassland under the coupled influence of CC and HA; (3) focusing on the adaptation and impact of pikas and pests on grassland ecology under the influence of CC and HA; (4) following the changes in the biological chain of the QTP grassland under the influence of CC and HA; (5) investigating the impact of extreme climate of the QTP grassland ecology; (6) exploring the development of ecotourism of the QTP; (7) solving the livelihood issues of herders in QTP; (8) evaluating the restoration measures implemented in QTP; and (9) investigating the grassland restoration technology in alpine regions.

References

Adam P S M, Enrique R V, Hoori A *et al.*, 2020. Woody plant encroachment has a larger impact than climate change on dry land water budgets. *Scientific Reports*, 10(1): 8112.

Bai L, Shi C X, Shi Q D *et al.*, 2019. Change in the spatiotemporal pattern of snowfall during the cold season under climate change in a snow-dominated region of China. *International Journal of Climatology*, 39(15): 5702–5719.

Cai H Y, Yang X H, Xu X L, 2015. Human-induced grassland degradation/restoration in the central Tibetan Plateau: The effects of ecological protection and restoration projects. *Ecological Engineering*, 83: 112–119.

Cao H, Zhao X Q, Wang S P *et al.*, 2015. Grazing intensifies degradation of a Tibetan Plateau alpine meadow through plant-pest interaction. *Ecology and Evolution*, 5(12): 2478–2486.

Cao H, Zhu W Y, Zhao X Q, 2016. Effects of warming and grazing on growth and development of grassland caterpillar (*Gynaephora menyuanensis*). *Acta Prataculturae Sinica*, 25(1): 268–272. (in Chinese)

Cao J, Holden N M, Lü X T *et al.*, 2011. The effect of grazing management on plant species richness on the Qinghai-Tibetan Plateau. *Grass and Forage Science*, 66(3): 333–336.

Cao J J, Adamowski J F, Deo R C *et al.*, 2019. Grassland degradation on the Qinghai-Tibetan Plateau: Reevaluation of causative factors. *Rangeland Ecology and Management*, 72(6): 988–995.

Cao J J, Holden N M, Adamowski J F *et al.*, 2018a. Can individual land ownership reduce grassland degradation and favor socioeconomic sustainability on the Qinghai-Tibetan Plateau? *Environmental Science and Policy*, 89: 192–197.

Cao J J, Wang X Y, Li M T *et al.*, 2018b. Effects of grassland management on soil nutrients and their spatial distribution on the Qinghai-Tibet Plateau, China. *Chinese Journal of Applied Ecology*, 29(6): 1839–1845. (in Chinese)

Cao J J, Xu X Y, Deo R C *et al.*, 2018c. Multi-household grazing management pattern maintains better soil fertility. *Agronomy for Sustainable Development*, 38(1): 6.

Cao W, Sheng Y, Wu J C *et al.*, 2017. Spatial variability and its main controlling factors of the permafrost soil-moisture on the northern-slope of Bayan Har Mountains in Qinghai-Tibet Plateau. *Journal of Mountain Science*, 14(12): 2406–2419.

Che R X, Deng Y C, Wang W J *et al.*, 2018. Long-term warming rather than grazing significantly changed total and active soil procaryotic community structures. *Geoderma*, 316: 1–10.

Chen H, Zhu Q, Peng C H *et al.*, 2013. The impacts of climate change and human activities on biogeochemical cycles on the Qinghai-Tibetan Plateau. *Global Change Biology*, 19(10): 2940–2955.

Chen H Y, Zhu T, 2015. The dilemma of property rights and indigenous institutional arrangements for common resources governance in China. *Land Use Policy*, 42: 800–805.

Chen J, Zhou X H, Wang J F *et al.*, 2016a. Grazing exclusion reduced soil respiration but increased its temperature sensitivity in a meadow grassland on the Tibetan Plateau. *Ecology and Evolution*, 6(3): 675–687.

