Long-Term Ecological Research and Experimental Demonstration Provide Theoretical and Technical Support for Adaptive Management of Alpine Grasslands (Postprint)

Authors: Cao Guangmin, Lin Li, Zhang Fawei, Li Yikang, Du Yangong, Guo Xiaowei, Li Qian, Qian Dawen, Bo Fan

Date: 2023-03-19T00:00:00+00:00

Abstract

Traditional theories posit that the extreme climatic environment of the Qinghai-Tibet Plateau has endowed regional ecosystems with inherent sensitivity and vulnerability, rendering them a global challenge for ecosystem management, conservation, and restoration. In the 1970s, the Northwest Institute of Plateau Biology, Chinese Academy of Sciences, established the Haibei Alpine Meadow Ecosystem Research Station. Long-term monitoring of ecosystem components has revealed the biological mechanisms of alpine grassland responses to climate change on the Qinghai-Tibet Plateau; elucidated successional processes of alpine grassland degradation under grazing disturbance; clarified biological mechanisms for maintaining alpine grassland stability; proposed an adaptive management model for alpine grasslands based on ecological process science; and initiated explorations into ecohydrological processes in alpine grasslands. This research station has pioneered fundamental theoretical research in applied ecology of alpine grasslands, providing technical support for regional sustainable development.

Full Text

Preamble

The traditional theory holds that the extreme climatic environment of the Qinghai-Tibet Plateau has created inherent sensitivity and vulnerability in regional ecosystems, making their management, maintenance, and restoration a worldwide challenge. In the 1970s, the Northwest Institute of Plateau Biology of the Chinese Academy of Sciences established the Haibei Research Station of Alpine Meadow Ecosystem. Long-term monitoring of ecosystem components

has revealed the biological mechanisms underlying alpine grassland responses to climate change on the Qinghai-Tibet Plateau, elucidated the successional processes of alpine grassland degradation under grazing disturbance, clarified the biological mechanisms for maintaining alpine grassland stability, proposed an adaptive management model for alpine grasslands based on ecological process science, and initiated exploration of ecohydrological processes in alpine grasslands. This research station has led fundamental research in applied ecology of alpine grasslands and provided technical support for regional sustainable development.

Keywords: alpine grassland, long-term evolution, stability maintenance, adaptive management, function enhancement
DOI: 10.16418/j.issn.1000-3045.2018.10.013

Alpine grassland is the dominant vegetation type on the Qinghai-Tibet Plateau, serving production, livelihood, and ecological functions. Since the 1970s, strong influences from climate change and human management concepts and practices have led to overuse of the productive functions of alpine grasslands, causing ecosystem stability to fluctuate, become imbalanced, or even collapse, resulting in large-scale grassland degradation. The Party and state have attached great importance to the ecological functions of the Qinghai-Tibet Plateau. Since the 21st century, the government has invested heavily in implementing the Three-River-Source grazing withdrawal and grassland restoration project, the Three-River-Source National Park construction, and the Qilian Mountains National Park pilot program to achieve benign restoration of alpine grassland functions and comprehensive regional ecological governance. For over 40 years, the Haibei Research Station (hereinafter referred to as "Haibei Station") has conducted research on the structure and function of alpine grasslands and their internal material exchange and energy flow, grassland productivity enhancement, alpine grassland responses and adaptation to climate change, carrying capacity of representative alpine grassland ecosystems, environmental-biological-soil-functional linkage mechanisms of alpine grassland evolution, adaptive zoning management techniques based on ecological processes, and research, development, and demonstration of key technologies for enhancing functions of typical damaged ecosystems. These efforts have contributed to safeguarding the ecological barrier function of the Qinghai-Tibet Plateau and promoting regional sustainable development.

1. Vegetation Types and Community Characteristics

By analyzing ecosystem structure, productivity allocation, and population reproduction patterns in alpine grasslands, Haibei Station pioneered biological research on alpine grasslands, filling research gaps on the Qinghai-Tibet Plateau and accumulating substantial scientifically valuable data that has provided important guidance for studies on alpine grassland ecological processes.

Since the 1960s, driven by the International Biological Program (IBP) and the

Man and the Biosphere (MAB) program, long-term research stations for various ecosystem types have been established worldwide. During the first 10+ years after its establishment, Haibei Station focused on the distribution characteristics, community structure, reproductive traits, and productivity of typical alpine grassland plant populations, providing foundational data for understanding alpine grassland ecosystems. Research has revealed that soil moisture conditions are the primary factor determining plant population distribution in alpine meadows, with distinct characteristics among different community types:

(1) Kobresia humilis meadows, one of the most widely distributed grassland types on the Qinghai-Tibet Plateau, feature relatively complex community structure with rich species composition of approximately 30 species/m^2 and total coverage around 85%. These meadows are primarily distributed on well-drained floodplains, foothills, and semi-shaded slopes. The community structure can be divided into two layers, with major companion species including *Stipa aliena*, *Elymus nutans*, *Poa* spp., *Gentiana straminea*, *Leontopodium nanum*, *Potentilla nivea*, *Oxytropis kansuensis*, *Potentilla anserina*, *Gueldenstaedtia diversifolia*, *Pedicularis kansuensis*, *Carex* spp., and various *Ranunculus* spp. *Kobresia humilis* is a cold mesophytic short-rhizome geophyte, 3–10 cm tall, with an average aboveground/belowground biomass ratio of 0.43 during the growing season. Its total reproductive effectiveness averages 49.63% across the life cycle, with sexual reproduction averaging 3.44% and vegetative reproduction 46.58%, approximately 14 times higher than sexual reproduction. The soil water potential niche width of *K. humilis* populations is 0.574 MPa.

(2) Kobresia pygmaea meadows have simple structure with fewer species, about 10 species/m^2. Common companion species include *Stipa aliena*, *Saussurea superba*, *Elymus nutans*, *Leontopodium nanum*, *Gentiana straminea*, *Potentilla nivea*, *Potentilla bifurca*, *Thalictrum alpinum*, and *Trigonella ruthenica*. The layer structure is not obvious, with only one layer and total coverage above 80%, mainly distributed on sunny and semi-sunny slopes. *Kobresia pygmaea* is a cold xeromesophytic short-rhizome geophyte with dwarf plants 3–5 cm tall that grow densely and easily form a compact turf layer. During the growing season, the average aboveground/belowground biomass ratio is 0.66, and total reproductive effectiveness averages 39.67%, with vegetative reproduction at 36.10% and sexual reproduction at 4.11%, making vegetative reproduction more than 8 times higher than sexual reproduction. The soil water potential niche width is 0.283 MPa.

(3) Kobresia tibetica swamp meadows are composed of hygromesophytic perennial herbs with relatively complex community structure, generally having two layers and fewer than 10 species/m^2. Companion species include *Blysmus sinocompressus*, *Carex atrofusca*, *Carex moorcroftii*, *Saussurea stella*, *Aster diplostephioides*, and *Gentiana farreri*. The average herb layer height is 15–25 cm with total coverage of 90–95%. The average aboveground/belowground biomass ratio is 1.49 during the growing season, mainly distributed in relatively wet low terraces and floodplains along river valleys. Average reproductive effectiveness across the life cycle is 22.39%, with vegetative reproduction at 19.46% (82.87% of total) and sexual reproduction at only 2.93%. The soil water potential niche width is 0.267 MPa.

(4) Elymus nutans communities have more complex structure than *Kobresia* meadows with richer species composition and total coverage of 60–80%. *Elymus nutans* plants are 20–60 cm tall with leaf layer height around 15 cm, generally occupying the upper layer, while residual *Kobresia* species occupy the lower layer. Other companion species include *Polygonum sibiricum*, *Potentilla anserina*, *Potentilla bifurca*, *Ajania tenuifolia*, *Pedicularis kansuensis*, *Potentilla nivea*, *Swertia przewalskii*, and *Ranunculus pulchellus*. The aboveground biomass far exceeds belowground parts, with an average ratio of 3.67. Vegetative and sexual reproductive effectiveness are similar, averaging 16.25% and 15.76% respectively, with a ratio of only 1.03. The soil water potential niche width is 0.633 MPa, suitable for relatively warm, sunny valley terraces, foothills, and loose-soil floodplains. These are secondary vegetation types that appear frequently in rodent-damaged areas within *Kobresia* meadows where soil is loose, moisture is moderate, and aeration is good.

2. Degradation Processes and Mechanisms

Typical alpine meadows generally have a two-layer community structure with grasses in the upper layer. Under heavy grazing, selective herbivory suppresses seed reproduction, altering community configuration and reproductive strategies. Grasses decrease while rhizomatous *Kobresia* species become dominant. Rapid and excessive root development increases root-soil and root-shoot ratios, accelerating the extreme development of surface soil biological crusts and turf layers. This reduces soil water infiltration rates and causes biological fixation of limited nutrients by roots, driving alpine meadow degradation through successive stages: grass-*Kobresia humilis* communities, *K. humilis* communities, *K. pygmaea* communities, and forbs-secondary bare land. The fundamental cause of ultimate *K. humilis* degradation is the warming-drying of the root environment and imbalanced nutrient supply-demand dynamics. The extreme thickening, cracking, and erosion of the turf layer in *K. pygmaea* meadows create large-scale erosion pits or forbs-"black soil type" secondary bare land, the main landscape feature of alpine meadow degradation, occupying about 60% of alpine meadow area. Because the turf layer prevents water infiltration, large numbers of *K. pygmaea* die, followed by turf layer erosion, eventually evolving into "forbs-secondary bare land" [Figure 1: see original paper].

