Dynamic response and adaptation of grassland ecosystems in the Three-River Headwaters Region under changing environment: a review

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Abstract

The Three-Rivers Headwaters Region (TRHR) is crucial to the sustainable development of China and Southeast Asian countries. For various reasons, the sustainability of grassland ecosystems in the region has been seriously challenged. This paper reviews remote sensing-based monitoring and simulation of TRHR grassland ecosystems; quantitative assessment of grassland degradation and its ecological effects; driving factors and mechanisms of grassland degradation; grassland conservation policies and restoration for degraded grassland. The review shows that although TRHR alpine grassland coverage and above-ground biomass of alpine grassland (AG-AGB) have generally increased over the past 30 years, the degradation has not been fundamentally curbed. Grassland degradation significantly reduced the surface soil nutrients and affected their distribution, and also aggravated soil erosion and deteriorated soil moisture conditions. Grassland degradation leads to loss of productivity and species diversity. Its adverse impact on production will reduce the well-being of pastoralists. The "warm and wet" trend of the TRHR climate promotes the restoration of alpine grasslands, but the widespread overgrazing is considered to be the main reason for grassland degradation. However, the two have very complex impacts on grassland, and further research is needed. Since 2000, the TRHR grassland restoration policy has achieved great results, but the formulation of the policy still needs to effectively integrate the market logic and strengthen the understanding of the relationship between ecological protection and cultural protection. In addition, appropriate human intervention mechanisms are urgently needed for the uncertainty of future climate change. It is recommended to implement technologies such as rodent control, light grazing, enclosure, weeding, and fertilization to restore slightly and moderately degraded grasslands. However, for the severely degraded "black soil beach", it needs to be restored by artificial seeding, and the stability of the plant-soil system needs to be emphasized to establish a relatively stable community to prevent secondary degradation.

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Abstract

The Three-Rivers Headwaters Region (TRHR) is crucial to the sustainable development of China and Southeast Asian countries. For various reasons, the sustainability of grassland ecosystems in the region has been seriously challenged. This paper reviews remote sensing-based monitoring and simulation of TRHR grassland ecosystems; quantitative assessment of grassland degradation and its ecological effects; driving factors and mechanisms of grassland degradation; grassland conservation policies and restoration for degraded grassland. The review shows that although TRHR alpine grassland coverage and above-ground biomass of alpine grassland (AG-AGB) have generally increased over the past 30 years, the degradation has not been fundamentally curbed. Grassland degradation significantly reduced the surface soil nutrients and affected their distribution, and also aggravated soil erosion and deteriorated soil moisture conditions. Grassland degradation leads to loss of productivity and species diversity. Its adverse impact on production will reduce the well-being of pastoralists. The "warm and wet" trend of the TRHR climate promotes the restoration of alpine grasslands, but the widespread overgrazing is considered to be the main reason for grassland degradation. However, the two have very complex impacts on grassland, and further research is needed. Since 2000, the TRHR grassland restoration policy has achieved great results, but the formulation of the policy still needs to effectively integrate the market logic and strengthen the understanding of the relationship between ecological protection and cultural protection. In addition, appropriate human intervention mechanisms are urgently needed for the uncertainty of future climate change. It is recommended to implement technologies such as rodent control, light grazing, enclosure, weeding, and fertilization to restore slightly and moderately degraded grasslands. However, for the severely degraded "black soil beach", it needs to be restored by artificial seeding, and the stability of the plant-soil system needs to be emphasized to establish a relatively stable community to prevent secondary degradation.

Keywords: Three-River Headwaters Region; Climate Change; Grassland degradation and restoration; Sustainable grazing

1 Introduction

The three-river headwaters region (TRHR) is the source of the Yangtze River, Yellow River and Lancang River. Located in the southern part of Qinghai Province, it is a veritable "Chinese Water Tower" (Figure 1). It is one of the most sensitive and fragile ecosystems, and is crucial to the sustainable development of Southeast Asian countries (Zhang et al., 2019a). It also occupies a special position in Chinese animal husbandry (Zhang et al., 2014). Grassland is the most dominant type of cover in TRHR and provides the most ecosystem services (Zheng et al., 2020).

However, single and continuous alpine meadows combined with harsh natural environment are the reasons for the fragile nature of TRHR alpine grasslands (Jiang and Zhang, 2016). Under climate change conditions, TRHR agricultural economic development, overgrazing, grassland abandonment and construction etc. lead to grassland degradation (Han et al., 2018). Important service functions of grassland ecosystems are degraded, especially ecological service functions, production services and herders' livelihoods are also affected. Sustainability of TRHR grassland ecosystems challenged (Dong and Sherman, 2015). The importance of addressing the challenges should be fully recognized, which is crucial for the sustainable development of TRHR as well as the middle and lower reaches.

Given the unique geography and strategic location of TRHR, there is an urgent need to review the scientific understanding of grassland ecosystems in the region, which is critical for innovative approaches to maintaining ecosystem services and improving the resilience of grassland ecosystems to global change. For its critical and unique ecosystem, innovative theories are desperately needed. Therefore, this paper reviews the dynamic monitoring of grassland in the TRHR under changing environment; TRHR grassland degradation and its quantitative assessment; ecological effects of grassland degradation; driving factors and mechanisms of grassland degradation; grassland ecosystem protection policies and restoration measures for degraded grasslands.

2 Dynamic monitoring of the Three-River Headwaters Region grassland under changing environment

2.1 Grassland monitoring and simulation based on NDVI

The normalized difference vegetation index (NDVI) in TRHR has been extensively studied by researchers. Most studies show an increasing trend in vegetation cover. E.g, Bai et al. (2020) synthesized multiple satellite data to calculate the annual average NDVI, and the results showed that the NDVI of TRHR showed a weak overall trend of growth from 2000 to 2015, and the grassland NDVI changed between 0.43 and 0.50, and the change range was between 0.23 and 0.27. The results of Ge et al. (2018) showed that in the first 15 years of the 21st century, 59.9% of the grassland vegetation coverage in the headwater of the Yellow River showed an upward trend. A study by Qian et al. (2010) based on data from the US Earth Resources Observation System showed that in TRHR, grassland NDVI increased after 1994, and since 2004, the increase has been larger. However, the study by Gillespie et al. (2019) showed (based on 8km $\times$ 8km pixel resolution images) during 1982-2015, no changes in NDVI were detected in TRHR, but the regional differences were significant, with an increase in the western region and a decrease in the eastern region. Zheng et al. (2018) showed that NDVI showed a weak downward trend in the first 12 years of the 21st century. One of the reasons for the discrepancies between the findings of these studies may be due to different data sources and different temporal resolutions.

The NDVI of TRHR has obvious regional differences (Liang et al., 2016) and has a high degree of spatiotemporal variability. Human-induced fragmentation of the landscape has contributed to this regional disparity (Bai et al., 2020). Further projections suggest that TRHR vegetation may show an increasing trend until the end of the 21st century (Zheng et al., 2018). There is still the possibility of mutation in the future, and grassland degradation may still occur (Shen et al., 2018), and continuous dynamic monitoring is still required to prevent the occurrence of degradation risks.

2.2 Grassland cover monitoring and simulation

Grassland cover and alpine grassland aboveground biomass (AG-AGB) are important for the restoration and management of TRHR grassland ecosystems. Vegetation coverage is an important index to describe vegetation changes (Jiapaer et al., 2011). Remote sensing is the only effective means to estimate grassland coverage and monitor its long-term dynamic changes in a wide range of harsh environments. Relatively few spectral mixture analysis studies have been used in the TRHR region. High-resolution satellite imagery over large areas is limited by high cost and weather conditions, while medium-resolution satellite images are more suitable for large-area scales due to their wide coverage and higher temporal resolution. Studies found that when using MODIS data to extract its endmember vegetation index (VI), the pixel dichotomy model was not suitable for simulating the grassland coverage of TRHR (Ge et al., 2018).