Chen J J, 2020. Research on change of fractional vegetation cover of alpine grassland and its environmental impact factors of Qinghai-Tibet Plateau. *Acta Geodaetica et Cartographica Sinica*, 49(4): 533. (in Chinese)

Chen K L, Yu X C, Yao B Q *et al.*, 2016b. Spatial distribution of Menyuan grassland caterpillars on alpine meadows under different grazing intensities. *Acta Agrestia Sinica*, 24(1): 191–197. (in Chinese)

Chen Q Y, Niu B, Hu Y L *et al.*, 2020a. Warming and increased precipitation indirectly affect the composition and turnover of labile-fraction soil organic matter by directly affecting vegetation and microorganisms. *Science of the Total Environment*, 714: 136787.

Chen T D, Jiao J Y, Wang H L *et al.*, 2020b. Progress in research on soil erosion in Qinghai-Tibet Plateau. *Acta Pedologica Sinica*, 57(3): 547–564. (in Chinese)

Chen X P, Wang G X, Huang K W *et al.*, 2017. The effect of nitrogen deposition rather than warming on carbon flux in alpine meadows depends on precipitation variations. *Ecological Engineering*, 107: 183–191.

Chen X Q, An S, Inouye D W *et al.*, 2015. Temperature and snowfall trigger alpine vegetation green-up on the world's roof. *Global Change Biology*, 21(10): 3635–3646.

Chi X X, Yin Z E, Wang X *et al*., 2016. Spatiotemporal variations of precipitation extremes of China during the past 50 years (1960–2009). *Theoretical and Applied Climatology*, 124(3/4): 555–564.

Chu H, Zhang C P, Dong Q M *et al*., 2019. The effect of grazing intensity and season on the soil seed bank and its relation with above-ground vegetation on the alpine steppe. *Agriculture*, *Ecosystems and Environment*, 285: 106622.

Cong N, Shen M G, Yang W *et al*., 2017. Varying responses of vegetation activity to climate changes on the Tibetan Plateau grassland. *International Journal of Biometeorology*, 61(8): 1433–1444.

Cui S, Zhu X, Wang S *et al*., 2014. Effects of seasonal grazing on soil respiration in alpine meadow on the Tibetan Plateau. *Soil Use and Management*, 30(3): 435–443.

Cui Y N, Li S W, Yu C Q *et al*., 2017. Effects of award-allowance payment policy for natural grassland conservation on income of farmer and herdsman families in Tibet. *Acta Prataculturae Sinica*, 26(3): 22-32. (in Chinese)

Danjiu L B, 2019. The negative effects of *cordyceps sinensis* excavation and development countermeasures. *Modern Agricultural Science and Technology*, (13): 91–92. (in Chinese)

Ding J X, Chen K L, Cui H *et al*., 2019a. Disturbance of *Ochotona curzoniae* on soil respiration in alpine marsh meadow plateau. *Ecological Science*, 38(6): 1–7. (in Chinese)

Ding X L, Chen S Y, Zhang B *et al*., 2019b. Warming increases microbial residue contribution to soil organic carbon in an alpine meadow. *Soil Biology and Biochemistry*, 135: 13–19.

Ding X T, Wang J H, 2018. Effects of the opening of the Qinghai-Tibet Railway on municipal solid waste management generation in Lhasa. *Waste Management and Research*, 36(3): 300–306.

Doetterl S, Stevens A, Six J *et al*., 2015. Soil carbon storage controlled by interactions between geochemistry and climate. *Nature Geoscience*, 8(10): 780–783.

Dong Q M, Zhao X Q, Wu G L *et al*., 2013. A review of formation mechanism and restoration measures of "black-soil-type" degraded grassland in the Qinghai-Tibetan Plateau. *Environmental Earth Sciences*, 70(5): 2359–2370.

Dong S K, Shang Z H, Gao J X *et al*., 2020. Enhancing sustainability of grassland ecosystems through ecological restoration and grazing management in an era of climate change on Qinghai-Tibetan Plateau. *Agriculture*, *Ecosystems and Environment*, 287: 106684.

Dong S K, Sherman R, 2015. Enhancing the resilience of coupled human and natural systems of alpine rangelands on the Qinghai-Tibetan Plateau. *Rangeland Journal*, 37(1): i–iii.

Dorji T, Hopping K A, Wang S *et al*., 2018. Grazing and spring snow counteract the effects of warming on an alpine plant community in Tibet through effects on the dominant species. *Agricultural and Forest Meteorology*, 263: 188–197.

