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Review

Alpine Grassland Degradation and Its Restoration in the Qinghai–Tibet Plateau

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Abstract: The alpine grasslands of the Qinghai–Tibet Plateau are one of the most famous grazing ecosystems in the world, providing a variety of ecosystem functions and services. The rate of grassland degradation has been slowed by the implementation of national grassland restoration projects, but the degradation of grasslands on the Qinghai–Tibet Plateau has not yet been fundamentally reversed, and some grasslands are still degraded to varying degrees. The main causes of grassland degradation on the Qinghai–Tibet Plateau are both human and natural factors. Human factors include overgrazing, over-cultivation, indiscriminate digging and mining, mineral resource development, infrastructure construction and use, and tourism development. Natural factors include climate change, wildlife destruction, pests, etc. Based on the principles of restoration ecology, a number of effective practices and integrated management responses for restoring degraded grasslands have been developed on the Qinghai–Tibet Plateau. The degraded grassland restoration practices include fencing, fertilization, sown grassland establishment, rodent control, and grazing management. Based on these practices, the comprehensive restoration of degraded grasslands and the establishment and sustainable management of sown grasslands in the alpine grasslands of the Qinghai–Tibet Plateau should be further strengthened, and research on the mechanisms of grassland degradation and restoration should be further developed.

Keywords: grassland degradation; overgrazing; climate change; grassland restoration

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1. Introduction

The Qinghai–Tibet Plateau (QTP) [1] in southwest China is known as the "roof of the world" and the "third pole of the earth" and is the "source of rivers" in China and Asia [2]. With an average elevation of over 4000 m above sea level, the QTP is a unique geographical unit with the highest elevation in the world [3]. The average annual temperature and precipitation on the QTP gradually decrease as the altitude increases from southeast to northwest, ranging from −6.12 to 14.95 °C and 17.6 to 1741.6 mm, respectively. Over the past 50 years, the average annual temperature on the Qinghai–Tibet Plateau is 4.85 °C and the average annual precipitation is 415.3 mm. Under the combined influence of the climate system and the geographical environment, the spatial pattern is warm and humid in the southeastern part of the plateau and cold and dry in the northwestern part [4]. As a 'sensor' and 'sensitive area' for climate change in Asia and the Northern Hemisphere [5], the QTP supports many ecosystems such as forests, shrubs, meadows, grasslands, and deserts [3], which are important for climate and water regulation, biodiversity support, forage provision, and tourism. These ecosystem services are primarily provided by alpine grasslands [6–8].

The QTP is covered with 1.51×10^8 hm^2 of grasslands, accounting for 60% of the area of the QTP [5]. As one of the world's most important grassland and rangeland ecosystems [9], the degradation of alpine grasslands on the QTP has become increasingly severe in recent decades due to both climate change and human activities [10]. However, grassland degradation has slowed with the implementation of national grassland restoration projects, but grassland degradation on the QTP has not been fundamentally reversed [11], and some grasslands are still degraded to varying degrees. Grassland degradation has led to an inverse transformation of the structure and function of grassland ecosystems, accompanied by a loss of productivity, soil acidification, loss of biodiversity, and even changes in ecosystem function [12–14]. Due to the negative impacts of grassland degradation and the importance attached to it at the national level, grassland degradation and restoration are gradually becoming important aspects of ecological research [15,16].

2. Basic Information on the Degradation of Alpine Grasslands on the Qinghai–Tibet Plateau

2.1. Sub-Regions of Alpine Grasslands on the Qinghai–Tibet Plateau

The main types of grassland vegetation on the QTP include alpine meadows, alpine shrubs, alpine grasslands, and alpine deserts [17]. Hu [18] classified the alpine grasslands of the QTP into five sub-regions: (1) Alpine grasslands and deserts in northwestern Tibet; (2) temperate mountain-lake basins and alpine grasslands in southwestern Tibet; (3) temperate grasslands, alpine grasslands, and alpine meadows in the Qilian Mountains and Qinghai Lake; (4) alpine meadows in the eastern QTP; (5) valley warm shrub meadows and mountain meadows in the southern Himalayas. With population growth and economic development, alpine grasslands are becoming increasingly degraded. By the end of the last century, the degradation of grasslands on the QTP had become a particular ecological and environmental crisis.