Empirical models are also one of the common methods for determining vegetation coverage. The empirical formula is used to estimate the vegetation cover and has been well verified in practice (Kergoat et al., 2015). VI is very well applied in this regard, but due to environmental differences in different regions, the performance of various vegetation indices is not the same. In simulating TRHR grassland coverage, NDVI performed better, while Enhanced Vegetation Index (EVI) was second (Ge et al., 2018). Also, using a single VI-based model often yields good results for only the specified area (Yang et al., 2018b). Multiple regression models further constrain the model by adding more correlated other variables and are therefore better than univariate VI models (Ge et al., 2018). Machine learning models are a more advanced approach. Many scholars have compared the prediction effects of different models in TRHR. For example, Ge et al. (2018) found that the support vector machine (SVM) model was the optimal model after comparing multiple models (pixel binary model, univariate VI model, multivariate model and SVM model). Similar to this result, Ai et al. (2019) compared four commonly used alpine grassland coverage estimation methods, including random forest classification (RFC), regression analysis (RA), multi-endmember spectral mixture analysis (MESMA), and SVMR, and showed that the SVMR-based grassland coverage estimation accuracy was similar to the RFC method, and the stability was also better.

Most of these studies show that the overall vegetation cover of TRHR is getting better (Bai et al., 2020). However, the changes of grassland cover in the TRHR area are complex and unstable. Therefore, the impact of subsequent warm-wet processes on vegetation will be difficult to predict (Liu et al., 2018), and should be monitored continuously. It should be noted that most of these monitoring methods only consider changes in overall grassland coverage, while ignoring species-related factors. However, the upward trend in grassland cover can often be the result of severe invasion by weeds. In order to reflect the real situation of grassland, Ai et al. (2019) classified grassland plant types into native plants and noxious weeds, and generated a distribution map based on their spectral difference bands. The results indicated that the distribution of native plant species was generally dominant.

2.3 Monitoring and simulation of aboveground biomass in alpine grassland

Grassland aboveground biomass (AGB) can characterize grassland attributes and grassland quality. It is one of the important indicators to study grassland ecosystem health, ecological service value and grassland degradation (Kong et al., 2019, Zeng et al., 2019, Zhao et al., 2021). There are two main methods for monitoring AG-AGB, namely traditional field measurement and remote sensing image-driven estimation. Traditional terrestrial methods estimate biomass by sampling in the field (Yang et al., 2018b). Field sampling can obtain accurate AGB, but its cost is relatively high, and the spatial difference is insufficiently considered (Li et al., 2016). Remote sensing-based methods use the relationship between spectrum, environment, and AGB to build a model to evaluate AGB (Liang et al., 2016). The selection of indicators and models is very important for estimation. The accuracy of model estimation depends on the selection of indicators. The increase in the number of indicators will inevitably improve the simulation quality of the model, but it will reduce the work efficiency, and the improvement of the model accuracy is also limited. However, the screening of key indicators in specific regions is still challenging. In the actual research of TRHR, the selection of indicators in various studies varies greatly (Zhao et al., 2021, Tang et al., 2021, Liang et al., 2016, Zeng et al., 2021). Zhao et al. (2021) focused on the selection of indicators, and identified 6 items (EVI, radiation, altitude, B5/B7, latitude, and precipitation) out of a total of 33 items that are of great significance for estimating AG-AGB. In terms of model selection, the prediction accuracy of the AG-AGB model constructed by the machine learning algorithm is higher than that of the traditional multiple regression model (Yang et al., 2018b, Tang et al., 2021). In the model-based research of TRHR, many scholars compared the models constructed by multiple algorithms. The results show that RF model predicts AG-AGB better than models constructed by Multiple Linear Regression (MLR), Backpropagation Artificial Neural Network (BP-ANN), SVM, Cubist, Classification and regression tree (CART), etc. (Liu et al., 2018, Zeng et al., 2021, Tang et al., 2021, Zhao et al., 2021). RF models also exhibit higher stability and accuracy (Liu et al., 2018). Most models show a gradual increase in TRHR AG-AGB from northwest to southeast, and an overall increase from 2000 onwards (Zhao et al., 2021, Tang et al., 2021, Liang et al., 2016, Yang et al., 2018b). However, there are also studies showing that the interannual changes of grassland AGB in most areas of TRHR from 2000 to 2018 were not obvious (Zeng et al., 2021). Some models also showed that the trend of change was different in different regions, with TRHR far east (Zeku, Henan) and far southwest (parts of Golmud and Yushu) AG-AGB increased significantly (16.5%), while Zhiduo northwest AG-AGB decreased significantly (3.8%) (Yang et al., 2018b).

The monitoring results of grassland in the TRHR area mostly showed an increase in grassland coverage and AG-AGB. Many researchers attribute the increasing trend to a combination of climate change and human factors. However, it should be noted that most of these monitoring methods only considered changes in overall grassland coverage or AG-AGB, but did not consider changes in grassland structural composition. But severe invasion by noxious weeds may lead to an increase in grassland biomass rather than a decrease. Therefore, in order to have a clearer understanding of the changes in grassland ecosystems, future research needs to pay attention to the related changes in the composition of grass species. (Table 1)

3 Degradation of the Three-River Headwaters Region Grassland

Multiple studies have shown that TRHR grassland ecosystem was degraded to varying degrees, which is proved by field surveys and satellite images. In the middle and late 1970s, the grassland degradation of TRHR basically began to form. From the 1970s to the 1990s, the grassland degradation process continued to occur, and different regions showed distinct patterns (Liu et al., 2008, Wang et al., 2006). However, some studies have also shown that after 1990, the increase in grassland coverage and AG-AGB of TRHR was greater than the decrease, showing an overall increasing trend, and the regional macro-ecological environment tended to improve (Liu et al., 2016a, Chen et al., 2020). At the watershed scale, the grassland in the headwater of the Yellow River has recovered relatively well, followed by the grassland in the headwater of the Yangtze River, and the grassland in the Lancang River has a poor status (Zhang et al., 2019b). From the perspective of the spatial distribution of grassland changes, there is a general recovery trend in the southeastern and central regions of TRHR, while the grassland quality tends to deteriorate in the northwest of TRHR (An et al., 2021, Yang et al., 2018b).

However, the restoration of TRHR grasslands is partial and temporary, and does not reflect overall or fundamental improvement, and grassland degradation has not been fundamentally suppressed (Shao et al., 2013, Cao et al., 2020). Most of the areas with larger increases in grassland coverage originally had lower grassland coverage, and most areas with decreased grassland coverage originally had higher grassland coverage (Ge et al., 2018). And it's slow when grasslands recover and fast when grasslands degrade (Bai et al., 2020). Some areas of TRHR (especially the high-altitude areas in the northwest) still have obvious degradation (Han et al., 2017, Yu et al., 2019, An et al., 2017, Xiong et al., 2019), and the degree of desertification and salinization is still expanding (Li et al., 2013a). Liu et al. (2014) used linear regression analysis and Hurst index analysis to reveal that the vegetation coverage increased in the northern part of TRHR and decreased in the southern part during 2000-2011. The uncertainty of grassland changes reflects the nature of the grassland in this region, which is prone to mutation and fragility. Studies have shown that the area of extremely degraded grassland in this region accounts for 5.68% of the TRHR area (Ai et al., 2020), which further illustrates the severe unhealth status of the TRHR grassland.

3.1 Quantitative assessment of grassland degradation

The diagnosis of grassland ecosystem degradation degree is the premise of grassland restoration (Wen et al., 2010, Wang et al., 2014). The earliest assessment of grassland degradation in TRHR was that Ma et al. (2002) integrated some visibility indicators such as grassland coverage, plant height, AG-AGB and proportion of palatable plants to classify grassland degradation into five grades: no degradation, mild, moderate, severe and extreme degradation. Mildly and moderately degraded grasslands are generally distributed in summer pastures and transitional pastures. Severely and extremely degraded grasslands are mostly distributed near residential sites or in the center of drinking water points. The terrain is generally gentle, and most of them are winter pastures. To further quantify the degree of alpine meadow degradation, Wen et al. (2010) constructed a comprehensive evaluation system on the basis of Ma et al. (2002) to define the Grassland Degradation Index (GDI). Using GDI to evaluate the TRHR Maqin alpine grassland, it is found that the dominant and sub-dominant grassland species have changed greatly at different degradation levels.