Fan C F, 2016. Economic formation and cultural changes of *Cordyceps sinensis* in Qinghai-Tibet Area. *Folklore Studies*, (1): 118–128. (in Chinese)

Fassnacht F E, Li L, Fritz A, 2015. Mapping degraded grassland on the eastern Tibetan Plateau with multi-temporal Landsat 8 data: Where do the severely degraded areas occur? *International Journal of Applied Earth Observation and Geoinformation*, 42: 115–127.

Fayiah M, Dong S K, Khomera S W *et al*., 2020. Status and challenges of Qinghai-Tibet Plateau's grasslands: An analysis of causes, mitigation measures, and way forward. *Sustainability*, 12(3): 1099.

Fu G, Zhang X Z, Zhang Y J *et al*., 2013. Experimental warming does not enhance gross primary production and above-ground biomass in the alpine meadow of Tibet. *Journal of Applied Remote Sensing*, 7(1): 073505.

Fu M D, Tian J L, Ren Y H *et al*., 2019. Functional zoning and space management of Three-River-Source National Park. *Journal of Geographical Sciences*, 29(12): 2069–2084.

Gao J B, Jiao K W, Wu S H, 2019. Investigating the spatially heterogeneous relationships between climate factors and NDVI in China during 1982 to 2013. *Journal of Geographical Sciences*, 29(10): 1597–1609.

Gong J, Li J Y, Yang J X *et al*., 2017. Land use and land cover change in the Qinghai Lake region of the Tibetan

Plateau and its impact on ecosystem services. *International Journal of Environmental Research and Public Health*, 14(7): 818.

Gu X Y, Zhou X Q, Bu X L *et al.*, 2019. Soil extractable organic C and N contents, methanotrophic activity under warming and degradation in a Tibetan alpine meadow. *Agriculture*, *Ecosystems and Environment*, 278: 6–14.

Guan S, An N, Zong N *et al.*, 2018. Climate warming impacts on soil organic carbon fractions and aggregate stability in a Tibetan alpine meadow. *Soil Biology and Biochemistry*, 116: 224–236.

Guo Bing, Zang W Q, Yang F *et al.*, 2020a. Spatial and temporal change patterns of net primary productivity and its response to climate change in the Qinghai-Tibet Plateau of China from 2000 to 2015. *Journal of Arid Land*, 12(1): 1–17.

Guo L, Chen J, Luedeling E *et al.*, 2018a. Early-spring soil warming partially offsets the enhancement of alpine grassland aboveground productivity induced by warmer growing seasons on the Qinghai-Tibetan Plateau. *Plant and Soil*, 425(1/2): 177–188.

Guo N, Wang A D, Degen A A *et al.*, 2018b. Grazing exclusion increases soil CO_2 emission during the growing season in alpine meadows on the Tibetan Plateau. *Atmospheric Environment*, 174: 92–98.

Guo X W, Dai L C, Li Q *et al.*, 2020b. Light grazing significantly reduces soil water storage in alpine grasslands on the Qinghai-Tibet Plateau. *Sustainability*, 12(6): 2523.

Han H B, Zhou B Y, Yan Y Q *et al.*, 2019. Analysis of vegetation coverage and its driving factors over Tibetan Plateau from 2000 to 2018. *Acta Agrestia Sinica*, 27(6): 1651–1658. (in Chinese)

Han Z, Song W, Deng X Z, 2016. Responses of ecosystem service to land use change in Qinghai Province. *Energies*, 9(4): 303.

Hao A H, Xue X, Peng F *et al.*, 2020. Different vegetation and soil degradation characteristics of a typical grassland in Qinghai-Tibet Plateau. *Acta Ecologica Sinica*, 40(3): 964–675. (in Chinese)

Harris R B, 2010. Rangeland degradation on the Qinghai-Tibetan Plateau: A review of the evidence of its magnitude and causes. *Journal of Arid Environments*, 74(1): 1–12.

Harris R B, Samberg L H, Yeh E T *et al.*, 2016. Rangeland responses to pastoralists' grazing management on a Tibetan steppe grassland, Qinghai Province, China. *Rangeland Journal*, 38(1): 1–15.

He S Y, Richards K, 2017. Kobresia meadow degradation and its impact on water status. *Ecohydrology*, 10(6): e1844.

