Degradation of alpine meadows exacerbated plant community succession and soil nutrient loss on the Qinghai-Xizang Plateau, China postprint

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Abstract

In recent decades, global climate change and overgrazing have led to severe degradation of alpine meadows. Understanding the changes in soil characteristics and vegetation communities in alpine meadows with different degrees of degradation is helpful to reveal the mechanism of degradation process and take the remediation measures effectively. This study analyzed the changes in vegetation types and soil characteristics and their interrelationships under three degradation degrees, i.e., non-degradation (ND), moderate degradation (MD), and severe degradation (SD) in the alpine meadows of northeastern Qinghai-Xizang Plateau, China through the long-term observation. Results showed that the aggressive degradation changed the plant species, with the vegetation altering from leguminous and gramineous to forbs and harmful grasses. The Pielou evenness and Simpson index increased by 24.58% and 7.01%, respectively, the Shannon-Wiener index decreased by 17.52%, and the species richness index remained constant. Soil conductivity, soil organic matter, total potassium, available potassium, and porosity declined. However, the number of vegetation species increased in MD. Compared with ND, the plant diversity in MD enhanced by 8.33%, 8.69%, and 7.41% at family, genus, and species levels, respectively. In conclusion, changes in soil properties due to degradation can significantly influence the condition of above-ground vegetation. Plant diversity increases, which improves the structure of belowground network. These findings may contribute to designing better protection measures of alpine meadows against global climate change and overgrazing.

Full Text

Preamble

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Degradation of alpine meadows exacerbated plant community succession and soil nutrient loss on the Qinghai-Xizang Plateau, China

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Abstract

In recent decades, global climate change and overgrazing have led to severe degradation of alpine meadows. Understanding the changes in soil characteristics and vegetation communities across different degradation degrees is crucial for revealing degradation mechanisms and implementing effective remediation measures. This study analyzed vegetation types, soil characteristics, and their interrelationships under three degradation degrees—non-degradation (ND), moderate degradation (MD), and severe degradation (SD)—in the alpine meadows of northeastern Qinghai-Xizang Plateau, China, through long-term observation. Results showed that aggressive degradation altered plant species composition, with vegetation shifting from leguminous and gramineous species to forbs and harmful grasses. The Pielou evenness and Simpson index increased by 24.58% and 7.01%, respectively, while the Shannon-Wiener index decreased by 17.52%, and the species richness index remained constant. Soil conductivity, soil organic matter, total potassium, available potassium, and porosity all declined. However, the number of vegetation species increased in MD. Compared with ND, plant diversity in MD enhanced by 8.33%, 8.69%, and 7.41% at family, genus, and species levels, respectively. In conclusion, degradation-induced changes in soil properties significantly influence above-ground vegetation conditions. Plant diversity increases, which improves the structure of belowground networks. These findings may contribute to designing better protection measures for alpine meadows against global climate change and overgrazing.

Keywords: alpine meadow; degradation; long-term observation; plant diversity; soil and vegetation characteristics

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Introduction

The Qinghai-Xizang Plateau, known as the "Water Tower of Asia," is a sensitive area of global climate change that encompasses diverse grassland types playing crucial roles in regional water cycles, ecological environments, and climatic regulation [?, ?, ?]. Among these grassland types, alpine meadows constitute one of the primary categories on the Qinghai-Xizang Plateau, covering approximately 97.68$\times10^{6}$ km^2 [?, ?]. Alpine meadows have nurtured rich species variety and germplasm resources due to their unique geographical characteristics, such as high altitude and large temperature differences, and thus significantly impact ecosystem service functions including climate regulation, water conservation, and soil formation and protection [?, ?]. However, heavy industrialization [?, ?], global climate change [?, ?, ?], overgrazing [?, ?], and irrational grassland management have caused grassland quality decline and ecological environment damage [?, ?]. Although the Chinese government has implemented various measures such as fencing, turf cutting, no-tillage reseeding, and fertilizer addition to prevent grassland degradation [?, ?, ?], more than half of the meadows have degraded to different degrees due to external disturbances and global climate change effects [?, ?].