Rodent activity and burrowing represent accompanying manifestations of grassland degradation, occurring explosively only when grasslands have degraded to a certain extent. Intensified rodent activity accelerates decomposition of aged turf layers and increases mineralization rates of soil organic matter. Available nitrogen, phosphorus, and potassium in rodent mound soils increase by 54.81%, 49.18%, and 7.2% respectively compared to native grasslands, creating favorable conditions for vegetation regeneration. Rodent mounds become excellent substrates for vegetation recovery, suggesting that rodent outbreaks may be a mechanism for self-regulation or restoration of grassland stability under natural conditions, with rodents acting as engineers of degraded grassland regeneration. This research demonstrates that changes in system components during alpine meadow degradation are mutually causal, with different driving forces, mechanisms, and stability maintenance bottlenecks at various successional stages. Adaptive management based on grassland ecological processes is key to sustainable alpine grassland use and provides theoretical support for adaptive management.

This research pioneered process-based studies of alpine grasslands, accumulating substantial baseline data that remains highly relevant for current research on alpine grasslands and global change, alpine grassland evolution under human disturbance, and adaptive management and function enhancement techniques for grazed alpine grasslands.

3. Climate Change Impacts and Stability Maintenance

Through long-term monitoring and simulation experiments, we discovered that alpine grasslands employ a regulatory strategy of passively selecting suitable ecological evolutionary pathways by altering community structure, which reduces the overall stress response of the ecosystem to external disturbances and ensures system stability.

The Qinghai-Tibet Plateau is experiencing climate change characterized primarily by warming. Since 2000, Haibei Station has established long-term experiments including simulated warming-grazing, simulated hydrothermal changes [Figure 2: see original paper], vertical belt (3,200–3,800 m) reciprocal transplantation, alpine wetland desiccation, and nutrient addition. These experiments have revealed special biological mechanisms by which alpine grasslands respond to environmental changes and ecological processes for maintaining system stability.

Continuous 32-year meteorological observations at Haibei Station show that from 1980–2014, temperature increased at a rate of 0.42°C/10 a ($p < 0.001$) while precipitation decreased at –32.9 mm/10 a ($p = 0.10$). Soil water content also showed a linear decline, with average soil moisture at 5 cm and 45 cm depths during the growing season decreasing from 42.7% ± 5.9% and 44.2% ± 2.4% in 2002–2003 to 24.9% ± 3.8% and 31.9% ± 10.5% in 2009, representing decreases of 17.8 and 12.3 percentage points respectively.

Grassland productivity monitoring indicates that aboveground net primary productivity (ANPP) of alpine meadows and gross primary productivity of alpine shrublands are 164.10 ± 4.27 g C m^{-2} a^{-1} and 511.8 ± 11.3 g C m^{-2} a^{-1} respectively, with interannual variation of 2–5%, demonstrating high stability in grassland productivity under climate change. Eddy covariance measurements also show that alpine *Kobresia* meadows and alpine shrub meadows exhibit weak carbon sink characteristics of 113.65 ± 93.33 g C m^{-2} a^{-1} and –74.4 ± 12.7 g C

m^{-2} a^{-1} respectively, values comparable to aboveground primary productivity. Under grazing conditions, this carbon returns to the atmosphere through food chain transfer, resulting in essentially balanced ecosystem carbon budgets.

The Qinghai-Tibet Plateau alpine grasslands possess enormous carbon storage capacity, with total grassland area of 1.6 million km^2 and total carbon storage of 26.47 Pg C, accounting for 5.1% of China's vegetation carbon storage and 24.3% of soil carbon storage. Alpine grasslands have substantial carbon sequestration potential derived from vegetation-soil carbon pool reconstruction through degraded grassland restoration. Implementation of grazing withdrawal and cropland conversion to grassland in northern China has sequestered soil organic carbon at rates of 130.4 g C m^{-2} a^{-1} (0–40 cm) and 128.0 g C m^{-2} a^{-1} (0–30 cm). However, due to the harsh climate, fragile and sensitive ecosystems, and intensive human disturbance on the Qinghai-Tibet Plateau, realizing this carbon sequestration potential will be a long and difficult process.

Although hydrothermal changes do not affect grassland primary productivity, they alter biodiversity and community structure, causing a shift in dominant plant populations from surface-rooted sedges to deep-rooted grasses. The root-shoot ratio decreases as deep-rooted grasses increase and shallow-rooted sedges decrease, a pattern confirmed across the entire plateau by meta-analysis [Figure 3: see original paper]. Grazing experiments also show that with increasing grazing intensity, plant community functional group composition changes, enhancing the capacity to acquire deep soil moisture and ensuring grassland system stability.

Vertical belt reciprocal transplantation experiments demonstrate that warming advances three early phenological events (green-up, budding, and initial flowering) and two late events (initial yellowing and withering) by 4.8–8.2 days/°C and 3.2–7.1 days/°C respectively, while cooling delays early phenology by 3.8–6.9 days/°C and advances late phenology by 3.2–8.1 days/°C. Initial and final fruiting stages show relatively minor changes to maximize fruit maturation and dispersal, maintaining relatively stable fruiting periods to adapt to climate change.