He S Y, Richards K, Zhao Z Q, 2016. Climate extremes in the Kobresia meadow area of the Qinghai-Tibetan Plateau, 1961–2008. *Environmental Earth Sciences*, 75(1): 1–15.

Hoham R W, Remias D, 2020. Snow and glacial algae: A review. *Journal of Phycology*, 56(2): 264–282.

Hopping K A, Knapp A K, Dorji T *et al.*, 2018a. Warming and land use change concurrently erode ecosystem services in Tibet. *Global Change Biology*, 24(11): 5534–5548.

Hopping K A, Yangzong C, Klein J A, 2016. Local knowledge production, transmission, and the importance of village leaders in a network of Tibetan pastoralists coping with environmental change. *Ecology and Society*, 21(1): 25.

Hopping K A, Yeh E T, Gaerrang *et al.*, 2018b. Linking people, pixels, and pastures: A multi-method, interdisciplinary investigation of how range land management affects vegetation on the Tibetan Plateau. *Applied Geography*, 94: 147–162.

Hu X, Li X Y, Li Z C *et al.*, 2020. 3-D soil macropore networks derived from X-ray tomography in an alpine meadow disturbed by plateau pikas in the Qinghai Lake watershed, north-eastern Qinghai-Tibetan Plateau. *Journal of Soils and Sediments*, 20(4): 2181–2191.

Hu Y G, Zhang Z H, Wang Q *et al.*, 2017. Variations of N_2O fluxes in response to warming and cooling in an alpine meadow on the Tibetan Plateau. *Climatic Change*, 143(1/2): 129–142.

Huang L, Cao W, Xu X L *et al.*, 2017. The ecological effects of ecological security barrier protection and construction project in Tibet Plateau. *Journal of Natural Resources*, 33(3): 398–411. (in Chinese)

Jiang C, Li D Q, Gao Y N *et al.*, 2017a. Impact of climate variability and anthropogenic activity on streamflow in the Three Rivers Headwater region, Tibetan Plateau, China. *Theoretical and Applied Climatology*, 129(1/2):

667–681.

Jiang C, Zhang L B, 2016. Effect of ecological restoration and climate change on ecosystems: A case study in the Three-Rivers headwater region, China. *Environmental Monitoring and Assessment*, 188(6): 382.

Jiang F, Li G Y, Qin W *et al*., 2019. Setting priority conservation areas of wild Tibetan gazelle (*Procapra picticaudata*) in China's first national park. *Global Ecology and Conservation*, 20: e00725.

Jiang L L, Wang S P, Zhe P *et al*., 2017b. Effects of grazing on the acquisition of nitrogen by plants and microorganisms in an alpine grassland on the Tibetan Plateau. *Plant and Soil*, 416(1/2): 297–308.

Ke L H, Ding X, Li W K *et al*., 2017. Remote sensing of glacier change in the central Qinghai-Tibet Plateau and the relationship with changing climate. *Remote Sensing*, 9(2): 114.

Le C, Ikazaki K, Siriguleng *et al*., 2014. Grassland degradation caused by tourism activities in Hulunbuir, Inner Mongolia, China. *IOP Conference Series*: *Earth and Environmental Science*, 18(1): 012137.

Lei L P, Zeng Z C, Zhang B, 2012. Method for detecting snow lines from MODIS data and assessment of changes in the Nianqingtanglha Mountains of the Tibet Plateau. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 5(3): 769–776.

Leng R, Yuan Q Z, Wang Y S *et al*., 2020. Carbon balance of grasslands on the Qinghai-Tibet Plateau under future climate change: A review. *Sustainability*, 12(2): 533.

Li F, Wu Z, Xu C *et al*., 2014. The spatial distribution of cordyceps resources suitability in the source region of three rivers. *Acta Ecologica Sinica*, 34(5): 1318–1325. (in Chinese)

Li G R, Li X L, Chen W T *et al*., 2020. Effects of degradation severity on the physical, chemical and mechanical properties of topsoil in alpine meadow on the Qinghai-Tibet Plateau, west China. *Catena*, 187: 104370.

Li J C, Wang Y, Zhang L S *et al*., 2019a. Aeolian desertification in China's northeastern Tibetan Plateau: Understanding the present through the past. *Catena*, 172: 764–769.