2.2. Degradation Status and Gradients of Alpine Grasslands on the Qinghai-Tibet Plateau

Grassland degradation refers to the process of retrograde succession in grassland ecosystems, where the quality of grassland (including plants and soils) declines and the composition, structure, and function of the ecosystem are significantly altered as a result of human activities or adverse natural factors [19]. Grassland degradation is caused by human activities and natural climate change. Ekvall [19] and others first identified the 'black soil' phenomenon on the QTP, which refers to severe degradation of grasslands caused by overgrazing, rodent damage, freeze-thaw and wind (water) erosion, resulting in sparse vegetation, reduced cover, less edible forage, bare soil, deterioration of soil structure and physical and chemical properties, and increased soil erosion. This has led scientists to be concerned about the degradation of grasslands on the plateau. It was only in the 1990s, with the rapid development of China's population and economy, that scientists discovered that grassland degradation was becoming more serious and that grassland degradation on the Tibetan Plateau had become an ecological and environmental crisis. In order to identify the degradation of grasslands, the relevant government departments drew up a map of the distribution of degraded grasslands in northern China, discussed the problems associated with grassland degradation, and continued to implement various environmental and ecological construction projects to curb the negative impact of human activities on the environment [20]. In the 1990s, the total area of degraded grassland on the plateau was 4.25×10^7 hm^2, representing 32.69% of the available grassland [21]. The total area of degraded grassland in the "black soil" increased from 3.97×10^6 hm^2 in the 1980s to 7.03×10^6 hm^2 in the 1990s, and the proportion of degraded grassland area increased from 9.33% to 16.54%.

In recent decades, experts and scholars have studied and discussed grassland degradation, but the classification methods and criteria for grassland degradation have not been fully harmonized [22,23]. In 1996, Wang [24] determined the degree of grassland degradation based on vegetation succession. Li [25] classified the degree of grassland degradation in China as mild, moderate, severe, and extreme. To quantify the degree of grassland degradation, Liu [26] proposed ten evaluation indicators of grassland degradation, primarily including the three aspects of grassland productivity, degraded species characteristics, and soil physical characteristics. Ma [27] looked more at the aspect of grassland productivity and classified degraded grasslands into four classes based on this indicator. In 2003, the Ministry of Agriculture of the People's Republic of China proposed grading indicators for the degradation of natural grasslands, classifying the degree of grassland degradation into four levels from eight items, including plant community characteristics, plant community composition structure, indicator plants, aboveground grass production, soil nutrients, surface characteristics, soil physical and chemical properties, and soil nutrients, indicating a continuous process of grassland degradation, i.e., undegraded grassland, slightly degraded grassland, moderately degraded grassland, and severely degraded grassland.

2.3. Degradation Process

As grassland degradation continues to increase, the functions of different ecosystems in grasslands continue to decline. Grassland degradation is primarily reflected in the decline of grassland ecological attributes (e.g., grassland productivity, biodiversity, soil organic matter, etc.) and other ecosystem services (e.g., forage yield, forage quality, etc.). As grassland degradation increases, vegetation cover gradually decreases [28], the soil surface is directly exposed to strong solar radiation, soil air permeability decreases, and soil bulk density increases, affecting plant root development [15,29]. Coupled with rodent damage, soil water and nutrients gradually move to deeper layers [30], which is unfavorable for the growth of sedge family vegetation. Although the dominance of Gramineae does not change significantly, the biomass of weeds increases and gradually replaces the sedge plants, resulting in a lower proportion of high-quality forage grasses [29]. As weeds need to absorb less soil N, the input of organic matter into the soil from the root system is reduced, limiting the accumulation of soil organic matter to some extent [31]. In addition, the degraded soil environment further reduces soil microbial activity and soil enzyme activity, which inhibits the decomposition of soil organic matter and reduces soil nutrients to some extent [32].

3. Factors of Degradation of Alpine Grasslands

The main causes of the degradation of alpine grasslands on the QTP are both human factors and natural factors. Human factors include overgrazing, excessive land reclamation, indiscriminate mining, mineral exploitation, infrastructure construction and use, and tourism development. Natural factors include climate change, wildlife destruction, and insect pests.