Metagenomic analysis shows that wetland desiccation and nitrogen deposition reduce CH_4 production potential, thereby decreasing net CH_4 emissions, while reducing nitrification potential and increasing denitrification potential, collectively affecting N_2O emissions. Integrating responses of CO_2, N_2O, and CH_4 to desiccation reveals that both water table decline and nitrogen input reduce the global warming potential of greenhouse gas emissions from alpine wetlands. Contrary to conventional wisdom that wetland water table decline enhances soil phenol oxidase activity to promote organic carbon degradation, we found that as water tables drop, ferrous iron conversion to iron oxides protects more lignin, and the "iron gate" effect centered on ferrous iron oxidation inhibits wetland carbon loss. This microbial and soil chemical mechanism provides new insights for explaining and predicting soil carbon dynamics during wetland drying.

Alpine environments favor soil organic matter accumulation, creating grasslands with "abundant total nutrients but deficient available nutrients." Alpine plants primarily utilize nitrogen in the form of NO_3^-, and alpine grassland nitrogen cycling is dominated by nitrification, contributing 54% of system N_2O emissions. Freeze-thaw cycles physically tear and fragment dead plant roots. Soil microbial groups are controlled by aboveground biomass, soil C/N ratio, and NH_4^+-N content. Livestock excrement alters soil C/N ratios, promotes increases in N mineralization and nitrification genes while decreasing denitrification genes, and reduces methane, carbon sequestration, and decomposition genes due to aboveground litter removal, accelerating grassland biogeochemical cycling and playing a positive role in maintaining nutrient balance.

4. Water Cycling and Grazing Adaptation

Annual evapotranspiration from alpine grassland ecosystems at Haibei Station is 598.0 mm/a, with precipitation of 472.8 mm/a. Vegetation transpiration dominates evapotranspiration at 66.4%, primarily controlled by net atmospheric radiation. The "unidirectional" formation of frozen soil causes deep soil moisture to migrate upward as vapor, accumulating at the surface and storing as ice, with vapor migration contributing about 11% of water to seasonal frozen soil formation. Spring "bidirectional" thawing of frozen soil meets the water demand for grass green-up during "spring drought," improving water use efficiency. Seasonal frozen soil plays a special role in alpine grassland water cycling.

Under heavy grazing disturbance, dominant plant populations undergo morphological evolution toward dwarfing, fine-felting, and turf formation to increase herbivory difficulty and enhance self-recovery capacity through root redundancy. Although both temperature increase and precipitation reduction significantly reduce plant species diversity and community stability, temperature primarily affects stability by reducing asynchrony in species growth, while precipitation pattern changes have no significant effect on community stability. Reduced community stability is not significantly related to species diversity. Grazing alters community structure and diversity by changing forage reproductive strategies.

Alpine meadows show strong adaptability to grazing. Monitoring of plant community productivity in *Kobresia* meadows at different successional stages under the same environmental conditions shows that interannual variation contributes 9.2% to productivity variation, spatial heterogeneity 7.2%, while grazing disturbance intensity contributes 83.6%. Under future global warming, alpine meadow ANPP will not be limited by soil nutrients nor cause changes in soil carbon storage, and moderate grazing benefits ecosystem carbon turnover.

Research demonstrates that alpine grassland ecosystem components improve material and energy cycling pathways, select suitable plant community structural characteristics for environmental conditions, and passively form perfect combinations with environmental conditions, greatly increasing system resistance and self-recovery capacity. Heavy grazing rather than climate change is the main factor causing alpine grassland degradation, with current human pressure far exceeding the grassland self-regulation threshold, representing the primary cause of degradation.

5. Grazing Management and Livestock Optimization

Since the 1970s, Haibei Station has studied alpine grassland carrying capacity. Research shows alpine meadow productivity is moderate, requiring 0.68–1.54 ha per sheep unit (average 1.11 ha). Using the conversion coefficient applicable to pastoral China (one cattle unit equals 3.0 sheep units), each cattle unit requires 2.04–4.62 ha (average 3.33 ha). The suitable stocking rate for alpine meadow grassland (winter pasture) is 3.12 sheep units/ha (equivalent to 5 mu/sheep unit), and for alpine *Dasiphora fruticosa* shrub summer pasture is 2.67 sheep units/ha (equivalent to 6 mu/sheep unit). Using rotational grazing and appropriately extending summer pasture grazing time can increase the regional average stocking rate (9.29 mu/sheep unit) by 35%.