Li J R, Liu Z H, 2017. High-cold meadow plants respond to long-term warming. *Qinghai Prataculture*, 26(3): 18–24. (in Chinese)

Li L H, Zhang Y L, Wu J S *et al*., 2019b. Increasing sensitivity of alpine grasslands to climate variability along an elevational gradient on the Qinghai-Tibet Plateau. *Science of the Total Environment*, 678: 21–29.

Li S C, Wang Z F, Zhang Y L, 2017. Crop cover reconstruction and its effects on sediment retention in the Tibetan Plateau for 1900–2000. *Journal of Geographical Sciences*, 27(7): 786–800.

Li W, Wang J L, Zhang X J *et al*., 2018a. Effect of degradation and rebuilding of artificial grasslands on soil respiration and carbon and nitrogen pools on an alpine meadow of the Qinghai-Tibetan Plateau. *Ecological Engineering*, 111: 134–142.

Li X L, Perry G LW, Brierley G J, 2018b. A spatial simulation model to assess controls upon grassland degradation on the Qinghai-Tibet Plateau, China. *Applied Geography*, 98: 166–176.

Li X M, Peng Y L, Yue J, 2019c. Ecological management of degraded alpine pasture areas under the development of tourism industry. *Pratacultural Science*, 36(5): 1435–1444. (in Chinese)

Li Y, Li J J, Are K S *et al*., 2019d. Livestock grazing significantly accelerates soil erosion more than climate change in Qinghai-Tibet Plateau: Evidenced from 137Cs and 210Pbex measurements. *Agriculture*, *Ecosystems and Environment*, 285: 106643.

Liu B L, Guo K, Li C *et al*., 2020. Copper prospectively in Tibet, China: Based on the identification of geochemical anomalies. *Ore Geology Reviews*, 120: 102632.

Liu S B, Zamanian K, Schleuss P M *et al*., 2018. Degradation of Tibetan grasslands: Consequences for carbon and nutrient cycles. *Agriculture*, *Ecosystems and Environment*, 252: 93–104.

Lu F, Hu H F, Sun W J *et al*., 2018. Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. *PNAS*, 115(16): 4039–4044.

Lu Q S, Ning J C, Liang F Y *et al*., 2017a. Evaluating the effects of government policy and drought from 1984 to 2009 on rangeland in the Three Rivers Source Region of the Qinghai-Tibet Plateau. *Sustainability*, 9(6): 1033.

Lu X Y, Kelsey K C, Yan Y *et al*., 2017b. Effects of grazing on ecosystem structure and function of alpine grasslands in Qinghai-Tibetan Plateau: A synthesis. *Ecosphere*, 8(1): e01656.

Luo L H, Duan Q T, Wang L X *et al.*, 2020. Increased human pressures on the alpine ecosystem along the Qinghai-Tibet Railway. *Regional Environmental Change*, 20(1): 33.

Mao D H, Luo L, Wang Z M *et al.*, 2015. Variations in net primary productivity and its relationships with warming climate in the permafrost zone of the Tibetan Plateau. *Journal of Geographical Sciences*, 25(8): 967–977.

Mccarthy M C, Enquist B J, 2007. Consistency between an allometric approach and optimal partitioning theory in global patterns of plant biomass allocation. *Functional Ecology*, 21(4): 713–720.

Miehe G, Schleuss P M, Seeber E *et al.*, 2019. The *Kobresia pygmaea* ecosystem of the Tibetan highlands: Origin, functioning and degradation of the world's largest pastoral alpine ecosystem–Kobresia pastures of Tibet. *Science of the Total Environment*, 648: 754–771.

Mo X G, 2020. Grassland productivity on the Qinghai-Tibetan Plateau since 1980. *National Tibetan Plateau Data Center*. doi: 10.11888/Ecolo.tpdc.270430.

Mu C C, Abbott B W, Zhao Q *et al.*, 2017. Permafrost collapse shifts alpine tundra to a carbon source but reduces N_2O and CH_4 release on the northern Qinghai-Tibetan Plateau. *Geophysical Research Letters*, 44(17): 8945–8952.

Mu J P, Zeng Y L, Wu Q G *et al.*, 2016. Traditional grazing regimes promote biodiversity and increase nectar production in Tibetan alpine meadows. *Agriculture*, *Ecosystems and Environment*, 233: 336–342.