The most significant variation of grassland degradation is a decline in vegetation cover and increased soil bareness rate, followed by soil nutrient loss and changes in vegetation functional groups [?, ?], ultimately disrupting the soil-vegetation equilibrium. Soil nutrients support normal plant growth, while photosynthesis and other processes facilitate compound exchange and energy transfer between vegetation and soil [?, ?]. This dynamic equilibrium is essential for maintaining overall grassland ecosystem stability. Therefore, studying the impacts of soil degradation on vegetation functional groups is of great significance. Additionally, some studies have reported synergistic effects of vegetation degradation and soil degradation [?, ?]. The fundamental purpose of managing degraded alpine meadows can be achieved by improving the soil environment [?, ?] and cultivating high-quality pasture grasses suitable for the area, such as selecting and breeding grasses with excellent traits and expanding seed banks [?, ?]. It is also necessary to investigate changes in soil characteristics caused by severe grassland degradation and the succession patterns of key and dominant plant species [?, ?, ?].

Degradation reduces grassland yield and quality, deteriorates soil, pollutes groundwater, and impedes ecological functions. While studies of alpine meadow restoration have focused on increasing grazing capacity, the long-term effects of grassland degradation on vegetation and soil characteristics have received less attention [?, ?, ?, ?]. Therefore, this study aims to reveal relationships between grassland degradation and vegetation-soil changes across different degraded alpine meadows on the Qinghai-Xizang Plateau, China. The specific objectives are: (1) to characterize soil and vegetation changes during grassland degradation; (2) to reveal the evolution of dominant forage during degradation; and (3) to analyze whether degradation degree changes the ability of alpine meadows to resist climate change. This study will help understand the effects of alpine meadow degradation on vegetation and soil, further clarify degraded grassland restoration, and provide references for exogenous nutrient addition and vegetation improvement in alpine meadows.

2.1 Study Area

The study area is located at the Haibei Scientific Station, Northwest Plateau Research Institute, Menyuan Hui Autonomous County, Qinghai Province, China (37°36 48 N; 101°18 33 E; 3200–3600 m a.s.l.). The area has a distinct temperate continental climate with weak Southeast Asian summer monsoon influence. Restricted by high altitudes, temperatures are extremely low, with an annual average temperature of -1.7°C and precipitation of approximately 560 mm. Precipitation is concentrated from May to September during the plant growth season, accounting for about 80.00% of annual precipitation [**?**, **?**]. The soil type is alpine meadow soil. The constructive species was *Kobresia humilis* Serg., with dominant species including *Elymus nutans* Griseb., *Stipa aliena* Keng, *Gentiana straminea* Maxim., and *Oxytropis kansuensis* Bunge.

2.2 Methods

Three degradation types were identified in the study area: non-degradation (>90.00% average coverage; ND), moderate degradation (60.00%-90.00% average coverage; MD), and severe degradation (<60.00% average coverage; SD) (Fig. 1 [Figure 1: see original paper]). Three sample plots were randomly selected, with three replicates per plot and approximately 100 m distance between plots, totaling 9 sample plots and 27 soil samples. Soil samples of about 2 kg were collected at 0–20 cm depth in September 2023. This study evaluates alpine meadow resistance to external disturbances based on the central role of vegetation and soil in the ecosystem. Vegetation functional group and soil characteristics together reflect alpine meadow health and capacity to cope with external environmental changes [**?**, **?**, **?**].

2.2.1 Vegetation Survey Three replicated plots were randomly established within degraded alpine meadows, with approximately 100 m distance between each plot. For each plot, 0.5 m^2 quadrats were set up in ND, MD, and SD for vegetation surveys. Plant number, height, and coverage of each species were recorded. Importance value (IV) was calculated based on relative abundance, height, and frequency of each species [**?**, **?**]. The Shannon-Wiener index, Simpson index, species richness index, and Pielou evenness index were calculated [**?**, **?**, **?**].

2.2.2 Soil Sample Collection and Measurement A soil auger (30 mm diameter) was used to collect soil samples from 0–20 cm depth at each plot. Three soil samples within each plot were mixed to ensure uniformity. Each composite sample was air-dried and sieved through a 2-mm mesh for physical-chemical property analysis. Measurement methods are shown in Table 1 .