Alpine regions have harsh natural conditions with short warm seasons. The grass growing season is only 100–150 days with low forage yield, while the cold season is long with a withered grass period lasting up to 7 months, resulting in scarce forage storage. Traditional livestock population structures are unreasonable with imbalanced livestock species ratios. Sheep herds typically have a breeding stock ratio around 40%, and yaks around 35%. Sheep are generally raised to over 5 years old (ewes 6–7 years), and yaks to 8 years (cows 8–9 years), with large proportions of aged animals severely affecting reproduction, culling, and commercial rates. The "summer-full, autumn-fat, winter-thin" cycle wastes substantial forage and reduces material and energy conversion efficiency. During the cold season, a 3–4-year-old ewe consumes 9.24×10^{9} J of energy annually but deposits only 2.24×10^{8} J, representing an average conversion efficiency of 2.4%, merely 15.34% of warm-season efficiency. For maintenance, sheep consume 4.31×10^{8} J of body energy, equivalent to 2.64×10^{9} J of intake energy. Each hectare of grassland in *Kobresia* meadow areas provides 2.29×10^{10} J of energy for livestock, while energy loss per sheep during the cold season equals the energy provided by 0.12 ha of grassland, causing forage waste.

Addressing this situation, Haibei Station studied rational livestock population structures and measures for alpine pastoral areas. The recommended culling plan involves removing all wether lambs, old and weak sheep each autumn, plus 3.17% of adult ewes. This approach increases the culling rate to 52.79%, yielding 4.9×10^{4} J of energy or 3.65 kg live weight of sheep products per 100 kg of forage consumed. For Tibetan sheep, the optimal structure is 67.8% breeding ewes, 28.36% replacement ewes, and 3.84% breeding rams and replacement rams, a structure now recognized by herders in the Qilian Mountains.

Due to seasonal imbalance between forage production and livestock nutritional needs in alpine pastoral areas, material and energy conversion efficiency is reduced and substantial forage resources are wasted. Yak fattening in winter warm sheds is a primary measure to resolve the forage-livestock contradiction and seasonal imbalance while maintaining sustainable grassland animal husbandry. Research shows that using a feed formula of 35% oat hay, 20% rapeseed cake, and 41% highland barley for complete stall-feeding in warm sheds during winter increases absolute and relative weight gain by 31.44% and 26.59% respectively compared to free grazing, thereby increasing yak culling rates and forage utilization efficiency. Considering both economic and ecological benefits, fattening yaks during July–September annually yields good results when forage utilization is 50%. For maximum grassland utilization, grazing fattening of yak calves on artificial grasslands is optimal before September 15, while natural grassland grazing fattening is best before the end of October. In Tibetan sheep production areas with winter lambing, slaughtering sheep at 22 months yields higher economic benefits, with carcass weights reaching over 30 kg.

The unique climate of the Qinghai-Tibet Plateau causes countless livestock deaths during the long cold season, creating serious economic losses. Building plastic warm sheds to improve sheep wintering conditions is highly practical for developing pastoral economies. During the cold season (December–March), average temperature inside sheds (–4.41°C) is 7.36°C higher than outside (–11.76°C), increasing lamb survival rates to over 95% while reducing energy consumption of breeding ewes during winter. This technology has been widely applied and promoted in alpine regions of the Qinghai-Tibet Plateau, receiving high attention from herders and local governments as a major component of pastoral area infrastructure projects.

6. Restoration Techniques and Demonstration

Based on long-term observations of alpine meadow degradation processes and mechanisms on the plateau surface, Haibei Station proposed local standards for assessing alpine meadow degradation status and conducted research on "household-scale alpine grassland function enhancement technology integration and demonstration." Results show that grasses are grazing-suppressed functional groups while sedges are grazing-promoted functional groups, requiring different grazing methods including delayed grazing during critical periods, rotational grazing, reduced grazing, or rest grazing. Overgrazing during the green-up period causes rapid consumption of stored plant nutrients, hindering photosynthate expansion and forage biomass increase; continuous overgrazing during seed maturity causes reproductive barriers in seed plants and leads to dominant population succession. Grazing during the non-growing season has minimal impact, with appropriate grazing intensity being "eat half, leave half." Yaks' coarse feeding behavior, high trampling intensity, and strong aboveground biomass removal capacity alter the environment of grassland soil biological crusts, accelerating the development, dormancy, and death of algal and lichen crusts. For grasslands with thick turf layers and dense biological soil crusts, artificial turf cutting can improve seed germination and establishment, increase precipitation infiltration, and provide suitable habitats for forage growth. Long-term grassland enclosure causes large accumulation of surface litter, severely affecting growth of seed-reproducing forages and understory grasses, and can also lead to grassland degradation. The appropriate enclosure period depends on the successional stage.

From perspectives of nutrient cycling, water use, and seed dispersal, natural alpine grasslands should adopt a grazing system of "delayed spring grazing, nomadic summer grazing, rotational autumn grazing, and free winter grazing" to ensure sustainable use. However, due to limited grassland area in household ranches and high dependence on grasslands, this system is difficult to implement. Based on grassland successional status and functional bottlenecks, rotational grazing during key growth stages is more acceptable to herders.