However, grassland degradation is a complex ecological process, which includes not only vegetation degradation, but also soil changes. In addition to visible indicators, invisible indicators (such as underground biomass, nutrients in soil, etc.) are also important parameters reflecting the degradation of grassland ecosystems (Lin et al., 2015). Plant species diversity and soil nutrients are important predictors of different degradation stages of alpine meadows, and severe degradation will lead to the migration of alpine meadow plant communities (Wang et al., 2014). Therefore, soil-plant systems must be analyzed from the perspective of a multidisciplinary strategy (Brevik et al., 2015). Urease, ratio of microbial biomass nitrogen (MBN) to total nitrogen (TN), hydrolase and soil organic carbon (SOC) were the most important indicators for evaluating soil quality. The ratio of microbial biomass carbon (MBC)/MBN is a key factor affecting grasslands above moderately degraded levels. In extremely degraded grasslands, almost all parameters are key factors, which means that human disturbance has a significant impact on soil quality (Li et al., 2013c). Li et al. (2013c) comprehensively considered the physical and chemical properties of soil and soil organisms, and constructed a systematic index to apply it to soil quality evaluation of TRHR plateau alpine grassland under different disturbance intensities, and divided grassland into three categories: non-degraded grassland with high soil quality index (SQI) , moderately degraded grassland with medium SQI, and severely degraded grassland with low SQI. Lin et al. (2015) divided the entire degradation succession of Tibetan alpine Kobresia grasslands into six stages. Their study found that easily observable features such as plant functional group (PFG) type and mattic epipedon state were associated with less observable features such as root state. Therefore, PFG type, root system, and soil status can measure the degradation level of grassland ecosystems. This will help the grassland to determine the degradation level more easily, so the grassland can be protected more reasonably.

In order to assess the degree of grassland degradation in TRHR, An et al. (2017) comprehensively considered topography, hydrothermal factors, and soil factors, and divided grassland into 20 grassland productivity units. The grassland degradation level was measured by the change in net primary productivity (NPP) of grassland using the grassland productivity unit technique. The results showed that the grassland degradation degree in this area was 32.86% in 1990, 36.7% in 2004, and increased by 3.84% in 15 years. Banma, Gande, Henan, Jiuzhi, Tongde and Zeku are the least degraded in the eastern region of TRHR. The Qumalai degradation level was relatively highest. In 1990, the proportion of degraded grassland in Qumalai reached 63.33%, and the proportion increased to 77.47% in the following 14 years. Maduo and Chengduo were relegated by more than 40%. However, it should be noted that since the interannual variation of AG-AGB may be the result of climatic factors or grassland degradation, the influence of climatic factors needs to be corrected in the relevant assessment of grassland status based on temporal and spatial changes of AG-AGB. Moreover, the Climate Use Efficiency Index (CUE) index combined with local climatic conditions can show the degradation of soil to a certain extent. In addition to this, extreme weather events are also an important factor, as they can lead to degradation of grassland ecosystems in a short period of time. Therefore, some scholars use CUE to judge the dynamics of TRHR grassland ecosystems. An et al. (2021) proposed a new climate use efficiency index (NCUE) to monitor grassland changes by comprehensively considering a series of climatic factors closely related to vegetation growth and their coordinated climatic factors. The results showed that during the 31 years from 1982 to 2012, grassland degradation and restoration coexisted, accounting for 20.49% and 23.89%, respectively. Zhang et al. (2019b) further combined CUE with vegetation net primary productivity (NPP), grassland coverage and surface bare rate to construct a more complete evaluation index to evaluate regional grassland dynamics. The results showed that from 2001 to 2016, the headwater of the Yellow River had high NPP, grassland vegetation coverage and CUE, and a low degree of desertification; the headwater of the Yangtze River had low NPP, grassland vegetation coverage and CUE, and a high degree of desertification. During this period, the vegetation coverage and VI of TRHR grassland showed an upward trend, and the bald spot rate and NPP showed a decreasing trend.

3.2 Ecological effects of grassland degradation

The degradation of the TRHR alpine grassland ecosystem significantly affects the service functions of the grassland ecosystem, and the impact of grassland degradation can be reflected in the aspects of ecology, production and livelihoods (Long, 2007, Dong et al., 2020).

Ecological functions are inherent in the system and are the basis for the maintenance and development of the system. From an ecological point of view, grassland degradation in TRHR has greatly weakened ecological functions such as carbon sinks, climate regulation, soil conservation, water conservation, biodiversity conservation, and nutrient cycling (Dong et al., 2020, Wang et al., 2014). Grassland degradation can lead to poor soil quality or even to desert grasslands in the region, resulting in changes in seed banks, and changes in soil properties such as soil moisture, SOC, TN and soil bulk density, soil microorganisms, and soil enzymes (An et al., 2021). With soil degradation in this area, the soil fertility of the uppermost soil layer within 30 cm decreased significantly (Wang et al., 2014). In different degradation succession stages, the correlation between the biomass of alpine meadow community and soil nutrients (TN, available nitrogen, total phosphorus, available phosphorus, SOC and soil MBC, etc.) in the previous succession stage was positive. With grassland degradation, SOC and TN showed a downward trend, and the distribution of SOC was greatly affected. The proportion of light fraction carbon in total organic carbon (TOC) gradually decreased, while the proportion of heavy fraction carbon in TOC gradually increased (Wang et al., 2009). A study conducted at TRHR showed that non-degraded grassland had the highest SOC content. Compared with the non-degraded grassland, the SOC content decreased by 21.89%, 38.30% and 43.15% with the development of degradation, respectively.

The TN content in the non-degraded grassland was also higher than that in any of the degraded grasslands (0.908 kg·m^{-2}, 0.786 kg·m^{-2} and 0.769 kg·m^{-2} for moderate, severe and extreme degradation, respectively) (Li et al., 2014). The loss of SOC caused by grassland degradation will have a positive feedback on climate warming, which will intensify the warming.

The high soil erosion intensity in the source area increased with the deterioration of meadow vegetation (Li et al., 2009). The average soil erosion modulus decreased linearly with the increase of vegetation coverage, and the correlation coefficient R^2[?]0.997. The average erosion modulus of severely degraded meadow is 2.23 times that of mildly degraded meadow, and the maximum erosion modulus is 2.96x10^{6}kg*km^{-2}*a^{-1}. About 121.28x10^7 t of soil and water conservation capacity is lost due to degradation every year in the TRHR "wasteland" grassland (XU et al., 2013). Grassland degradation not only worsens soil holding capacity, but also worsens soil moisture conditions. Land degradation causes severe water scarcity near the soil surface, and the detrimental effect of land degradation on moisture conditions may be greater than expected since the effect will be doubled by a larger active layer thickness due to degradation compared to the experimental warming effect alone (Xue et al., 2017). For example, when alpine meadow grassland is degraded, its coverage is reduced, and when weeds replace the original dense-rooted pine grass and grasses, the soil water-holding capacity will be significantly reduced, and the soil will tend to be dry. Changes in soil and root systems provide higher thermal conductivity, which in turn accelerates soil degradation processes, leading to water infiltration and ultimately a significant decrease in water conservation (WANG et al., 2003). Declining soil water-holding capacity also makes summer flooding worse, and future climate change could lead to more frequent extreme flooding in the Yangtze River Basin. So putting the two together will make things worse (Li et al., 2017).

Grassland degradation is a crucial factor affecting vegetation composition and plant diversity (Xing et al., 2021). The species diversity and productivity of TRHR alpine meadows decreased significantly with different degradation stages, and the severe degradation degree led to the migration of alpine meadow plant communities (Wang et al., 2014, Wang et al., 2009). Degradation of grasslands will undoubtedly lead to the fragmentation of these specific habitats for TRHR. Endangered plant species will be more likely to be compromised by fragmentation of alpine grasslands, as this will include reducing fragment size and increasing distance to sites with similar habitats (Li et al., 2013a). Those species with shorter life cycles may therefore experience greater variation in individual numbers, a combination that could be dangerous for small populations with shrinking habitats, which will undoubtedly lead to a loss of species diversity in grassland ecosystems. And predictably the harsh environment of TRHR makes this sort of thing even more devastating.