Table 1 Methods for measurement of soil physical-chemical characteristics

Index	Abbreviation	Measurement method	Reference
Soil total potassium		Flame photometry	Bao, 2000
Soil available potassium		Ammonium acetate leaching-flame photometry	
Electrical conductivity		Conductivity meter method	
Soil porosity		Ring knife method	
Soil organic matter		Potassium dichromate external heating method	

2.3 Data Analysis The Shannon-Wiener index (H'), Simpson index (D), species richness index (R), and Pielou evenness index (E) were used to assess plant diversity using the following equations [**?**, **?**, **?**, **?**]:

$$H' = -\sum_{i=1}^{n} P_i \ln(P_i)$$

$$D = \sum_{i=1}^{n} P_i^2$$

$$R = S$$

$$E = H'/H'_{\max}$$

$$IV = (\text{relative cover} + \text{relative density} + \text{relative plant height})/3$$

where P_i is the proportion of individuals belonging to species i; n is the number of species; $H'_{\max}$ is the maximum Shannon index; S is the total number of species present; and IV is the importance value of each species within the sampled area.

Data were analyzed using SPSS v.20.0 software. Significant differences in soil physical-chemical properties across degradation levels were compared using one-way ANOVA followed by least-square standard deviation tests. Pearson' s correlation analysis investigated interactions between plant diversity indices and soil environmental factors. Figures were plotted using Origin v.2022.

3.1 Changes in Vegetation Composition

As degradation intensified, vegetation types and importance values (IV) in alpine meadows changed notably. *E. nutans* emerged as the dominant species in ND and MD, accounting for 40.05% and 33.61% of IV, respectively. However, its IV decreased by 6.44%, while that of *P. anserina* increased up to 28.55%. Subdominant species included *Medicago archiducis-nicolai* Sirj. (13.95%), *Lancea tibetica* Hook. f. et Thoms. (15.67%), and *E. nutans* (25.15%). Primary-associated, secondary-associated, and occasional species varied according to degradation degree (Table 2).

Variations in plant height and cover structure led to competitive inhibition among certain dominant species due to taller cover, resulting in slowed or ceased growth processes that facilitated vegetation community succession. MD and SD exhibited dominance at family, genus, and species levels compared with ND. At the family level, numbers were 9.09% and 18.18% higher in MD and SD than in ND, respectively (Fig. 2a [Figure 2: see original paper]); at the genus level, they were 9.52% higher than ND (Fig. 2b); and at the species level, they were 8.00% and 4.00% higher, respectively (Fig. 2c). The IV of gramineous and leguminous plants decreased by 8.00% and 8.84% in MD, and by 7.04% and 5.37% in SD, respectively, compared with ND. The IV of forbs increased by 16.84% and 12.41% in MD and SD, respectively. Harmful grasses were highest in MD, followed by ND, and lowest in SD (Fig. 2d). These differences across taxonomic levels reflect the inherent complexity of biodiversity and ecological adaptability, influencing not only morphological and physiological characteristics of distinct plant taxa but also ecosystem structure and function as critical determinants of stability.

3.2 Changes in Vegetation Diversity Index

The Shannon-Wiener index was greater in MD with more abundant community species compared with ND, while SD had the lowest species diversity (Fig. 3a [Figure 3: see original paper]). The Simpson index was highest in MD, reflecting uneven species distribution, followed by SD and ND (Fig. 3b). The Pielou evenness index was directly proportional to degradation degree across all three meadow types (Fig. 3c). Furthermore, the species richness index for MD exceeded those of ND and SD (Fig. 3d). These results demonstrate that grassland degradation significantly influences diversity indices, with differences primarily stemming from shifts in vegetation functional group attributes. In contrast, the species richness index was relatively less affected, suggesting that although specific species composition may change in response to environmental alterations, overall biodiversity can remain relatively stable within certain limits. This observation underscores the complexity inherent in understanding mechanisms by which grassland degradation impacts vegetation structure and function.