Nutrient regulation can serve as a means to control plant functional groups. Although alpine grassland plants have the highest global levels of nitrogen and phosphorus reuse efficiency at 65.2% and 67.4% respectively, sedge species have the lowest living tissue N and P contents (16.7 $mg \cdot g^{-1}$ and 1.1 $mg \cdot g^{-1}$) but the highest reuse efficiencies (69.1% and 78.7%). Grazing causes rapid declines in surface soil nutrient content, with nitrogen limitation on forage growth becoming particularly evident with increasing grazing intensity.

Grasses are nitrogen-loving crops with high nitrogen demand. Exogenous nitrogen supplementation effectively increases grass proportion and biomass, while *Kobresia* species respond slowly to nitrogen addition. Forage nutrient demand is constrained not only by nutrient content but also by nutrient ratios and forms. Exogenous nutrient addition changes surface nutrient status, alters species richness at the community level, causes fluctuations in aboveground productivity, and even changes surface soil enzyme activities, affecting grassland biogeochemical self-regulation.

Heavy grazing is the dominant factor causing degradation of grassland production functions, and grazing system adjustment is the most effective measure for enhancing grassland function. Haibei Station research shows that grazing system selection depends on the sensitivity intensity and survival strategies of dominant functional groups to grazing pressure. Restoration measures include: reduced grazing for grass-*Kobresia humilis* communities; rotational-rest grazing for *K. humilis* and *K. humilis* + *K. pygmaea* mosaic communities; rest grazing for *K. pygmaea* communities; and artificial reconstruction for forbs-"black soil type" degraded grasslands. Changing livestock composition (cattle to sheep) can effectively restore degraded *Kobresia* grasslands. Reduced grazing promotes grass and legume growth, significantly increasing grass relative coverage and biomass while suppressing sedges and forbs. Compared to free grazing, grazing prohibition increases vegetation coverage and biomass by 43.4% and 39.6% respectively, substantially enhancing grassland function after just 2 years and representing a highly effective management measure.

Based on these adaptive management research results, Haibei Station conducted household-scale alpine grassland function enhancement technology demonstrations in the Qilian Mountains, training over 300 herders in topics including degradation characteristics, grazing techniques for different successional states, and degraded grassland restoration and reconstruction. Field diagnostics were performed on six herder families' grasslands, with on-site guidance on livestock types and rotational grazing methods for different degradation states, achieving good results and herder recognition [Figure 4: see original paper].

Using degraded grassland restoration techniques, Haibei Station studied mining impacts on grassland ecology, productivity, surface water transmission, and slag heap vegetation restoration in the Qilian Mountains Muli mining area. Through experimental demonstration and comprehensive consideration of restoration effects, costs, and secondary environmental damage, "leveling and direct seeding" was selected as the optimal method for vegetation restoration of damaged land, reducing restoration costs by approximately 28,000 yuan/mu compared to the government-promoted "soil covering" method and providing guidance for ecological management in Qilian Mountains mining areas [Figure 5: see original paper].

7. Future Directions for National Park System Construction

The Qilian Mountains are an important ecological security barrier in western China, a major water source area for the Yellow River basin, and a priority biodiversity conservation region. Grazing is the primary land use in the Qilian Mountains' natural grassland ecosystems. However, constrained by the plateau's cold climate, forage has a short growing season, grassland productivity is low, ecosystems are fragile, and self-repair capacity is weak. Grasslands, especially summer pastures in piedmont areas, have degraded severely under long-term overgrazing, reducing not only production functions but also impacting mountain runoff and snowmelt transmission, decreasing water conservation functions. The Qilian Mountains are also important coal mining areas for Qinghai and Gansu provinces, with accelerated resource development since 2000 causing wetland ecological damage, altered surface water transmission channels, and even river disappearance.

With the development of the Qilian Mountains National Park system, alpine grasslands are transitioning from production to ecological functions. Guided by the ecological civilization concept of "respecting nature, conforming to nature, and protecting nature," ensuring the authenticity of alpine ecosystems and achieving harmonious human-nature development has become the future focus for serving national park system construction and regional sustainable development.

Haibei Station has conducted fixed-point monitoring and research in the Qilian Mountains for 40 years, performing multiple regional surveys on the Qinghai-Tibet Plateau to study ecosystem evolution and spatial differentiation characteristics, proposing adaptive zoning management strategies based on ecological processes, and providing baseline data for Qilian Mountains National Park system construction. The station has also established a "grazing disturbance experiment" platform at the ecosystem level for alpine *Kobresia humilis* meadows, a climate change simulation platform for hydrothermal changes and nutrient addition, and a small watershed water balance platform. Future research will focus on biological mechanisms of grassland biological elements' responses to grazing disturbance, integration of grassland function enhancement and degraded ecosystem restoration technologies, and providing more accurate data for ecological construction.