Grassland degradation reduces vegetation cover, height and productivity, changes in grassland community composition, and allows the invasion of noxious weeds, all of which undermine grassland ecological sustainability (Xing et al., 2021). From a production point of view, grassland degradation will undoubtedly impair the yields of primary products (grass, medicinal materials, fungi, fuel) and secondary products (milk, meat, hair, hides). From the perspective of herdsmen's livelihood, grassland degradation has reduced herdsmen's well-being, resulting in the emergence of a large number of ecological refugees (Dong et al., 2020). (Figure 2)

4 Driving factors and mechanisms of grassland degradation

The combination of the fragility of the ecosystem formed by its natural environment and the excessive human disturbance has led to the degradation of grassland on the Qinghai-Tibet Plateau (Dong et al., 2020). The bald spots of alpine meadows occurs and develops due to the unreasonable use of vegetation, burrowing by rodents, soil loosening, and wind and water erosion (YANG et al., 2005). Habitat aridification caused by the bald spots of the grass layer in the alpine meadow prompted the reverse succession of the top plant community dominated by stable Artemisia species. As the area of these bald spots increased, the native vegetation with Artemisia as the dominant species was gradually replaced by poisonous weeds. The alpine meadow is gradually replaced by the bald spot landscape - "black soil beach" (YANG et al., 2005). Studies have shown that at the beginning of degeneration, PFG types gradually from rhizome bunchgrasses to rhizome plexus and denseplexus grasses, then root overgrowth leads to mattic epipedon thickening, the balance between nutrients and water in the soil is broken, the degradation gradually accelerates followed by fissures and collapse of the mattic epipedon (Lin et al., 2015). The "hydrothermal hole effect" also appears (Shang et al., 2018). Moisture and heat will be reduced through these hollows, destabilizing the "root-soil-permafrost" system in and around the hollows, creating island-like meadows, and this will accelerate the loss of native forages (Shang et al., 2016). In addition, grassland degradation affects the composition and quantity of seeds in seed rain, and its involvement with vegetation is also affected, and the ability of many weed species to produce large amounts of seed rain leads to further grassland degradation (Shang et al., 2013). With the further aggravation of grassland degradation, harmful weed species flourished and allelopathically inhibited other plants (Shang et al., 2017), gradually establishing sustainable populations. After establishing sustainable communities, noxious weed species begin to spread nearby or beyond with the help of factors such as climate warming and overgrazing (Xing et al., 2021). After severe grassland degradation, the alpine meadow plant community has migrated, and the response of plant diversity, plant productivity, and soil nutrients has mutated (Wang et al., 2014), and the grassland will also lose its ability to restore itself.

It should be noted that the degradation characteristics of different grassland types are different. Alpine meadow and alpine steppe ecosystems are more stable than alpine desert ecosystems and show stronger resistance to disturbance (Tang et al., 2015). The underlying mechanism is that the more complex structure and composition of alpine meadow and steppe ecosystems may make them more elastic and more stable (Joner et al., 2011).

4.1 Impact of climate change on grassland ecosystem

Over the past 60 years, the TRHR has experienced significant warming, and the rate is higher than that of the global and overall Qinghai-Tibet Plateau (Bai et al., 2020, Chen et al., 2020, Jin et al., 2022, Hu et al., 2022, Li et al., 2013a, Bardgett et al., 2013, Jiang et al., 2017). Warming varies by season and region (Liang et al., 2013). The warming of TRHR since the 21st century is mainly the result of the increase in temperature in the cold season (Liang et al., 2013). From 1982 to 2014, the growing season temperature in the TRHR region showed the most significant upward trend in the northwest and southeast (Chen et al., 2020). Precipitation has increased slightly in the TRHR region in recent decades (Jin et al., 2022, Li et al., 2013a, Hu et al., 2022, Bai et al., 2020). The regional differences in precipitation increase are obvious. Chen et al. (2020) showed that the areas with significant increases in growing season precipitation in the TRHR region from 1982 to 2014 were located in the northeastern and western parts of the TRHR, with a maximum rate of up to 1.45 mm yr^{-1}. Therefore, in general the climate in the region has been in line with the "warm and wet" trend for at least the past few decades (Bardgett et al., 2013, Jiang et al., 2017, Qian et al., 2010). But there are also studies showing that the TRHR climate has shown a "warm and dry" trend in the past 40 years (Li et al., 2013a). The trend of "warm-dry" or "warm-wet" in the TRHR region varies significantly in different regions (Liang et al., 2013). In addition, the increasing trend of reference evapotranspiration (ET_O) in the TRHR suggests a possible future climate transition to warmer and drier climates (Wang et al., 2020, Li et al., 2012). Climate warming has also caused serious environmental problems. For example, the TRHR region has reported a significant reduction in the area of permafrost in recent decades, and those areas where the permafrost disappears consistently show the highest temperature increases, resulting in a thinning of permafrost thickness and eventual disappearance (Hu et al., 2022).

4.1.1 Effects of climate change on plant growth and composition

Most remote sensing-based model studies show that climate change has promoted the growth of vegetation in the TRHR over the past 20 years (Zhang et al., 2016a), mainly due to climate warming (Bai et al., 2020, Zeng et al., 2021, Cao et al., 2020, Fan et al., 2010). TRHR has a low-temperature and rainy climate, which suggests that temperature constrains alpine grassland vegetation more strongly than rainfall (Xu et al., 2011). The growth of grassland vegetation benefits from a better thermal environment created by rising surface temperature, and permafrost is no longer a limiting factor for root growth. The degradation rate of organic matter is also accelerated. Elevated temperature may increase the photosynthetic rate of grassland, thereby increasing its NPP (Yang et al., 2009). Warming temperatures also lead to an earlier start of the growing season of alpine grasslands (Zhang et al., 2013a), which may prolong the vegetation growth period (Han et al., 2018) and increase its carbon sink capacity (Piao et al., 2007). In addition, the regulating effect of temperature on precipitation and cloud cover will also promote vegetation growth (Chen et al., 2020).

Rising temperatures also have many negative impacts on TRHR grasslands (Xiong et al., 2019). In the western TRHR, due to poorer moisture conditions, warmer temperatures may increase vegetation evapotranspiration, leading to increased moisture constraints on grassland vegetation growth. Studies have shown that climate warming is beneficial to healthy alpine ecosystems, but in degraded meadows at TRHR, rising temperatures exacerbate degradation by exacerbating degradation-induced droughts (Xue et al., 2017), thereby inhibiting meadow plant growth. In addition, the degradation of permafrost, linked to rising temperatures, leads to a drop in the groundwater table, which in turn inhibits the growth of shallow-rooted plants, leading to the degradation of alpine meadows (Song et al., 2018, Hu et al., 2022). The long-term effect of the deepening of the ecological groundwater level will promote the change of vegetation species and the regional evolution of plants. This in turn leads to the degradation and even desertification of alpine grasslands (Jin et al., 2022).

The effect of temperature on grassland productivity is nonlinear. And there are obvious differences in different regions of TRHR. The annual average temperature in most grassland areas of TRHR has a positive effect on AGB and NPP (Xiong et al., 2019, Zeng et al., 2021). Studies have shown that the effect of temperature on AG-AGB in the eastern region of TRHR is significantly stronger than that in the western and southwestern regions. The rise in temperature in the western region of TRHR may lead to the worsening of the originally severe water conditions in the region due to vegetation evapotranspiration, resulting in increased water restrictions on vegetation growth (Zeng et al., 2021). However, this nonlinear increase and different responses to temperature increase in different climates suggest the existence of interactions between other non-temperature factors and temperature on plant growth (Piao et al., 2014).

Most areas of TRHR belong to a semi-arid and semi-humid climate, and the lack of water severely limits the growth of plants. Precipitation is an important water source for grassland growth and affects the spatiotemporal pattern of AG-AGB. Studies have shown that in the TRHR region, taking 2001 as a node, the temperature and radiation before 2001 were the factors restricting the increase of NPP and then changed to precipitation (Zhang et al., 2016a), which highlights the importance of the impact of precipitation on grassland vegetation. Zheng et al. (2018) showed that precipitation, rather than air temperature, was considered to be the key factor responsible for changes in TRHR NDVI values, especially the average precipitation for 2 consecutive months. And, in terms of overall vegetation, rainfall is a decisive factor in improving vegetation productivity, because increased rainfall can lengthen the growth period of vegetation, which is beneficial to the accumulation of NPP (Bai et al., 2020). Furthermore, TRHR precipitation affects the sensitivity of AG-AGB to mean annual precipitation (MAP). If the region has a high drought risk (MAP<400mm), the sensitivity of AG-AGB to annual mean precipitation is low, and its change is small. Probably because of the high resistance of vegetation in these arid and semi-arid environments (Gao et al., 2019a); AG-AGB was susceptible to precipitation when MAP varied between 400-700 mm, the increase in precipitation is favorable for AG-AGB; In humid areas (MAP>700mm), AG-AGB was not significantly affected by MAP, or even negatively affected. This reflects that sufficient precipitation can promote the growth of grassland leaves and leaf photosynthetic capacity, thereby improving grassland productivity. However, excessive precipitation, whether in saturated or excess conditions, may unbalance soil moisture and gases, affecting plant uptake of nutrients and light, such that increased precipitation does not contribute significantly to productivity, or even leads to reduced productivity (Zeng et al., 2021). Zhang et al. (2016a) showed that since 2000, more precipitation in the central region of TRHR is not conducive to plant growth, and high precipitation leads to lower air temperature and radiation (Han et al., 2018), which inhibits plant synthesis of organic carbon. In addition, high rainfall also reduces vegetation productivity by increasing topsoil loss, thereby reducing soil organic matter (Gao et al., 2013).