3.3 Changes in Soil Characteristics

As alpine meadow degradation intensified, soil characteristics underwent continuous changes. Specifically, electrical conductivity (EC), soil organic matter (SOM), total potassium (TK), and available potassium (AK) values declined significantly with degradation intensification (Fig. 4a [Figure 4: see original paper]-d). Additionally, soil porosity (SP) decreased but stabilized during later degradation stages (Fig. 4e). These findings indicate that intensifying degradation corresponds with declining soil nutrient content, deteriorating aeration, altered granular structure, and uneven nutrient distribution. At the macro-level, soil physical-chemical indicators were highly disproportionately distributed among ND, MD, and SD. Higher AK contents suggest more balanced status, while SOM and TK contents were significantly low. This variability profoundly influenced soil ecosystem stability (Fig. 5 [Figure 5: see original paper]), as even micro-changes in soil nutrients can trigger chain reactions, altering nutrient status, changing microbial growth environments, affecting decomposition and regulation processes, and thus endangering overall soil ecosystem stability and health.

3.4 Correlation Between Soil and Vegetation Characteristics

Pearson' s correlation analysis investigated relationships between soil and vegetation characteristics (Fig. 6 [Figure 6: see original paper]). Results showed significant positive correlations among all measured soil properties, indicating synergistic effects among nutrient components. Conversely, negative correlations occurred between soil characteristics and species diversity indices. For example, the Pielou evenness and Simpson indices exhibited significantly negative correlations with SOM, EC, AK, TK, and SP, suggesting uneven plant distribution with fewer dominant species in alpine meadows. The Shannon-Wiener index and species richness index were positively correlated with soil properties, indicating interdependent and synergistic relationships among soil properties where alterations in one index can markedly influence and cascade into others, demonstrating complex soil ecosystem interactions. However, the intricacy of these relationships primarily arises because different vegetation types have varying requirements and preferences for specific soil attributes, leading to intricate soil-vegetation interactions.

4.1 Effect of Alpine Meadow Degradation on Vegetation Characteristics

Vegetation communities serve as indicators of grassland health. As alpine meadow degradation progresses, these communities undergo varying degrees of succession. In ND, *E. nutans* (IV=40.05%) from Gramineae and *M. archiducis-nicolai* (IV=13.95%) from Leguminosae were predominant (Table 2), suggesting potential grazing utilization. Furthermore, leguminous grasses accounted for the largest proportion in ND (Fig. 2b), helping maintain nitrogen balance in grassland ecosystems. Many leguminous grasses harbor rhizobacteria in their root systems that form nodules for nitrogen fixation [?, ?], effectively capturing atmospheric N and positively influencing nitrogen cycling and deposition [?, ?]. This positive feedback loop promoted growth of Gramineae and Leguminosae.

In MD, proportions of Gramineae and Leguminosae decreased while harmful grasses and forbs increased, forming the highest plant species numbers. Potential reasons include: (1) decreased soil fertility from degradation affected growth of Gramineae and Leguminosae, which require high soil nutrients [?, ?], reducing their numbers; (2) harmful grasses and forbs exhibit fast growth and strong adaptability [?, ?], surviving and reproducing under harsh conditions and dominating habitats where Gramineae and Leguminosae might grow; and (3) the potential function of MD cannot be neglected despite lower grazing utilization than ND [?, ?]. Many harmful grasses and forbs have extensive canopies and well-developed root systems [?, ?], protecting alpine meadows from rain-induced erosion and inhibiting black soil area expansion [?, ?]. Lower grazing utilization means less livestock disturbance, further enhancing MD' s natural resilience to some extent [?, ?, ?].

In contrast, SD had the most forbs and least harmful grasses due to low vegetation cover and bare soil, giving forbs competitive advantage and increasing their populations. Certain forbs may act as pioneer species capable of rapidly colonizing bare soil surfaces [?, ?], preventing erosion and creating favorable conditions for subsequent communities. Additionally, certain forbs such as *L. sagitta* and *P. sibiricum* possess significant medicinal value along with robust resistance to low temperatures, drought, and salinity. These forbs have adapted to SD' s ecological environment and play crucial roles in maintaining ecosystem stability and balance [?, ?].