Pan T, Zou X T, Liu Y J *et al.*, 2017. Contributions of climatic and non-climatic drivers to grassland variations on the Tibetan Plateau. *Ecological Engineering*, 108: 307–317.

Qian D W, Yan C Z, Xiu L N *et al.*, 2018. The impact of mining changes on surrounding lands and ecosystem service value in the southern slope of Qilian Mountains. *Ecological Complexity*, 36: 138–148.

Qiao N, Xu X L, Cao G M *et al.*, 2015. Land use change decreases soil carbon stocks in Tibetan grasslands. *Plant and Soil*, 395(1/2): 231–241.

Qiu J, 2008. China: The third pole. *Nature*, 454: 393–396.

Sangji Z X, 2015. Tibetan Buddhism's customs of releasing and protecting lives and environmental protection concepts. *The Voice of Dharma*, (4): 18–23. (in Chinese)

Schuur E A G, McGuire A D, Schädel C *et al.*, 2015. Climate change and the permafrost carbon feedback. *Nature*, 520(7546): 171–179.

Shang W, Zhao L, Wu X D *et al.*, 2015. Soil organic matter fractions under different vegetation types in permafrost regions along the Qinghai-Tibet Highway, north of Kunlun Mountains, China. *Journal of Mountain Science*, 12(4): 1010–1024.

Shao Q Q, Cao W, Fan J W *et al.*, 2017. Effects of an ecological conservation and restoration project in the Three-River Source region, China. *Journal of Geographical Sciences*, 27(2): 183–204.

Shen H, Dong S K, Li S *et al.*, 2019. Grazing enhances plant photosynthetic capacity by altering soil nitrogen in alpine grasslands on the Qinghai-Tibetan Plateau. *Agriculture*, *Ecosystems and Environment*, 280: 161–168.

Shrestha U B, Bawa K S, 2014. Economic contribution of Chinese caterpillar fungus to the livelihoods of mountain communities in Nepal. *Biological Conservation*, 177: 194–202.

Su X K, Wu Y, Dong S K *et al.*, 2015. Effects of grassland degradation and re-vegetation on carbon and nitrogen storage in the soils of the Headwater Area Nature Reserve on the Qinghai-Tibetan Plateau, China. *Journal of Mountain Science*, 12(3): 582–591.

Sun F, Chen W, Liu L *et al.*, 2015. The density of active burrows of plateau pika in relation to biomass allocation in the alpine meadow ecosystems of the Tibetan Plateau. *Biochemical Systematics and Ecology*, 58: 257–264.

Sun S W, Kang S C, Zhang Q G *et al.*, 2020a. Study on mercury in the cryosphere of the Qinghai-Tibet Plateau and its environmental significance. *Chinese Journal of Nature*, 42(5): 364–372. (in Chinese)

Sun X M, Wang C Q, Dong L L *et al.*, 2020b. Research on planting area and industrial development strategy of Tibetan medicine, China. *Journal of Chinese Materia Medica*, 45(11): 2708–2713. (in Chinese)

Tian F, Cheng Y X, Zhou G L *et al.*, 2019. Relations of density of pika burrows with plant community structure and soil in alpine meadow on the eastern Qinghai-Tibetan Plateau. *Pratacultural Science*, 36(4): 1094–1104. (in Chinese)

Walt L V D, Cilliers S S, Kellner K *et al*., 2015. To what extent does urbanization affect fragmented grassland functioning? *Journal of Environmental Management*, 151: 517–530.

Wang D B, Ji C T, Lin H L, 2019a. A DNDC model evaluation of alpine meadow soil carbon response to climate change. *Acta Prataculturae Sinica*, 28(12): 197–204. (in Chinese)

Wang J, Wang Y, Li S C *et al*., 2016a. Climate adaptation, institutional change, and sustainable livelihoods of herder communities in northern Tibet. *Ecology and Society*, 21(1): 5.

Wang L, Yu H Y, Zhang Q *et al*., 2018a. Response of aboveground biomass of alpine grassland to climate changes on the Qinghai-Tibet Plateau. *Journal of Geographical Sciences*, 28(12): 1953–1964.