3.1. Human Factors in the Degradation of Alpine Grasslands

3.1.1. Overgrazing

The QTP has a grassland-based ecological environment due to its special geographical conditions, and for thousands of years, most of the local people have lived by grazing, making the QTP one of the most important grazing areas in China [9]. With China's economic and social development and population growth, the demand for high-quality protein has increased over the years, and the pressure of livestock on grasslands has further increased [33,34]. Based on the grass-livestock balance of the QTP from 2000 to 2018, Wang [35] evaluated the grass–livestock balance of counties and cities in the QTP and found that 57% of counties in the plateau are in overload, with the largest areas in Qinghai Province and Tibet Autonomous Region, where the percentage of counties in overloaded status was as high as 60% and 74%, respectively. The overall livestock pressure on the QTP is higher. Overgrazing has a significant impact on the fragile grassland ecosystem of the QTP and is one of the major causes of grassland ecosystem degradation [36,37].

Free grazing inhibits the growth of many high-quality forage grasses, resulting in significant reductions in plant height and leaf area, with individual plants showing significant dwarfing [38,39]. The normal growth and development of forage grasses are further inhibited by the reduction in plant leaf area, leading to a significant reduction in photosynthetic efficiency [40]. In addition, overgrazing can affect the native vegetation community by reducing the proportion of high-quality forage grasses and decreasing biomass [41]. The decrease in the proportion of good pasture contributes to the degradation of grassland ecology, leading to reverse succession in vegetation community ecology [34]. Trampling and excreta caused by grazing also affect the structure and function of belowground communities such as soil, root systems, and microorganisms, altering the rate of decomposition of organic matter, which, in turn, affects ecosystem nutrient cycling [42,43]. In addition, long-term trampling by livestock has led to soil consolidation, reduced soil nutrients, and increased sand content, resulting in reduced soil hydraulic conductivity and thus increased soil erosion, leading to grassland degradation [41].

3.1.2. Over-Cultivation

Since 1949, China's population increased dramatically, and the food problem gradually became apparent. To solve the food shortage problem, large-scale reclamation of "wasteland" was initiated, and a large part of the "wasteland" was natural grassland [37]. Between 1956 and 1959, 6.67×10^5 hm^2 of grassland was reclaimed as farmland in Qinghai Province. Due to the inadequate water supply and unsuitable crop temperatures, most of the farmland was rapidly abandoned, and thirty years later, the abandoned land has not fully recovered, with plants in a secondary successional stage and a much higher rodent population than in grassland under normal conditions [36]. Some farmers and herders in remote areas are motivated by profit to start illegal reclamation, which also leads to the gradual conversion of high-quality grasslands with good natural conditions and high productivity into arable land, increasing pressure on grasslands and causing grassland degradation [44], and also leads to the sanding of three times the reclaimed area [45,46]. Thus, grassland reclamation and cultivation are also major causes of grassland degradation.

3.1.3. Indiscriminate Digging and Mining

The QTP is the birthplace of Tibetan medicine and Tibetan pharmacology, of which Tibetan medicinal resources are important biological resources in China, with medicinal, economic, scientific research, livelihood, cultural heritage, ecological, and edible value. With the development of human society and the importance attached to the traditional medicine industry, Tibetan medicine has also seen flourishing development, but driven by short-term economic interests, farmers and herdsmen, as well as foreign seasonal diggers, have begun a long-term casual and predatory exploitation of Tibetan herbal resources on the QTP. Wild Tibetan medicinal resources have now been destroyed in a short period of time, with *Cordyceps*, *Fritillaria* spp., *Saussurea involucrata*, and some other high-value resources [47]. The indiscriminate exploitation of wild Tibetan medicinal resources also leads to the destruction of other surrounding vegetation [48], and the interaction with rodents and strong winds exposes the soil to soil erosion, pasture degradation, and even sanding. It is estimated that one excavator destroys thousands of square meters of grassland in a year [48]. Therefore, indiscriminate excavation not only leads to the destruction of medicinal plant habitats but also exacerbates the shrinkage of natural grasslands, putting some species at risk.

3.1.4. Development of Mineral Resources

The QTP is rich in mineral resources. According to relevant information, the potential value of mineral resources on the QTP was as high as 600 billion RMB as early as 2010 [49]. Mineral resources are one of the original resources essential for social development, and with the development of society and the progress of science and technology, people's demand for mineral resources has increased, and the QTP has become a popular mining area due to its unique mineral resource conditions. The exploitation of mineral resources has led to rapid economic development in the QTP, but at the same time, a number of geological problems have arisen. For example, illegal mining of the Muli Coal Mine has led to the destruction of a large number of alpine grasslands, the destruction of topography and landscape by open-pit mining in Laji Mountain, the degradation of vegetation communities by alluvial gold mining in the southern QTP, and the mudslide disaster at the Jiama Copper Mine [50,51]. The high altitude, cold climate, and short plant growth cycle of the QTP make it difficult for vegetation to recover naturally once damaged, and it is much more difficult and economically costly to manage artificially than in the east [51–53]. Therefore, the irrational exploitation of mineral resources has also led to the destruction of large areas of grassland on the QTP.