4.2 Effect of Alpine Meadow Degradation on Soil Characteristics

Soil characteristics play important roles in the soil-vegetation system and are dominant factors affecting plant growth. Soil deterioration is the primary driver of alpine meadow degradation, stemming from substantial changes in physical-chemical properties [?, ?]. Regarding physical properties, increased degradation greatly altered soil characteristics, with both EC and SP showing decreasing trends. First, changes in soil granular structure, probably due to anthropogenic disturbances and severe livestock trampling, led to decreased porosity [?, ?].

Second, degradation caused succession of aboveground vegetation communities and inhibited growth of plants with root systems containing high salt and ion levels, thus affecting soil EC [?, ?]. These changes not only reshape overall soil structure and inhibit respiration rates but also affect atmospheric CO_2 levels and soil carbon accumulation rates [?, ?].

Soil nutrients are crucial for normal above-ground vegetation growth. This study reported that increased degradation significantly reduced SOM, TK, and AK contents. This decline can be attributed to SOM originating partially from plant residues [?, ?]. Consequently, surface vegetation degradation markedly decreased vegetation cover, reducing SOM generated through soil decomposition. Furthermore, degradation increased soil erosion risk, causing substantial SOM loss from wind and water erosion. Additionally, alkaline soils within the study area may have accelerated SOM loss [?, ?]. Decreases in TK and AK contents can be linked to degradation processes promoting increases in forbs and harmful grasses due to their high potassium uptake [?, ?]. This phenomenon disrupted K morphological transformation and hindered cross-border signal regulation [?, ?], ultimately diminishing TK and AK contents. More critically, global climate change is altering plant root morphology while reducing areas associated with inter-root nutrient uptake [?, ?, ?]. Over time, this disruption will affect the dynamic balance among soil-microbe-plant systems, leading to decreased soil nutrient content and ongoing shifts within vegetation functional groups.

In summary, grassland restoration efforts should prioritize vegetation restoration and soil quality improvement. When developing restoration strategies, it is essential to consider multiple factors such as climatic conditions, rodent infestations, and overgrazing to ensure scientifically sound, feasible, and environmentally sustainable solutions [?, ?, ?]. This integrated approach aims to restore soil health while promoting vegetation diversity, thereby effectively mitigating and reversing grassland ecosystem degradation.

4.3 Strategies to Deal with Alpine Meadow Degradation

Alpine meadow degradation can lead to severe ecological deterioration and sudden biodiversity declines. In addressing climate change and overgrazing, it is essential to focus on complex interactions between internal and external environments in alpine meadows and seek external interventions to combat degeneration. For soil characteristics, excessive fertilizer reliance should be avoided. Alpine meadow soils are rich in nutrients, including roots, soil microorganisms, and unactivated nutrients [?, ?, ?]. Therefore, during restoration, incorporating beneficial microorganisms may be an effective strategy to activate these nutrients through microbial metabolic activities and synergistic interactions with root-associated microorganisms, enabling plant uptake and reducing exogenous fertilizer needs [?, ?]. Moreover, maintaining favorable vegetation conditions is crucial for mitigating degradation. However, this does not necessarily imply high uniformity among vegetation types. Different species exhibit varying resistance levels to cold temperatures, drought, and human disturbances [?, ?], contributing to ecosystem stability. Additionally, vegetation diversity helps prevent irreversible degradation resulting from rapid succession caused by factors such as global climate change and severe disturbances [?, ?, ?].

4.4 Limitation and Implication

Alpine meadow degradation is a dynamic process involving many factors [?, ?]. This study investigated three degradation levels (ND, MD, and SD) to more accurately elucidate their characteristics and facilitate targeted restoration measures. Furthermore, this study advocates introducing appropriate grass species within alpine meadows to effectively mitigate ecological deterioration through promotion of vegetation diversity [?, ?].