Although in the past 20 years, climate change in the TRHR has generally promoted the growth of grassland vegetation, the dominant factors are different in different regions and different periods. For example: The dominant factors in TRHR vegetation growth during 1995-2014 were precipitation in the west, temperature in the southeast and south, and solar radiation in the northeast (Chen et al., 2020). Vegetation changes have obvious zonal characteristics, which may be due to the inconsistency in the rate of temperature increase in each region of the TRHR (Bai et al., 2020). Although projections suggest that the vegetation of the TRHR will increase until the end of the 21st century under the $RCP_{4.5}$ climate change scenario (Zheng et al., 2018), the risk of future regional degradation remains due to the potentially abrupt and fragile nature of the TRHR. Futhermore, The increasing trend of ET_O in the TRHR suggests that a future climate transition to a warmer and drier climate will accelerate the transition from grassland to heathland, especially in the high-altitude regions of the midwest of TRHR (Wang et al., 2020). And with the improvement of grassland degradation level in this area, the proportion of weeds gradually increased, and with the trend of warm and humid climate, the invasion rate of weeds was further accelerated (Xing et al., 2021).

4.1.2 The impact of climate change on grassland plant phenology

The main drivers of plant phenological changes are air temperature and precipitation. In addition, grazing and nitrogen deposition may also affect phenological changes (Shen et al., 2022), and snowfall may also play a key role in the actual growing season (Liu et al., 2016b). Studies have reported that since the 1980s, many alpine grasslands have generally experienced early start and delayed end of the growth period, which has prolonged the growth period (Shen et al., 2022, Piao et al., 2007). Piao et al. (2007) suggested that the increase in the length of the growing season in alpine meadows from 1982 to 1999 may be due to the increase in temperature. In order to further reveal the related mechanism of phenological change, some scholars also studied the thermal growth season change of TRHR, and then compared it with the actual growth season. The thermal growing season is closely related to temperature changes. Liu et al. (2016b) used TRHR 1960-2013 daily temperature data and field observation phenology data to show that the temperature increase in winter and spring is a key factor affecting the early start of the actual growing season. For the actual growing season, the early end of the season is affected by the increase in summer temperature, while the delay of its end is affected by the increase in summer precipitation. Although the duration of the thermal growing season has become longer due to rising temperatures, the duration of the actual growing season may not have increased, but rather an overall advance. The earlier start of both was associated with the response to temperature increase, while the later end of the thermal growing season was associated with the earlier end of the actual growing season. One of the possible explanations is that, due to the short growth period of grassland in this area, the increase of thermal energy can accelerate the completion of the growth cycle. Another possible explanation is that warm summers lead to water scarcity and inhibit grassland growth (Richardson et al., 2013, Angert et al., 2005). In addition, the effects of temperature and water on phenology have obvious interactions, and the sensitivity of grassland plant phenology to temperature increase is also regulated by water (Shen et al., 2022). Due to the regional differences in TRHR climate and its changes, there may be regional differences in its phenological responses. Changes in the phenology of TRHR grassland ecosystems may, in turn, affect the interactions between grassland plant species, resulting in changes in ecosystem structure and impacts on ecosystem functions such as carbon and water cycles.

4.1.3 Impact of climate change on soil

Climate warming increases evapotranspiration and aggravates surface water infiltration, which gradually induces land degradation in TRHR alpine meadows, eventually leading to topsoil drought (Xue et al., 2017). The increase in air temperature makes the soil temperature rise and the permafrost thaw. Soil moisture in the root zone infiltrates due to the thawing of the permafrost, which eventually leads to poor soil moisture status (Hu et al., 2022).

Climate change negatively affects soil carbon and nitrogen pools (Su et al., 2015). Changes in soil organic carbon density (SOCD) of TRHR are sensitive to temperature increase. SOCD in TRHR showed significant interannual variation from 1981-2010, but the trends over 30 years were not consistent. The downward trend in SOCD after 2003 was associated with climate warming and increased spatial heterogeneity of precipitation. After 2003, the decrease in precipitation in the east often leads to the decomposition of SOC, while the increase in precipitation in the west leads to a relatively stable SOC. Model projections suggest that due to the warm-wet trend of the future climate in the TRHR, heterotrophic respiration will increase and may overtake plant production during 2011-2070, leading to a decrease in SOC. After 2071, the increment of NPP is higher than that of heterotrophic respiration, and SOCD starts to rise, especially in the west. And, the simulated SOC responses to climate change also have significant regional differences. The decrease in SOCD in the east and the increase in the west may be caused by the regional differences in carbon input produced by plants. The carbon input in the western region may increase, but the carbon input in the eastern region remains relatively unchanged or even decreases (Zhao et al., 2013).

4.2 Effects of grazing on grassland ecosystems

With the rapid development of the TRHR agricultural economy since the 1980s, overgrazing, grassland abandonment, and construction have all had a significant impact on ecological processes, resulting in grassland degradation, habitat loss, and landscape fragmentation (Wang et al., 2016b, Zhang et al., 2016a). These effects significantly affect the ecological welfare of downstream residents (Fang, 2013). And, grazing partially offsets the positive contribution of climate change to grasslands (Chen et al., 2020). Many researchers agree that overgrazing is the main cause of grassland desertification (Gao et al., 2020).

4.2.1 Status of overgrazing

Most studies show that although the grazing pressure in TRHR has decreased in the past 20 years, it is still in a state of overgrazing (Zhang et al., 2014, Dong et al., 2015, Fan et al., 2010), and it is necessary to further reduce the number of livestock in TRHR to alleviate the grazing pressure(Zhang et al., 2017, Zhang et al., 2019a, Gao et al., 2020, Yu et al., 2021, Yang et al., 2018a). All winter pastures in the TRHR region are overgrazed. However, only 37.5% of the summer pasture area is overgrazed (Dong et al., 2015). Grazing pressure on winter pastures is much higher than summer pastures because these pastures are closer to settlements and watering facilities. Longer grazing time and greater grazing intensity usually result in more degraded pastures in winter than in summer (ZHANG et al., 2006, Zhang et al., 2017). Furthermore, The degree of overgrazing varies in different counties. Zhang et al. (2014) showed that in 2010, the total number of overgrazing sheep in TRHR was $652\text{x}10^4$ sheep units (SU), the average overgrazing rate was 67.88%, and the average overgrazing number was 27.43 SU km^{-2}. Tongde, Xinghai, Yushu, Henan and Zeku had higher overgrazing rates, Zhiduo, Golmud and Dari, Qumalai and Maduo had no overgrazing, and the rest of the counties also had overgrazing. Zhang et al. (2019a) showed that the grazing population in the TRHR area exceeded the carrying capacity by 132,800 people from 2000 to 2015, especially in counties such as Xinghai, Tongde, Zeku, Yushu, Nangqian, and Chengduo. In addition, the balance between grassland carrying capacity and livestock and wildlife is critical to maintaining the stability of grassland ecosystems (Gao et al., 2020). The ratio of domestic animals to wild ungulates in the TRHR area is estimated to be approximately 4.5:1 (Yu et al., 2021, Yang et al., 2018a). A study in Maduo County showed that grasslands are mildly overloaded when only livestock are considered, but moderately overloaded when livestock and large wild herbivores are considered. Therefore, if large wild herbivores are not considered when calculating the forage balance, grazing pressure will be underestimated by about 22% (Yang et al., 2018a). In addition, the division of national park functional areas has a significant impact on the balance of grass and livestock in the Yellow River Source National Park. After the implementation of the zoning plan, the grassland in the Yellow River Source National Park is still overloaded. Under the condition that the number of grazing livestock remains unchanged, the grazing pressure has doubled, and the conflict between pasture and livestock has become more obvious (Yang et al., 2019).