3.1.5. Infrastructure Development and Use

The QTP is one of the key areas in China's Western Development Strategy and the Belt and Road Initiative. With the implementation of the 8th and 9th Five-Year Plans and the development of the Western Development Strategy, the state has increased its investment in transport on the QTP, and a large number of infrastructure construction projects (e.g., railways, roads, power grids) are the guarantee for the smooth implementation of these national strategies. The construction of infrastructure inevitably crosses the natural grasslands of the QTP [54,55], and due to the fragility of the grasslands on the QTP, the construction and use of infrastructure inevitably cause a lot of damage to the natural environment.

The construction of new roads and railways can disrupt the survival of native grassland plant communities, destroy soil microtopography, alter microclimates, and create large amounts of rock outcrops [56]. The destruction of native vegetation on roadside slopes is extremely difficult to restore and can easily lead to soil erosion and ecological degradation [57]. For example, some studies have shown that the Qinghai–Tibet railway project has the greatest impact on alpine grasslands and alpine meadows, which are higher than other ecosystems [58]. The construction of the project will create a large amount of engineered land, and the original vegetation of these engineered lands will be directly removed [59,60], which, on the one hand, seriously affects the self-renewal ability of plant populations in alpine meadows, which are mainly propagated by bud banks [55], causing fragmentation of grassland landscapes [61]; on the other hand, it destroys the structure of soil aggregates, increases surface water evaporation, reduces soil water storage capacity, and causes severe soil erosion [55,62], further leading to grassland degradation on the QTP. In addition, road traffic not only increases the export of heavy metal pollutants to the surrounding environment [59] but can also change the distribution of plant communities along the route and even lead to the loss of plant and animal species [63]. With the development of road transport on the QTP, the enrichment of heavy metals in grassland soils from road traffic has become a major cause of current and future grassland degradation [45].

3.1.6. Tourism Development

With the development of the Internet economy, increasing development has also been brought to the QTP. The development of tourism has not only brought a large number of tourists and increased income, a large number of support facilities and jobs, and economic growth to the QTP but has also created a number of environmental problems. Due to the large size of the various natural areas on the QTP, the lack of rational development and negligent management has led to a series of problems, such as the lack of fencing, which allows tourists to trample freely or even drive into flat meadows or gently sloping grasslands for picnics and other activities, causing great damage to the natural ecological environment around the scenic spots. At the same time, degradation on both sides of the scenic road and radiated degradation are important aspects of alpine grassland ecosystem degradation [37]. For example, a study by Sun et al. [64] showed that grassland tourism reduces grassland plant species richness, the diversity index, and aboveground biomass to varying degrees. Grassland tourism significantly reduces some soil nutrients and increases soil bulk density and compactness. The influx of tourists and service workers is more likely to cause grassland degradation, for example, studies have shown that relatively densely populated areas in northern Tibet are prone to grassland degradation [65]. Therefore, grassland degradation caused by tourism development should not be ignored.

3.2. Natural Factors of Alpine Grassland Degradation

3.2.1. Climate Change

The QTP is a sensitive area to climate change, and in recent years, global warming due to the greenhouse effect has exacerbated the overall deterioration of the alpine grassland ecosystem, resulting in an increase in temperature and severe desertification and degradation of grasslands on the QTP [39]. Among climate change factors, temperature and precipitation play an important role [66], as temperature increases, soil moisture decreases [67,68], the number of shallow-rooted plants decreases due to their poor drought tolerance [69], and the proportion of grasses adapted to arid conditions increases [70], but reduced light intensity in the lower layers of the community put low plants at a competitive disadvantage and inhibits seed germination [71], which, in turn, changes the species composition of the grassland and significantly reduces species richness in alpine grasslands [72,73]. However, some studies showed that warming did not significantly affect plant diversity [74]. In addition, annual precipitation has increased in the northeastern, central, and southwestern parts of the QTP, while annual precipitation has decreased in the southeastern parts, and increased precipitation has increased species richness [67] and species diversity [75] in plant communities to some extent. However, it has also been shown that changes in precipitation do not significantly affect plant diversity [76], and that species richness in alpine grasslands gradually decreases with increasing precipitation [70]. Temperature increases and precipitation together alter plant community structure [77,78], with warming reducing species richness but increased precipitation slowing this trend [79,80], possibly due to warming increasing plant respiration and evapotranspiration and precipitation supplementing vegetation water demand [70,80], but the magnitude of the effect of warming and precipitation depends on the outcome of the interaction between the two.