It is important to note that changes in vegetation characteristics and soil nutrient status from alpine meadow degradation are critical for future restoration and management efforts. However, this study only monitored vegetation and soil data from selected alpine meadows on the Qinghai-Xizang Plateau over a one-year period, making it difficult to comprehensively and systematically reveal dynamic degradation characteristics. Therefore, future research should concentrate on temporal and spatial heterogeneity by extending study durations and expanding geographical coverage to gain deeper insights into degradation mechanisms [?, ?]. Additionally, climate change and external disturbances are key degradation drivers [?, ?]. This study did not incorporate variables such as precipitation, temperature, or grazing pressure, limiting completeness and applicability of findings. Subsequent research should comprehensively consider these factors.

Conclusions

Alpine meadow degradation is a complex process regulated by various factors, and ecosystem restoration is time-consuming and challenging. As degradation intensified, species richness gradually stabilized, but community structure changed significantly, particularly decreasing Gramineae and Leguminosae while increasing forbs and harmful grasses. Additionally, deterioration of soil aeration properties and significant nutrient content decline led to succession of dominant species. In conclusion, restoring alpine meadows in the context of global climate change requires primary focus on maintaining and optimizing the soil-vegetation system balance. This study emphasizes that the key is improving ecosystem resilience to external disturbances and changes rather than pursuing excessive grazing utilization.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Anjali G, Aditi K. 2024. A holistic approach to sustainable manufacturing: Rework, green technology, and carbon policies. *Expert Systems with Applications*, 244: 122943, doi: 10.1016/j.eswa.2023.122943.

Anna L, Daniela H, Josef Z. 2015. Structures of microbial communities in alpine soils: Seasonal and elevational effects. *Frontiers in Microbiology*, 26(6): 1330, doi: 10.3389/fmicb.2015.01330.

Bao S D. 2000. *Soil Agrochemical Analysis* (3rd ed). Beijing: China Agriculture Press. (in Chinese)

Bethany J, Silva G A, Nelson C, et al. 2019. Optimizing the production of nursery-based biological soil crusts for restoration of arid land soils. *Applied and Environmental Microbiology*, 85(15): e00735-19, doi: 10.1128/AEM.00735-19.

Borchard N, Wolf A, Laabs V, et al. 2012. Physical activation of biochar and its meaning for soil fertility and nutrient leaching–a greenhouse experiment. *Soil Use and Management*, 28(2): 177–184.

Brierley G, Li X L, Fryirs K, et al. 2022. Degradation and recovery of alpine meadow catenas in the source zone of the Yellow River, Western China. *Journal of Mountain Science*, 19(9): 2487–2505.

Britton J A, Gibbs S, Fisher M J, et al. 2019. Impacts of nitrogen deposition on carbon and nitrogen cycling in alpine *Racomitrium* heath in the UK and prospects for recovery. *Environmental Pollution*, 254: 112986, doi: 10.1016/j.envpol.2019.112986.

Bullard T F. 2012. Human or natural impacts? Comparing prehistoric and modern geomorphic response to extreme change in a Mediterranean ecosystem from excessive grazing, Southern California, U.S.A. *Quaternary International*, 279-280: 74.

Chen K Y, Xing S, Shi H L, et al. 2023. Long-term fencing can' t benefit plant and microbial network stability of alpine meadow and alpine steppe in Three-River-Source National Park. *Science of the Total Environment*, 902: 166076, doi: 10.1016/j.scitotenv.2023.166076.

Chen S D, Elrys S A, Yang W Y, et al. 2024. Soil recalcitrant but not labile organic nitrogen mineralization contributes to microbial nitrogen immobilization and plant nitrogen uptake. *Global Change Biology*, 30(4): e17290, doi: 10.1111/GCB.17290.

Chippano T, Mendoza R, Cofre N, et al. 2021. Divergent root P uptake strategies of three temperate grassland forage species. *Rhizosphere*, 17: 100312, doi: 10.1016/j.rhisph.2021.100312.

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

Evanylo G K, Porta S N, Li J L, et al. 2016. Compost practices for improving soil properties and turfgrass establishment and quality on a disturbed urban soil. *Compost Science & Utilization*, 24(2): 136-145.