4.2.2 Effects of grazing on plants

Studies have shown that moderately grazing yaks significantly reduced the maximum height of adult grassland vegetation (Niu et al., 2010). Fencing significantly increases above-ground vegetation productivity (Wu et al., 2009). Under long-term enclosure conditions, the total aboveground biomass of fenced and non-grazing grasslands was higher than that of free-grazing grasslands (Fan et al., 2013). This suggests that fencing management can promote plant biomass, especially herb biomass and belowground biomass in the uppermost

0-10 cm. Vegetation shift to low and sparse type due to excessive consumption and trampling of grassland by livestock (Wang et al., 2009).

Grazing also has effects on plant composition and diversity. Vertebrate herbivores control diversity by altering species composition, including the invasion of non-native species and the extinction of native species. Herbivores can maintain plant diversity as grazing benefits native flowering plants and increases ground light (Borer et al., 2014). The disturbance intensity determines the composition and diversity of grassland species in different pasture types to a certain extent. Fencing reduces plant species diversity (Fan et al., 2013), but long-term fencing is beneficial to the improvement of forage functional groups and inhibits the development of harmful weed functional groups (Wu et al., 2009). Mild and moderate grazing intensities grazing intensity can promote plant diversity (Tang et al., 2015) and nectar production in alpine grasslands due to increased numbers of florets and flower heads, reduced competition for light, and increased numbers of flowering individuals per plot (Mu et al., 2016), which supports moderate perturbation hypothesis. The plant diversity-biomass-cover relationship on alpine plateaus may be decoupled by overgrazing livestock (Fayiah et al., 2019), and overgrazing creates bare patches that provide suitable habitats for receiving weed seed rain and cultivating weed seedlings. On the impact of grazing practices on grass species diversity. Studies have found that multifamily grazing pastures (pastures are not fenced and are grazing by multiple households) have higher species richness than single-family grazing pastures (pastures are separated by fences and are grazing by single households), because single-family operations may concentrate sustained, higher grazing pressure on small areas of grassland, leading to a reduction in plant diversity (Cao et al., 2011).

Grazing not only affected species richness, but also adversely affected soil moisture and TN. Not only that, but indirectly increase the density of spring seed bank and decrease the density of summer seed bank through these effects. Grazing regimes changed the species composition of the vegetation, but the seed bank composition did not change much. Although seed bank size did not change much with grazing intensity, it reduced the number of persistent seeds (Ma et al., 2018), and persistent seed banks are important for grassland restoration.

4.2.3 Effects of grazing on soil

Grazing alters soil properties by altering plant functional group composition, biomass loss, and nutrient cycling in alpine pasture ecosystems, with significant negative effects on soil physical and nutrient properties. Grazing intensity is one of the key factors affecting soil properties in grassland ecosystems (Dong et al., 2012). In recent decades, TRHR soil erosion acceleration was significantly associated with livestock numbers and intensive grazing, but not with precipitation. Grazing is more important than climate change for soil erosion. Overgrazing reduces vegetation cover and fine roots and thus accelerates soil erosion (Li et al., 2019). Grazing activities have a negative impact on soil moisture retention. Grazing reduces the moisture content in the upper 30 cm soil layer of alpine steppe, alpine meadows and temperate steppe, especially in the 10-20 cm soil layer of alpine meadows (Wang et al., 2019). The upper soil hardness and pH of different grazing treatments in the alpine meadow ecosystem showed an increasing trend with increasing grazing activity, but a significant difference in hardness was observed between the summer pasture and winter pasture grazing treatments. Grazing had a significant effect on soil total phosphorus and available phosphorus content. With the increase of grazing intensity and the increase of total potassium and available potassium, SOM, SOC and TN decreased significantly, and the C/N ratio also showed a similar law. Soil properties such as soil carbon and nitrogen generally decreased with increasing grazing intensity, possibly due to the increased turnover of plant matter and litter, as well as physical damage to soil, accelerated soil C and N loss due to high grazing intensity (Dong et al., 2012). Similar to Fan et al. (2013), the total carbon and C/N ratios in the aboveground tissues of fenced and ungrazed grasslands were significantly higher than those of free-grazing grasslands.

4.3 The influence of plateau pika on grassland ecosystem

Pika activity is also one of the factors contributing to TRHR grassland degradation. Studies have shown that pika activity reduced soil moisture, hardness, SOC and TN (Chen et al., 2017). With the increase of pika density, the aboveground biomass, species number, cover and leaf area index (LAI) of grassland decreased. Higher cave densities decreased net ecosystem CO2 exchange (NEE), gross ecosystem productivity (GEP), and ecosystem respiration (ER) (Liu et al., 2013). However, Yi et al. (2016) have shown that pikas deplete 8 to 21 percent of the average annual NPP of alpine grasslands. The effect of pika mound on the reduction of vegetation cover, biomass, soil carbon and nitrogen was much smaller than that of bald spot, all less than 10%. Large voids in pristine grasslands are the result of strong root systems, while those in new and old pika mounds and bald patch soils are smaller and discontinuous. Water generally preferentially passes through soil macropores, while in new and old pika mounds and bald patches more readily occurs at the surface, resulting in topsoil loss (Hu et al., 2020). In addition, fine-grained soils loosened by pika activity can be blown away by frequent strong winds, thereby increasing the proportion of gravel in the soil (Liu et al., 2013), thereby increasing soil erosion and hindering vegetation restoration (Chen et al., 2017). Coupling of overgrazing and rodent infestation may lead to the formation of bare patches, ultimately leading to severe degradation of TRHR grasslands (Wen et al., 2013) (Figure 3).

5 Restoration of degraded grasslands

5.1 Protection policy of grassland ecosystem

Since 2000, due to the obvious adverse effects caused by grassland degradation, the government and researchers have gradually realized the importance of TRHR grassland protection, and formulated a series of environmental protection policies, which have achieved remarkable results (Wang et al., 2017). In order to achieve effective management, TRHR environmental protection projects pay more attention to the integration of market-based logic in the formulation of conservation policies. However, the market mechanism emphasized in the actual policy design is not reflected in practice, because there is no well-integrated scientific measurement standard, lack of accountability mechanism, and weak supervision and implementation.. Furthermore, this negatively affects pastoralists due to the coercive nature of registration. The effectiveness of market logic-based environmental policies can thus be harnessed by using more scientific metrics, more liberal registration, and subsidizing money based on actual restoration results of grasslands (Wang et al., 2016a). Policy formulation should pay more attention to the adjustment of market prices, the implementation of incentive policies and the promotion of emerging technologies, to guide the rational use of land, to promote rational use of land, and to ensure the safe and sustainable development of ecosystems (Zhang et al., 2013c). In addition, it is important to help residents of TRHR to deeply identify with grassland restoration plans and use conservation techniques (Sheng et al., 2019). This is because residents' participation is largely dependent on the benefits they receive and their perception of the benefits of the program. Therefore, we can ensure the successful implementation of the policy through education and the use of incentive policies (Sheng et al., 2019). Furthermore, the trigger and feedback of family decision-making are very important and need enough attention, which has important practical significance for the protection of alpine grassland. (Su et al., 2022). Managers should also enhance their understanding of the relationship between ecological and cultural conservation in the TRHR region, which will improve future ecosystem management and cultural conservation. This is because successful management cannot happen without acknowledging the local Tibetan people and their traditional customs and culture as part of the conservation process (Shen and Tan, 2012). Resource management of any kind is essentially about how to manage sustainably while preserving, and even improving, the lifestyles and cultures of those who harvest and use resources.