3.2.2. Wildlife Destruction

Grasslands are not only a material security for livestock but also a natural habitat for wildlife survival [81]. A variety of wild rodents are widely distributed on the QTP, and rodents are known for their incredible reproductive rates and gnawing abilities, making them one of the most important pest taxa worldwide [82]. The damage caused by rodents to grassland ecosystems is primarily in the form of large amounts of nibbling and storage of high-quality grasses, soil digging, and mounding, resulting in habitat destruction, grassland degradation, and the reduction of livestock carrying capacity, thus seriously threatening the ecological security of grasslands and the sustainable development of grassland livestock [83,84].

Ochotona curzoniae and *Myospalax baileyi* are classified as indigenous rodents that are widely distributed on the QTP. They not only have strong physiological adaptations but can also dig underground burrows to withstand the harsh climatic conditions of the plateau and avoid predation by natural predators; at the same time, the special reproductive mode of this animal population (multiple mating systems) results in its population being able to grow rapidly [85]. A study showed that the average area of bare ground caused by each mound in alpine grasslands was 2231.7 cm^2 [86],

Sun et al. (2015) found that the area of rodent infestation in Qinghai Province alone in the past 15 years was between 7 and 10×10^6 hm^2, and the area of damage was approximately two-thirds of the area of occurrence [85]. In addition, some studies have shown that in areas with a high density of *Ochotona curzonia* populations, the proportion of biomass of weed community reached approximately 60%, while the proportion of native high-quality forage grasses was only approximately 20% [87], and the total biomass in high-density areas was significantly lower than that in low-density areas. In particular, the average total biomass during the growing season was approximately 55% lower than the highest [85], with similar damage caused by *Myospalax baileyi* and significant reductions in cover and biomass in areas where *Myospalax baileyi* rodent infestations occurred [88]. In addition, rodent damage can alter the ecosystem structure and processes in a short period of time, causing severe damage to QTP grasslands [85].

In addition to the damage caused by small rodents to the grasslands of the QTP, the threat posed by large herbivores to the grasslands of the QTP cannot be ignored. In recent years, as the conservation of wildlife and their habitats has progressed and time has passed, the populations of some key protected species have recovered rapidly, and some habitats have even been degraded by overexploitation and trampling due to excessive populations of large herbivorous wildlife, threatening regional ecological security [89]. For example, Yang [90] showed that the impact of large wild herbivores on the grass-livestock balance in Maduo County, Sanjiangyuan District was obvious: The realistic livestock carrying capacity and livestock pressure increased by 22%. Dong [89] showed that the population of *Equus kiang* had exceeded the maximum ecological capacity of suitable habitats in the reserve, and the excessive growth of the population of *Equus kiang* may pose a risk of habitat degradation.

3.2.3. Insect Pests

Grassland pests are widespread, numerous, and damaging, and pose a serious threat to grasslands. Pests play an important role in grassland ecosystems, and their activities strongly influence the dynamic balance of grassland ecosystems. The *Gynaephora alpherakii* is one of the major grassland pests on the QTP. The *Gynaephora alpherakii* can nibble the whole Kobresia plant together with roots and stems, which is very harmful to the grass. The pest caused an average annual loss of 2.31 × 106 t of grassland, accounting for 23.1% of the country's total forage demand. Such multi-feeding and selective feeding has seriously affected the flowering of forage grasses, inhibited the growth and normal development of forage grasses, and instead led to the gradual increase in toxic weeds, resulting in the degradation and even sanding of grasslands [41,91]. According to previous studies, the *Gynaephora alpherakii* disaster had a damaged area of 1.47×10^5 hm^2 only in Maqin County, Qinghai Province [91]. In Haibei Prefecture, Qinghai Province, the *Gynaephora alpherakii* damaged area in 2009 was 1.02×10^5 hm^2, and the locust damage area was approximately 1.27×10^5 hm^2 [92]. The severely damaged grassland vegetation is difficult to recover within two years, and the productivity and livestock carrying capacity of grassland have been significantly reduced, which may cause grassland degradation [91].