Fan Q Y, Wang H K, Mao C L, et al. 2022. Structure and signal regulation mechanism of interspecies and interkingdom quorum sensing system receptors. *Journal of Agricultural and Food Chemistry*, 70(2): 429-445.

Feng T J, Qi Y L, Zhang Y F, et al. 2024. Long-term effects of vegetation restoration and forest management on carbon pools and nutrients storages in northeastern Loess Plateau, China. *Journal of Environmental Management*, 354: 120296, doi: 10.1016/j.jenvman.2024.120296.

Gao X X, Dong S K, Xu Y D, et al. 2019. Resilience of revegetated grassland for restoring severely degraded alpine meadows is driven by plant and soil quality along recovery time: A case study from the Three-River Headwater area of Qinghai-Tibetan Plateau. *Agriculture, Ecosystems and Environment*, 279: 169-177.

Gu C J, Liu L S, Zhang Y L, et al. 2023. Understanding the spatial heterogeneity of grazing pressure in the Three-River-Source Region on the Tibetan Plateau. *Journal of Geographical Sciences*, 33(8): 1660-1680.

He J S, Liu Z P, Yao T, et al. 2020. Analysis of the main constraints and repair techniques of degraded grassland on the Tibetan Plateau. *Science & Technology Review*, 38 (17): 66-80. (in Chinese)

He K J, Huang Y M, Qi Y, et al. 2021. Effects of nitrogen addition on vegetation and soil and its linkages to plant diversity and productivity in a semi-arid steppe. *Science of the Total Environment*, 778: 146299, doi: 10.1016/j.scitotenv.2021.146299.

Hekkala A M, Tarvainen O, Tolvanen A. 2014. Dynamics of understory vegetation after restoration of natural characteristics in the boreal forests in Finland. *Forest Ecology and Management*, 330: 55–66.

Hu C, Xia J, She D X, et al. 2024. Precipitation exacerbates spatial heterogeneity in the propagation time of meteorological drought to soil drought with increasing soil depth. *Environmental Research Letters*, 19(6): 064021, doi: 10.1088/1748-9326/AD4975.

Hu T, Peter S, Ellen M, et al. 2018. Root biomass in cereals, catch crops and weeds can be reliably estimated without considering aboveground biomass. *Agriculture, Ecosystems and Environment*, 251: 141–148.

Li G R, Li X L, Chen W T, et al. 2019. Effects of degradation severity on the physical, chemical and mechanical properties of alpine meadow on topsoil of the Qinghai-Tibet Plateau, west China. *CATENA*, 187: 104370, doi: 10.1016/j.catena.2019.104370.

Li J W, Xie J B, Zhang Y, et al. 2022a. Interactive effects of nitrogen and water addition on soil microbial resource limitation in a temperate desert shrubland. *Plant and Soil*, 475(1–2): 361–378.

Li N N, Cui Y Z, Zhang Z J, et al. 2024. Overexpression of vacuolar H+-pyrophosphatase from a recretohalophyte *Reaumuria trigyna* enhances vegetative growth and salt tolerance in transgenic *Arabidopsis thaliana*. *Frontiers in Plant Science*, 13(15): 1435799, doi: 10.3389/fpls.2024.1435799.

Li T F, Kamran M, Chang S H, et al. 2022b. Climate-soil interactions improve the stability of grassland ecosystem by driving alpine plant diversity. *Ecological Indicators*, 141: 109002, doi: 10.1016/j.ecolind.2022.109002.

Liang Y M, He X Y, Liang S C, et al. 2014. Community structure analysis of soil ammonia oxidizers during vegetation restoration in southwest China. *Journal of Basic Microbiology*, 54(3): 180–189.

Ma L, Zhang Z H, Shi G X, et al. 2022. Warming changed the relationship between species diversity and primary productivity of alpine meadow on the Tibetan Plateau. *Ecological Indicators*, 145: 109691, doi: 10.1016/j.ecolind.2022.109691.

Ma Q Q, Chai L R, Hou F J, et al. 2019. Quantifying grazing intensity using remote sensing in alpine meadows on Qinghai-Tibetan Plateau. *Sustainability*, 11(2): 417, doi: 10.3390/su11020417.