References

1. Zhou Xingmin, Li Jianhua. Main vegetation types and their geographical distribution patterns at the Haibei Alpine Grassland Ecosystem Research Station. Alpine Meadow Ecosystem, 1982, (1): 9-18.
2. Deng Zifa, Xie Xiaoling, Zhou Xingmin. Study on the reproductive strategy of *Kobresia humilis* populations in alpine meadows. Chinese Journal of Ecology, 2001, 20(6): 68-70.
3. Deng Zifa, Xie Xiaoling, Zhou Xingmin, et al. Reproductive ecology of *Kobresia pygmaea* populations in alpine meadows. Acta Botanica Boreali-Occidentalia Sinica, 2002, 22(2): 344-349.
4. Deng Zifa, Xie Xiaoling, Zhou Xingmin, et al. Reproductive ecology of *Kobresia tibetica* populations in alpine meadows. Chinese Journal of Applied and Environmental Biology, 2001, 7(4): 332-334.
5. Cao Guangmin, Du Yangong, Liang Dongying, et al. Differentiation characteristics and mechanisms of passive and active degradation of alpine *Kobresia* meadows. Journal of Mountain Science, 2007, 25(6): 641-648.
6. Cao Guangmin, Long Ruijun, Zhang Fawei, et al. Causes of erosion pits in degraded alpine *Kobresia humilis* meadows in the Three-River-Source region. Grassland and Turf, 2010, 30(2): 16-21.
7. Wang Quanye, Bian Jianghui, Shi Yinzhu. Effects of plateau zokor mounds on vegetation succession and soil nutrient elements in *Kobresia humilis* meadows. Acta Theriologica Sinica, 1993, 13(1): 31-37.
8. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
9. Cao Guangmin, Zhao Xinquan, Wang Xi, et al. Dataset of Chinese Ecosystem Research Network—Grassland and Desert Ecosystem Volume—Qinghai Haibei Station. Beijing: China Agriculture Press, 2010.
10. Li H Q, Zhang F W, Li Y N, et al. Seasonal and inter-annual variations in CO_2 fluxes over 10 years in an alpine shrubland on the Qinghai-Tibetan Plateau, China. Agricultural and Forest Meteorology, 2016, 228: 95-103.
11. Yu G R, Zhu X J, Fu Y L, et al. Spatial patterns and climate drivers of carbon fluxes in terrestrial ecosystems of China. Global Change Biology,

2013, 19: 798-810.
12. Zeng C, Zhang F, Wang Q, et al. Impact of alpine meadow degradation on soil hydraulic properties over the Qinghai-Tibetan Plateau. Journal of Hydrology, 2013, 478(2): 148-156.
13. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
14. Jiang L L, Wang S P, Meng F D, et al. Relatively stable response of fruiting stage to warming and cooling relative to other phenological events. Ecology, 2016, 97: 1961-1969.
15. Liu H, Mi Z, Lin L, et al. Shifting plant species composition in response to climate change stabilizes grassland primary production. PNAS, 2018, 115(16): 4051-4056.
16. Wang S, Wilkes A, Zhang Z, et al. Management and land use change effects on soil carbon in northern China's grasslands: a synthesis. Agriculture, Ecosystems & Environment, 2011, 142(3): 329-340.
17. Li Y K, Ouyang J Z, Li L, et al. Alterations to biological soil crusts with alpine meadow retrogressive succession affect seeds germination of three plant species. Journal of Mountain Science, 2016, 13(11): 1-11.
18. Lin Li, Zhang Degang, Cao Guangmin, et al. Short-term responses of quantitative characteristics of plant communities to different utilization intensities in alpine *Kobresia* meadows. Acta Ecologica Sinica, 2016, 36(24): 8034-8043.
19. Cao Guangmin, Long Ruijun. Bottlenecks and solutions for natural restoration of "black soil beach" type degraded grasslands in the Three-River-Source region. Acta Agrestia Sinica, 2009, 17(1): 4-9.
20. Ma Yushou, Li Shixiong, Wang Yanlong, et al. Effects of rest grazing during green-up period on vegetation of degraded alpine meadows. Acta Agrestia Sinica, 2017, 25(2): 290-295.
21. Sun Yanan, Li Qian, Li Yikang, et al. Effects of nitrogen and phosphorus addition on soil enzyme activities in alpine meadows. Acta Prataculturae Sinica, 2016, 25(2): 18-26.
22. Pi Nanlin, Wang Qiji. Study on optimal grazing schemes and improving livestock economic benefits in Qinghai alpine meadow pastures. Qinghai Journal of Animal and Veterinary Sciences, 1989, (4): 7-10.
23. Dong Quan, Pi Nanlin, Xu Xinyi, et al. Discussion on the optimization of population structure and culling schemes for Tibetan sheep in Haibei. Acta Ecologica Sinica, 1984, 4(2): 188-199.
24. Dong Quanmin, Zhao Xinquan, Xu Shixiao, et al. Experimental study on yak fattening in winter warm sheds in alpine pastoral areas. Qinghai Journal of Animal and Veterinary Sciences, 2003, 33(2): 5-7.
25. Dong Quanmin, Zhao Xingquan, Xu Shixiao, et al. Experimental study on yak fattening in alpine pastoral areas. China Herbivore Science, 2004, 24(5): 8-11.
26. Zhao Xinquan, Pi Nanlin, Wang Qiji. Mathematical simulation of optimal