4. Alpine Grassland Restoration Techniques

By applying the theory of restoration ecology and using various measures to restore degraded grasslands, grassland ecosystem functions can be enhanced and grassland health can be restored to some extent [93]. Some commonly used restoration measures include sown and semi-sown grassland establishment, fence closure and grazing prohibition, grass seed replanting, and toxic weed prevention and removal [23,94]. In general, different grassland restoration measures have their own focus and scope, and the correct selection of grassland restoration measures is a prerequisite for the success of grassland restoration.

4.1. Enclosure

Fencing is widely regarded as a simple restoration method for degraded grasslands, and it is often assumed that the system will recover itself in a fenced environment [95]. This is primarily because fencing can effectively reduce herbivore feeding on grasslands, thus effectively restoring vegetation cover and species richness [96], increasing the stability of vegetation community structure [97], and contributing to the stability of the grassland ecosystem and the natural recovery of productivity. However, long-term fencing can also reduce grassland cover and productivity [98], likely because long-term fencing promotes the formation of monodominant species in grasslands and competes for the habitat of other vegetation, thus reducing biomass [99].

Fencing also has a positive effect on improving the physical and chemical properties of the soil in grassland. Following the implementation of the Returning Grazing to Grass project in China, vegetation cover and biomass increased, and continuous fencing increased the resistance of grasslands to soil carbon and nitrogen loss, improving soil fertility and increasing above- and below-ground biomass [100]. In addition, according to scientists, the best grazing prohibition period should last 6 to 20 years, and the duration of fencing needs to be tailored to the specific local context [62,101–103].

4.2. Fertilization

Improving soil nutrient conditions through fertilization is a direct way to meet the nutrient needs of degraded grassland vegetation [104]. The appropriate application of N, P, and K fertilizers can increase grassland biodiversity and productivity [105]. Currently, N fertilization is widely used in alpine grasslands on the QTP, and N application can improve grassland productivity by increasing the effective soil N content [106]. However, excessive application of N fertilizer can cause a decline in grassland biodiversity [107]. In addition, phosphorus fertilizer is beneficial for the growth of plant roots and leaves, primarily by increasing the photosynthetic efficiency of plants to increase the dry matter content of plants [108], while the use of phosphorus fertilizer can increase the cold hardiness of forage grasses and improve their productivity [109]. A mixture of nitrogen and phosphorus fertilizers and organic fertilizers can increase the aboveground biomass of sandy grasslands [110], and the higher the amount of ammonia and phosphorus applied, the higher the crop yield [111]. Ma [112] increased fodder production by 55% by applying microbial solutions. Among them, micronutrient fertilizers primarily enhance forage production by improving plant photosynthesis, while rare earth element fertilizers can stimulate soil microorganisms and increase their activity, thus improving forage productivity [113]. Therefore, there is still a need for future research on the optimal fertilizer application rates and fertilizer types for different grass types.

4.3. Sown Grassland

Sown grassland establishment has a positive effect on alleviating grass–livestock conflicts [114]. The main seeding plants currently applied in alpine grasslands include high-quality forage such as *Elymus nutans*, *Poa crymophila*, and *Festuca sinensisi*. Sown grassland can bring the grass cover close to the native vegetation three years after establishment [115]. Wang [116] also proved this by studying the sown grassland in the headwaters of the Three Rivers. The physical and chemical properties of the soil in the planted ley will also change. The content of soil organic matter is low in the planted ley [95]. Soil organic matter content is lower in planted grasslands, and the longer the restoration period, the higher the soil nutrient content (e.g., organic carbon, total nitrogen) [117], but the total potassium content decreases, suggesting that fertilization of planted grasslands should increase the application of potassium fertilizer [118]. However, the number of plant species used in the restoration of sown grasslands on the QTP is still low compared to natural communities, which makes the plant communities of sown grasslands unstable in the natural environment and highly susceptible to degradation. Therefore, in the later stages of sown grassland construction, the local plant community composition should be fully considered, and the number of seeded plant species should be increased. For example, Ma [119] suggested that a key technique for restoring black-soil-degraded grasslands is mixed seeding of a variety of perennial grasses, which can provide rapid and stable restoration of black soil degraded grasslands. In addition, no-till reseeding can promote the development of degraded grasslands in a benign direction with little or no damage to the native grassland vegetation. Reseeding can increase the above-ground biomass of grasses, reduce the proportion of weeds, effectively improve soil quality, and promote the recovery of degraded grasslands [120,121]. Therefore, to solve the shortage of wild fodder grass seed sources, the promotion of sown grassland planting and no-till replanting techniques are effective ways to be applied in the restoration of degraded grasslands on the Tibetan Plateau.