5.2 Restoration measures for degraded grassland

5.2.1 Adaptation to climate change

Due to regional differences in geographical background, climate change, hydrothermal conditions, and conflicts between pastures and livestock, there are great differences in the types, degrees, scales and time courses of regional grassland degradation. Therefore, it is very important to plan ecosystem restoration projects in a targeted manner according to the regional differences in each region (Liu et al., 2008). The trend of increased ET_O observed in summer months poses a threat to the growth of natural vegetation, suggesting that TRHR requires more irrigation, which has been determined to have a greater impact on vegetation than the observed decrease in ET_O in winter. Therefore, more measures will be needed in the future, such as artificial rainfall, to counteract the negative effects that occur during the summer months (Wang et al., 2020). In addition, research shows that recovering new species assemblages that have emerged due to climate change is very difficult, if not impossible (Li et al., 2013b). According to the trend analysis of grazing ability, climatic factors have a significant impact on the grazing ability of TRHR, and the grazing potential has changed drastically. Therefore, it is necessary to select and adjust strategies in a timely manner, optimize livestock breeds, and select grass species that are more adaptable to climate change. In addition, it is necessary to make various preparations for climate change as early as possible, and develop artificial intervention mechanisms to enable the healthy development of animal husbandry (Zhang et al., 2013b).

Ecological restoration measures should be prioritized in areas with relatively warm and humid climates, where grassland productivity will be greater (Xiong et al., 2014). However, from the perspective of the fragility of the ecosystem, arid regions also need to prioritize the implementation of ecological restoration measures (Di et al., 2017, Zhang et al., 2017). Promoting the use of solar energy in households is also important for improving ecosystem functioning and adapting to climate change. The use of solar energy equipment will provide more manure to the grassland, thereby greatly improving the ecosystem service value of the grassland, especially the alpine grassland in this area (Zhang et al., 2016b). In general, further comparative studies and mechanism analysis are essential to formulate better ecological restoration strategies in TRHR to cope with the uncertainties of future environmental changes (Zhang et al., 2017).

5.2.2 Sustainable grazing management

Moderate grazing is a good way to maintain grassland biodiversity, maintain the function of grazing ecosystem and develop the productivity of grassland ecosystem. Rational use is the best protection strategy (Wang et al., 2009). Based on the carrying capacity of the grassland, the yield of grass, the number of livestock and the number of herdsmen should be kept in balance. It is necessary to continue to reduce livestock, increase the slaughter rate, control the number of livestock, ease the pressure on grazing, and promote scientific breeding methods. In addition, it is necessary to regulate the number of herdsmen population, carry out population transfer, or directly realize the transformation from traditional animal husbandry to other industries (Zhang et al., 2019a). In addition, improved management efforts should go directly to cool-season pastures, and adjusting the proportion of seasonal grazing area is also an effective alternative strategy, which will achieve a "win-win" for both grasslands and households (Dong et al., 2015). Due to the deterioration of the balance between supply and demand in animal husbandry, planting forage crops or using highland barley varieties for crop rotation is an effective way to alleviate the imbalance between supply and demand of forage grass from the perspective of supply (Yang et al., 2021). Studies based on grassland sensitivity and impacts suggest that efforts to improve grassland adaptive capacity should be based on increasing the area of fenced pastures, warm sheds, sown grasslands, and reducing livestock densities, as well as strengthening TRHR ecological engineering protection. (Fang et al., 2021).

5.2.3 Restoration of "Black Soil Beach"

Diagnosis of grassland conditions is an important first step in grassland ecosystem management. The degree of degradation and recovery period of alpine meadows determine the probability of successful meadow recovery. The effectiveness of meadow restoration through long-term efforts is strongly related to the level of degradatio (Lin and Zhang, 2020). Depending on the degree of degradation, different measures should be taken (Wen et al., 2013). The study found that biotic drivers are more important than abiotic drivers in the vegetation heterogeneity of small-scale degraded alpine grasslands on sunny slopes. Therefore, to prevent grassland degradation, the primary task is to carry out reasonable grazing management on non-degraded grassland. For mildly and moderately degraded grasslands, it is recommended to implement rodent control, limit grazing to low stocking levels (Wen et al., 2013), and use fencing, weeding, and fertilization techniques for grassland restoration (Ma et al., 2002).

However, for the severely degraded "black soil beach", grazing prohibition and rodent control alone cannot restore severely degraded grasslands, and even if the stressors are removed, it is impossible to restore the grassland ecosystem to its original state. Studies have shown that the restoration of "black soil shoals" by fencing and abandoning tillage increases the stability of secondary plants in degraded grasslands of "black soil shoals", which is not conducive to the restoration of "black soil shoals" (Shang et al., 2008). Therefore, feasible protection and restoration measures need to be taken to prevent the alpine grassland from further degrading into a collapsed "black soil flat" state, that is, an irreversible state of grassland degradation (Wang et al., 2014). Targeted human interventions, including selective planting of pasture and artificial grass seeding, as well as ecological and biological control of high-altitude rodent populations, are recommended to restore 'irreversibly' degraded pastures (Li et al., 2013b). Studies have shown that weed species richness decreased as native forage grasses were artificially seeded, altering the plant composition of "black soil flats" in the short term (Shang et al., 2008). "Black soil beach" showed visible changes after 3 years of restoration, and the quality of forages increased with the increase of restoration time (Wu et al., 2022). Xu et al. (2022) showed that restoration behaviors (restoration of planting and enclosure) improved AG-AGB weakly, but significantly promoted species richness, target species richness, and target species AGB. This means that grassland cultivation can accelerate the restoration of degraded grasslands, allowing target species and communities to be established and developed.

But generally speaking, "black soil beach" is dominated by perennial weeds, which are more difficult to remove than annual weeds. Therefore, abandoning tillage and not replanting is not conducive to the restoration of "black soil beach" (Shang et al., 2008). It takes more than 9 years to restore the soil carbon and nitrogen storage in the alpine grassland through vegetation reconstruction on the "black soil beach", and the C and N storage changes in a "V" shape with the vegetation restoration time (Su et al., 2015). Scientific management of soil nitrogen availability during restoration and succession can delay the occurrence of secondary degradation of vegetation and grassland (Shi et al., 2022). During grassland reconstruction, proper planning is needed to enhance soil carbon and nitrogen storage potential, which is essential to maintain the healthy development of the ecosystem. Studies have shown that plants, soils, and plant-soil systems exhibit nonlinear resilience of artificially reconstructed grasslands along a temporal gradient. Plant resilience was highest in the 12th year. After 13 years of revegetation, revegetated grassland soils outperformed severely degraded grasslands. The elasticity of soil and the elasticity of plants are not synchronized in time gradient. Plant-soil system resilience was highest in the 16th recovery year. Therefore, from a system-wide perspective, the rebuilding time for severely degraded level grasslands will take at least 16 to 18 years to stabilize. It should be noted that although restored grasslands can be relatively stable after 16 to 18 years of reconstruction, the restored ecosystems are still much lower than healthy alpine meadows in terms of both plant and soil quality (Gao et al., 2019b). After 4 years of artificial planting and restoration of degraded grassland, the number of unrelated species in the community decreased, and the community's sensitivity to external disturbances increased, and there was a trend of reverse succession. The development of arable grassland leads to an increase in neutral interactions among plant species with prolonged recovery time. The proportion of positively and negatively correlated species decreased. In the later stage of recovery, the niche occupied by a single species is narrow, and species coexist harmoniously, reaching a relatively stable state (Wu et al., 2022). Therefore, in the long run, continuous monitoring should be carried out, and the monitoring accuracy and accuracy should be further improved, and appropriate manual intervention should be taken according to the situation to prevent the secondary degradation of artificial grassland (Li et al., 2014).

6 Conclusions

In terms of dynamic monitoring of the TRHR grassland under changing environments, many model comparison studies have determined that the SVMA method is a more suitable method (Ge et al., 2018, Ai et al., 2019). For the simulation of AG-AGB, the satellite-driven model emphasizes the selection of indicators and models for the accuracy of prediction, and the RF model usually shows higher stability and accuracy (Liu et al., 2018, Zeng et al., 2021, Tang et al., 2021, Zhao et al., 2021). Most studies show that TRHR overall grassland cover and AGB show a trend of improvement. In addition, the monitoring of TRHR grassland needs to pay more attention to considering changes in the composition of grassland structures, so as to have a clearer understanding of changes in grassland ecosystems.