Wang S J, Wei Y Q, Fang M, 2014. Integrated risk assessment of snow disaster in the Three Rivers Source Region, China. *Acta Prataculturae Sinica*, 23(2): 108–116. (in Chinese)

Wang S J, Zhou L Y, Wei Y Q, 2019b. Integrated risk assessment of snow disaster over the Qinghai-Tibet Plateau. *Geomatics*, *Natural Hazards and Risk*, 10(1): 740–757.

Wang X M, Ma W Y, Lang L L *et al*., 2015. Controls on desertification during the early twenty-first century in the water tower region of China. *Regional Environmental Change*, 15(4): 735–746.

Wang X Y, Yi S H, Wu Q B *et al*., 2016b. The role of permafrost and soil water in distribution of alpine grassland and its NDVI dynamics on the Qinghai-Tibetan Plateau. *Global and Planetary Change*, 147: 40–53.

Wang Y X, Sun Y, Wang Z F *et al*., 2018b. Grazing management options for restoration of alpine grasslands on the Qinghai-Tibet Plateau. *Ecosphere*, 9(11): e02515.

Wang Z Q, Zhang Y Z, Yang Y *et al*., 2016c. Quantitative assess the driving forces on the grassland degradation in the Qinghai-Tibet Plateau, in China. *Ecological Informatics*, 33: 32–44.

Wen J, Qin R M, Zhang S X *et al*., 2020. Effects of long-term warming on the aboveground biomass and species diversity in an alpine meadow on the Qinghai-Tibetan Plateau of China. *Journal of Arid Land*, 12(2): 252–266.

Wu J S, Li M, Fiedler S *et al*., 2019. Impacts of grazing exclusion on productivity partitioning along regional plant diversity and climatic gradients in Tibetan alpine grasslands. *Journal of Environmental Management*, 231: 635–645.

Wu S S, Yao Z J, Huang H Q *et al*., 2012. Responses of glaciers and glacial lakes to climate variation between 1975 and 2005 in the Rongxer basin of Tibet, China and Nepal. *Regional Environmental Change*, 12(4): 887–898.

Wu X D, Zhao L, Hu G J *et al*., 2018. Permafrost and land cover as controlling factors for light fraction organic matter on the southern Qinghai-Tibetan Plateau. *Science of the Total Environment*, 613: 1165–1174.

Xiong Q L, Xiao Y, Halmy M W A *et al*., 2019. Monitoring the impact of climate change and human activities on grassland vegetation dynamics in the northeastern Qinghai-Tibet Plateau of China during 2000-2015. *Journal of Arid Land*, 11(5): 637–651.

Xu M, Xu M, Li R Q, 2019. Progress of several crucial aspects in the biological and ecological research on the Chinese caterpillar fungus, ophiocordyceps sinensis. *Acta Ecologica Sinica*, 39(5): 1853–1862. (in Chinese)

Xu Y D, Li F, Xu C *et al*., 2015. Quantitative assessment of the ecological impact of Chinese Cordyceps collection in the typical production areas. *Ecoscience*, 22(2–4): 167–175.

Yan J, Danjiu L B, Ci D *et al*., 2019. Thoughts on degradation and restoration of grassland in the producing area of cordyceps sinensis in Nagqu, Tibet. *Hubei Journal of Animal and Veterinary Sciences*, 40(4): 37–40. (in Chinese)

Yang L, Liu M C, Min Q W, 2019. Natural disasters, public policies, family characteristics, or livelihood assets? The driving factors of farmers' livelihood strategy choices in a nature reserve. *Sustainability*, 11(19): 5423.

Yang X Y, Lin L, Li Y *et al*., 2017. Effects of warming and altered precipitation on soil physical properties and carbon pools in a Tibetan alpine grassland. *Acta Scientiarum Naturalium Universitatis Pekinensis*, 53(4): 765–774. (in Chinese)

Yeh E T, Samberg L H, Gaerrang *et al*., 2017. Pastoralist decision-making on the Tibetan Plateau. *Human Ecology*, 45(3): 333–343.

You Q G, Xue X, Peng F *et al*., 2017. Surface water and heat exchange comparison between alpine meadow and bare land in a permafrost region of the Tibetan Plateau. *Agricultural and Forest Meteorology*, 232: 48–65.

Yu C Y, Pang X P, Wang Q *et al.*, 2017. Soil nutrient changes induced by the presence and intensity of plateau pika (*Ochotona curzoniae*) disturbances in the Qinghai-Tibet Plateau, China. *Ecological Engineering*, 106: 1–9.