4.4. Rodent Control

Rodent control is also the focus of research on grassland restoration techniques. Commonly used rodent control methods include chemical, physical, biological, and sterile control methods [122]. For chemical control, i.e., drug control, commonly used drugs such as aluminum phosphide and sulphur dioxide [123,124] can reduce the density of rodent infestation in a short period of time, but may also kill natural enemies of rodents [125]. Regarding physical control methods, i.e., equipment for rodent control, commonly used tools include rat traps and snares, and certain crops such as corn kernels are needed as bait [123,124], but the efficiency of rodent control is low and the catch rate is not high [126]. Biological control methods include natural enemies such as owls and microorganisms that are harmless to humans and animals but highly pathogenic to rodents, such as *Botulinum toxins* [124], but the effectiveness of biological control is not ideal due to human activities, the endangerment of rodent natural enemies, and the strict conditions for microbial rodent control [123]. Sterility control methods primarily control the growth of the pest population by sterilizing the pest rodents, and commonly used methods include ligation and placing sterile agents such as printing creeper oil [127], but some sterile agents only target females or males, which is not selective and easily causes environmental pollution [83]. Rodent suppression plays an important role in the recovery of alpine meadow vegetation, so different control measures need to be taken depending on the degree of rodent infestation, combining biological and ecological control as much as possible, with biological rodent control being the main focus while optimizing grass community structure to prevent aggravation of the rodent infestation and enable the recovery of degraded grasslands [34,128].

4.5. Grazing Control

Rotational grazing can not only provide suitable habitat for new species, increase species numbers, maintain grassland productivity and diversity, and improve grassland resistance and resilience but also helps to maintain the stability of grassland ecosystem functions and enhance ecological service functions [129,130]. Compared with continuous grazing, rotational grazing can improve herbaceous productivity and soil organic carbon content [131,132]. To maintain the stability of grassland systems, we can start with warm-season grazing and cool-season protection to reduce grazing pressure on grassland [133], reasonably control the livestock carrying capacity of grassland, improve the slaughter rate of livestock [134], and combine grass and livestock to achieve a dynamic balance between grass and livestock, ultimately achieving sustainable use of grassland resources.

As discussed above, different grassland restoration measures can contribute to some extent to the recovery of degraded grasslands, and, in practice, they should be applied according to the specific environment of the degraded grassland. On the other hand, different grassland restoration measures are often very specific and there is an urgent need to develop appropriate integrated management models for alpine grassland degradation.

Figure 1 illustrates the restoration techniques and models for degraded grasslands in the context of integrated management of alpine grasslands on the QTP. For lightly degraded grasslands, the natural state is restored using the self-restoration mechanism of the grassland, with measures such as fencing or controlling grazing intensity to improve productivity and increase the number and diversity of plant species. For moderately degraded grasslands, restoration is primarily carried out in a semi-natural and semi-sown manner by adding some factors beneficial to the growth and development of the grassland, such as nitrogen fertilization and replanting of grass seeds, combined with the self-restoration capacity of the grassland to further stabilize the community structure of the grassland and increase its productivity and soil fertility. As severely degraded grasslands have very little capacity for self-recovery, sown re-establishment, and fertilizer application, together with rodent control techniques, are used until the grassland community structure is stabilized, grassland productivity is gradually restored, and soil fertility is improved. These integrated restoration methods have been implemented in degraded grasslands in Haibei and Guoluo Provinces of Qinghai Province and have shown some results [135].