slaughter age for Tibetan sheep. Pratacultural Science, 1989, (5): 12-15.
27. Li Yingnian, Pi Nanlin. Analysis and discussion on thermal effects of warm sheds in Qinghai pastoral areas. Journal of Domestic Animal Ecology, 1993, 14(4): 7-10.
28. Li Yikang, Zhang Fawei, Xu Xingliang, et al. Assessment of degradation successional status of alpine *Kobresia* meadows: DB63/T1414-2015. 2015.
29. Cao Guangmin, Du Yangong, Liang Dongying, et al. Assessment of degradation successional status of alpine *Kobresia* meadows: DB63/T1413-2015. 2015.
30. Ouyang Jingzheng. Effects of biological soil crust evolution in degraded meadows on seed germination of main plant functional groups. Beijing: University of Chinese Academy of Sciences, 2015.
31. Lin Li. Responses and adaptations of plants and soil to grazing intensity under different successional states in alpine meadows. Lanzhou: Gansu Agricultural University, 2017.
32. Zhou Xingmin, Zhao Xinquan, Cao Guangmin, et al. *Kobresia* Meadows in China. Beijing: Science Press, 2000: 217-264.
33. Jiang C, Yu G, Li Y, et al. Nutrient resorption of coexistence species in alpine meadow of the Qinghai-Tibetan Plateau explains plant adaptation to nutrient-poor environment. Ecological Engineering, 2012, 44(44): 1-9.
34. Du Y, Guo X, Zhou G, et al. Effect of Grazing Intensity on Soil and Plant δ^{15}N of an Alpine Meadow. Polish Journal of Environmental Studies, 2017, 26(3): 1071-1075.
35. Yang Y, Wu L, Lin Q, et al. Responses of the functional structure of soil microbial community to livestock grazing in the Tibetan alpine grassland. Global Change Biology, 2013, 19(2): 637-648.
36. Xu X, Hua O, Cao G, et al. Dominant plant species shift their nitrogen uptake patterns in response to nutrient enrichment caused by a fungal fairy in an alpine meadow. Plant & Soil, 2011, 341(1-2): 495-504.
37. Song M H, Yu F H, Ouyang H, et al. Different inter-annual responses to availability and form of nitrogen explain species coexistence in an alpine meadow community after release from grazing. Global Change Biology, 2012, 18(10): 3100-3111.
38. Xu X, Wanek W, Zhou C, et al. Nutrient limitation of alpine plants: Implications from leaf N: P stoichiometry and leaf δ^{15}N. Journal of Plant Nutrition and Soil Science, 2014, 177(3): 378-387.
39. Du Yangong, Liang Dongying, Cao Guangmin, et al. Effects of grazing intensity on turf surface layer and grassland nutrient and water utilization in *Kobresia* meadows (Brief Report). Acta Prataculturae Sinica, 2008, 17(3): 134-138.
40. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
41. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine

meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
42. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
43. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
44. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
45. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
46. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
47. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
48. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
49. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
50. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
51. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
52. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.

53. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
54. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
55. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.
56. Zhang Y, Zhang Z, Liu J. Burrowing rodents as ecosystem engineers: the ecology and management of plateau zokors *Myospalax fontanierii* in alpine meadow ecosystems on the Tibetan Plateau. Mammal Review, 2010, 33(3-4): 284-294.

Author Biography

CAO Guangmin, Ph.D., is a Professor at the Northwest Institute of Plateau Biology, Chinese Academy of Sciences (CAS), and Director of the Haibei Research Station of Alpine Meadow Ecosystem, CAS. His research focuses on grassland ecology and soil agrochemistry, particularly grassland ecosystem evolution processes, water conservation, and ecosystem adaptive management under natural and human disturbances. He serves as Chairman of the Qinghai Ecological Society, Director of the Qinghai Agricultural Society and China Society on Tibet Plateau, and Editorial Board Member of *Acta Ecologica Sinica* and *Journal of Mountain Area*. He has led over 10 projects including the National Natural Science Foundation of China and CAS Strategic Priority Research Program, and currently directs a Key Project of the National Natural Science Foundation and a Key Basic Research Project of the Ministry of Science and Technology. He has published more than 130 academic papers and 4 monographs. **E-mail:** caogm@nwipb.cas.cn

Note: Figure translations are in progress. See original paper for figures.