Yu H Y, Luedeling E K, Xu J C *et al.*, 2010. Winter and spring warming result in delayed spring phenology on the Tibetan Plateau. *PNAS*, 107(51): 22151–22156.

Yuan L M, Zhao L, Li R *et al.*, 2020. Spatiotemporal characteristics of hydrothermal processes of the active layer on the central and northern Qinghai-Tibet Plateau. *Science of the Total Environment*, 712: 136392.

Yuan Q Z, Wu S H, Dai E F *et al.*, 2017. NPP vulnerability of the potential vegetation of China to climate change in the past and future. *Journal of Geographical Sciences*, 27(2): 131–142.

Zeng C X, Wu J S, Zhang X, 2015. Effects of grazing on above- vs. below-ground biomass allocation of alpine grasslands on the northern Tibetan Plateau. *PLOS ONE*, 10(8): e0135173.

Zhang H, Shao X M, Zhang Y, 2015a. Which climate factors limit the radial growth of Qilian Juniper, the upper limit of the forest in the northeastern part of the Qinghai-Tibet Plateau? *Journal of Geographical Sciences*, 25(10): 1173–1182.

Zhang Q L, Yuan M L, 2013. Research status and prospect of grassland caterpillars (lepidoptera: lymantriidae). *Pratacultural Science*, 30(4): 638–646. (in Chinese)

Zhang R H, Su F G, Jiang Z J *et al.*, 2015b. An overview of projected climate and environmental changes across the Tibetan Plateau in the 21st century. *Chinese Science Bulletin*, 60(32): 3036–3047. (in Chinese)

Zhang W J, Zhang F, Qi J G *et al.*, 2017. Modeling impacts of climate change and grazing effects on plant biomass and soil organic carbon in the Qinghai-Tibetan grasslands. *Biogeosciences*, 14(23): 5455–5470.

Zhang X Z, Yang Y P, Piao S L *et al.*, 2015c. Ecological change in the Tibetan Plateau. *Chinese Science Bulletin*, 60(32): 3048–3056. (in Chinese)

Zhang Y, Dong S K, Gao Q Z *et al.*, 2016a. Climate change and human activities altered the diversity and composition of soil microbial community in alpine grasslands of the Qinghai-Tibetan Plateau. *Science of the Total Environment*, 562: 353–363.

Zhang Y, Gao Q Z, Dong S K *et al.*, 2015d. Effects of grazing and climate warming on plant diversity, productivity and living state in the alpine rangelands and cultivated grasslands of the Qinghai-Tibetan Plateau. *Rangeland Journal*, 37(1): 57–65.

Zhang Y L, Hu Z J, Qi W *et al.*, 2016b. Analysis of protection effectiveness of Qinghai-Tibet Plateau nature reserves based on NPP data and sample area comparison method. *Journal of Geographical Sciences*, 26(1): 27–44.

Zhang Y L, Qi W, Zhou C P *et al.*, 2014. Spatial and temporal variability in the net primary production of alpine grassland on the Tibetan Plateau. *Journal of Geographical Sciences*, 24(2): 269–287.

Zhao J, Chen Y, Han Y, 1995. Physical Geography of China. Beijing: Higher Education Press. (in Chinese)

Zhao X H, Deng H Z, Wang W K *et al.*, 2017. Impact of naturally leaking carbon dioxide on soil properties and ecosystems in the Qinghai-Tibet Plateau. *Scientific Reports*, 7: 3001.

Zhao X Q, Zhao L, Xu T W *et al.*, 2020. The plateau pika has multiple benefits for alpine grassland ecosystem in Qinghai-Tibet Plateau. *Ecosystem Health and Sustainability*, 6(1): 1463–1465.

Zheng Z T, Zhu W Q, Zhang Y J, 2020. Seasonally and spatially varied controls of climatic factors on net primary productivity in alpine grasslands on the Tibetan Plateau. *Global Ecology and Conservation*, 21: e00814.

Zong N, Chai X, Shi P L *et al.*, 2016. Responses of plant community structure and species composition to warming and N addition in an alpine meadow, northern Tibetan Plateau, China. *Chinese Journal of Applied Ecology*, 27(12): 3739–3748.