TRHR grasslands have been degraded to varying degrees in the past 50 years. Although grassland coverage and AG-AGB showed an overall increasing trend after 1990, this recovery did not reflect overall or fundamental improvement, grassland degradation has not been fundamentally curbed (Shao et al., 2013, Cao et al., 2020), and the risk of future regional degradation still exists. Grassland degradation is a very complex ecological process, including changes in both vegetation and soil. The assessment of grassland emphasizes the importance of analyzing the soil-plant system as a whole from the perspective of a multidisciplinary strategy (Brevik et al., 2015), and constructing a reasonable monitoring system for grassland degradation simulation. Once grasslands are graded for degradation, adjusting their use according to our degradation system will help prevent irreversible degradation of important grasslands. The ecological effects of TRHR alpine grassland degradation can be reflected in ecology, production and livelihoods (Long, 2007, Dong et al., 2020). Grassland degradation greatly weakens ecosystem functions such as carbon sequestration, climate regulation, soil conservation, water conservation, biodiversity protection, and nutrient cycling (Dong et al., 2020, Wang et al., 2014), and affects grassland production functions and herders' livelihoods. Grassland degradation significantly reduced surface soil nutrients and greatly affected the distribution of SOC; the resulting loss of SOC and a positive feedback on climate warming. The degree of grassland degradation is proportional to the intensity of soil erosion. And grassland degradation worsens soil moisture conditions, and the effects of this deterioration may be greater than previously thought. Grassland degradation not only leads to the decline of grassland species diversity and productivity, but also leads to fragmentation of specific habitats, which will undoubtedly accelerate the loss of species diversity. The adverse effects of degradation on the yield of primary and secondary products will also reduce the well-being of pastoralists.

The TRHR climate has generally shown a "warm and wet" trend in recent decades, and climate change has generally promoted the recovery and growth of alpine grasslands. Overgrazing is common in all counties and townships of TRHR, and is considered by many researchers to be one of the main reasons for grassland degradation. However, climate change and livestock grazing activities have a very complex impact on the grassland ecosystem of TRHR, and related research is still controversial, and further research is needed to unify these differences. The grassland changes and the dominant factors of the changes in different regions of the TRHR in different periods are different, and the uncertainty of changes will further increase under the background of climate warming. It is necessary to pay attention to the research on the driving mechanism of grassland change, and there are still relatively few quantitative studies on the impact of climate change and human activities on the grassland ecology of TRHR, which are crucial for the protection of grassland ecosystems, and a clear understanding will increase the likelihood of successful restoration of degraded grasslands. Therefore, the research on grassland change and its influencing factors is undoubtedly a process of continuous efforts. In addition, the impact of pika on the TRHR grassland needs to be further evaluated to determine the degree of impact on the grassland ecosystem as a whole to determine the status of the pika.

The TRHR ecological protection policy needs to emphasize the effective integration of market logic, consider the feedback and triggers of family decision-making, and help herdsmen understand the restoration plan and master restoration techniques through education and publicity (Sheng et al., 2019), so as to achieve all-round effective management. Conservation policies also need to enhance awareness of the relationship between ecological and cultural conservation in TRHR, and acknowledge that local Tibetans and their traditional customs and cultures are part of the conservation process so that successful management can be achieved.

The grazing capacity of TRHR has changed drastically due to climatic factors. In response to this, grazing capacity should be effectively regulated, better livestock breeds should be selected, and grass species more adaptable to climate change should be cultivated. In addition, it is necessary to make various preparations for climate change as early as possible, and to formulate artificial intervention mechanisms to enable the healthy development of local animal husbandry (Zhang et al., 2013b). Rational utilization is the best strategy for grassland protection. The likelihood of success of long-term grassland restoration strategies depends on the level of grassland degradation (Lin and Zhang, 2020), and different measures should be taken according to the degree of degradation (Wen et al., 2013). The effectiveness of rehabilitating meadows through cyclical efforts depends on the degree of degradation, and depending on the degree of degradation, different measures should be taken. It is recommended to implement rodent control, light grazing, enclosure, weeding, fertilization and other techniques for restoration of grasslands with mild and moderate degradation levels. But for the severely degraded "black soil beach", it needs to be restored by artificial seeding. Appropriate manual intervention is required to prevent secondary degradation during the restoration succession. Research in grassland restoration needs to emphasize the stability of plant-soil systems (Gao et al., 2019b) to establish relatively stable communities.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of

this paper.

Author contribution

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Shu-jun Li : methodology

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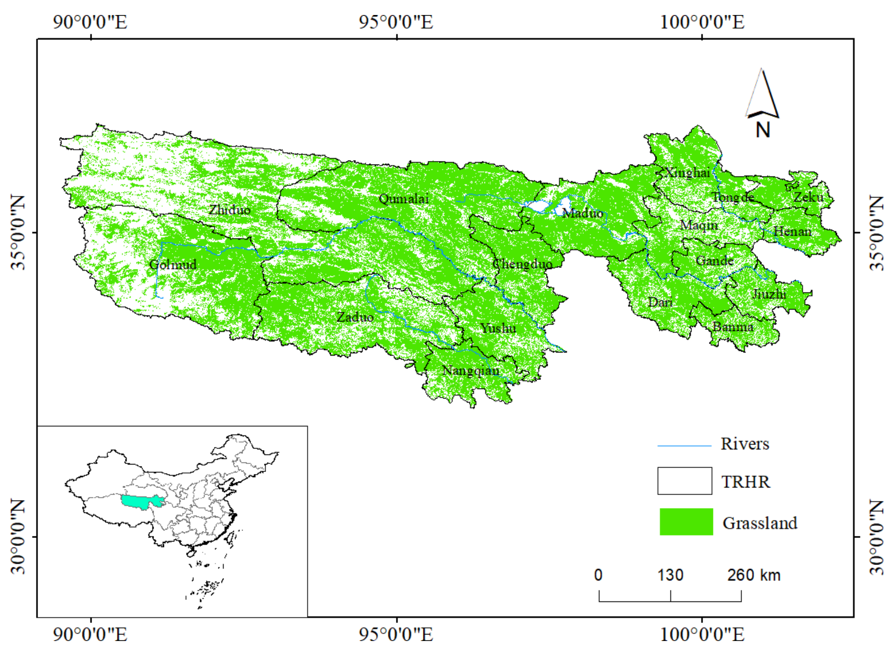

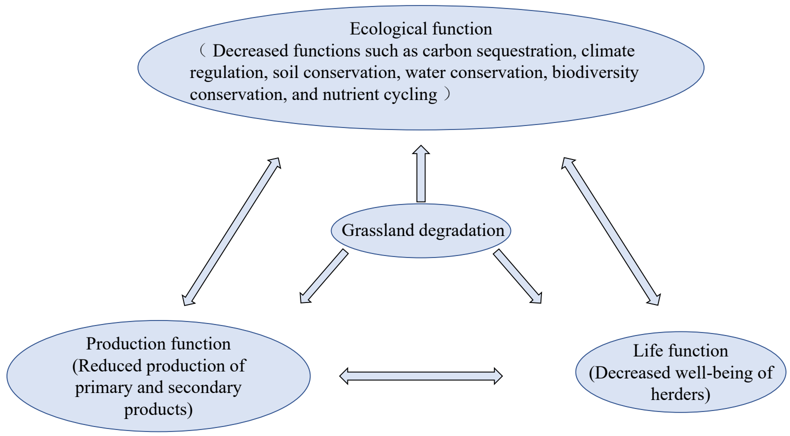

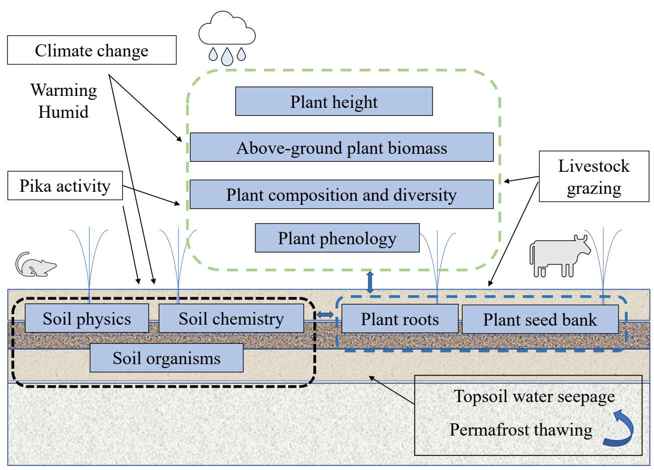

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