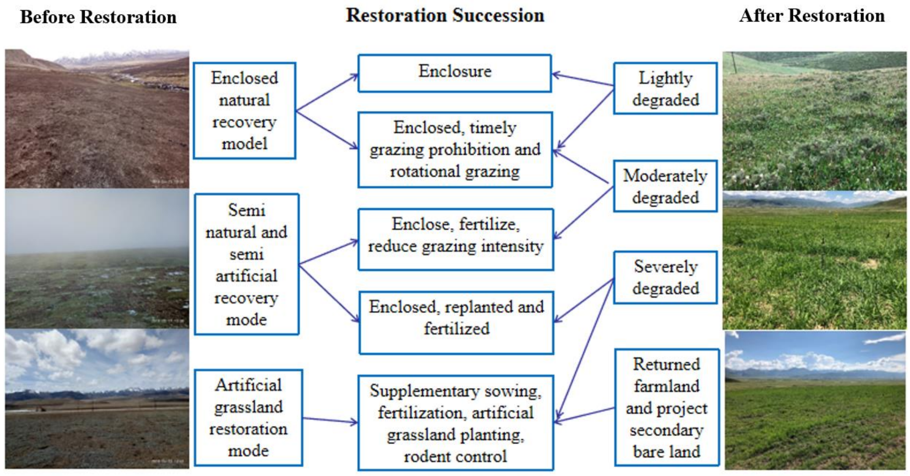

Figure 1. Methods and models for alpine grassland restoration.

5. Discussions

There is a lack of research on the effects of climate change on grassland vegetation dynamics. Most of the studies on the effects of warming on grassland plant diversity have only 3–5 years of results, and warming experiments were conducted in different ways and contexts, so there is a need for ongoing research on the effects of different warming times and different warming methods on grassland plant diversity in different grassland types. In addition, studies on the effects of increased or decreased precipitation on plant diversity due to increased extreme weather events caused by climate change have not considered the effects of extreme weather events on grassland plant diversity and should therefore be considered in future studies. At the same time, climate change factors jointly influence changes in grassland vegetation, and there are currently few experiments on the coupled effects of warming and precipitation, so further research on the effects of climate factor coupling on grassland vegetation needs to be strengthened.

The mechanisms of alpine grassland degradation are still very confusing, and although there has been much research into the loss of soil nutrients due to grassland degradation, there is still a lack of understanding of the magnitude and rate of decline of soil nutrients at different degrees of degradation and the mechanisms of interaction between plants, soils, and micro-organisms and soil fauna during degradation, and it is not clear how grassland degradation and restoration changes the composition of alpine grassland vegetation communities and the underlying mechanisms, so further research is needed.

At present, restoration and management techniques for degraded alpine meadows are fragmented and the treatment effects are not sustainable. There is an urgent need to develop adaptive restoration techniques for degraded alpine meadows to achieve the goal of sustainable restoration of degraded alpine meadows, significantly improve the ecological functions of the system, effectively protect and use them, and provide scientific basis, technical support, and demonstration models for the restoration of degraded grassland ecosystems.

Grassland restoration is temporal and spatial in nature, and the impact on grassland ecosystems during its lifetime is multifaceted and dynamic in performance; the optimization of restoration measures is not only relative to the objectives pursued but is also susceptible to the influence of other factors such as the environment and management and involves a degree of uncertainty and risk. Grassland restoration research at the system level should take this characteristic fully into account, and according to the specific objectives, the restoration measures of each grassland should be reasonably configured on a certain time scale to balance the contradiction between the supply and demand of the livestock carrying capacity of the system, in order to achieve the effective promotion of vegetation restoration and truly contribute to the sustainable development of grassland livestock farming.

There is a lack of high-level, practical, standardized, and comprehensive technical studies on sown grasslands in alpine pastures, as well as experimental studies on the sustainable use of sown grasslands at different altitudes and in different regions, and technically sound and efficient demonstration models. At the same time, there are few studies on the optimal integration and assembly of key technologies for the rejuvenation and succession rules of old sown grasslands in different altitudes and regions, which do not bring into play the overall effect of existing individual technologies, thus leaving research at the stage of repetition and low-level research of individual technologies, which is far from the requirements of the overall plan for ecological protection and construction in the region.

6. Conclusions

The degradation of alpine grasslands on the Qinghai–Tibet Plateau is caused by a combination of human and natural factors, including inappropriate grazing, excessive reclamation, indiscriminate excavation, mineral extraction, infrastructure construction and use, and tourism development. Natural factors include climate change, wildlife destruction and pest infestations. Man-made factors include long-term overgrazing and subsequent destruction by rodents and climate change, which accelerates the process of grassland degradation. Based on this background and the principles of restoration ecology, a number of effective practices and integrated management responses have been developed for the restoration of degraded grasslands on the Tibetan Plateau. Degraded grassland restoration practices include fencing, fertilization, sown grassland planting, rodent control, and grazing management. Based on these practices, the integrated restoration of degraded grasslands and the establishment and sustainable use of sown grasslands should be further strengthened in the alpine grasslands of the Tibetan Plateau.

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