Mao Y, Hu W, Chau H W, et al. 2020. Combined cultivation pattern reduces soil erosion and nutrients loss from sloping farmland on red soil in southwestern China. *Agronomy*, 10(8): 1071, doi: 10.3390/agronomy10081071.

Nassauer J I, Raskin J. 2014. Urban vacancy and land use legacies: A frontier for urban ecological research, design, and planning. *Landscape and Urban Planning*, 125: 245–253.

Nelson V R, Calvo R C, Ivan P T. 2005. Effects of forest harvesting techniques on species diversity in natural pine forest ecosystem. *Revista Chapingo Serie Ciencias Forestales Y Del Ambiente*, 11(2): 125–130.

Olofsson J, Tømmervik H, Callaghan T V. 2012. Vole and lemming activity observed from space. *Nature Climate Change*, 2(12): 880–883.

Peng F, Xue X, Li C Y, et al. 2020. Plant community of alpine steppe shows stronger association with soil properties than alpine meadow alongside degradation. *Science of the Total Environment*, 733: 139048, doi: 10.1016/j.scitotenv.2020.139048.

Pubudu K, Kandiah P, Liyanage D. 2021. Assessment of yield loss in green gram (*Vigna radiata* (L.) R. Wilczek) cultivation and estimation of weed-free period for eco-friendly weed management. *Biology and Life Sciences Forum*, 3(1): 22, doi: 10.3390/IECAG2021-09691.

Rane N R, Tapase S, Kanojia A, et al. 2022. Molecular insights into plant-microbe interactions for sustainable remediation of contaminated environment. *Bioresource Technology*, 344: 126246, doi: 10.1016/j.biortech.2021.126246.

Romio L C, Zimmer T, Bremm T, et al. 2022. Influence of different methods to estimate the soil thermal properties from experimental dataset. *Land*, 11(11): 1960, doi: 10.3390/land11111960.

Roy S, Liu W, Nandety R S, et al. 2020. Celebrating 20 years of genetic discoveries in legume nodulation and symbiotic nitrogen fixation. *Plant Cell*, 32(1): 15–41.

Sadeghi S H, Chamani R, Zabihi Silabi M, et al. 2023. Watershed health and ecological security zoning throughout Iran. *Science of the Total Environment*, 905: 167123, doi: 10.1016/j.scitotenv.2023.167123.

Schneider K, Leopold U, Gerschlauer F, et al. 2011. Spatial and temporal variation of soil moisture in dependence of multiple environmental parameters in semi-arid grasslands. *Plant and Soil*, 340(1–2): 73–88.

Shannon V L, Vanguelova E L, Morison J I L, et al. 2022. The contribution of deadwood to soil carbon dynamics in contrasting temperate forest ecosystems. *European Journal of Forest Research*, 141(2): 241–252.

Shao W Y, Zhang Z P, Guan Q Y, et al. 2024. Comprehensive assessment of land degradation in the arid and semiarid area based on the optimal land degradation index model. *Catena*, 234: 107563, doi: 10.1016/j.catena.2023.107563.

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

Strömberg C A E, Staver A C. 2022. The history and challenge of grassy biomes. *Science*, 377(6606): 592–593.

Sun N, Liu N J, Zhao X, et al. 2022. Evaluation of spatiotemporal resilience and resistance of global vegetation responses to climate change. *Remote Sensing*, 14(17): 4332–4332.

Sun S S, Zhao S L, Liu X P, et al. 2023. Grazing impairs ecosystem stability through changes in species asynchrony and stability rather than diversity across spatial scales in desert steppe, Northern China. *Agriculture, Ecosystems and Environment*, 346: 108343, doi: 10.1016/j.agee.2023.108343.

Wang H M, Sun J, Li W P, et al. 2016. Effects of soil nutrients and climate factors on belowground biomass in an alpine meadow in the source region of the Yangtze-Yellow Rivers, Tibetan Plateau of China. *Journal of Arid Land*, 8(6): 881–889.

Wang J, Zhao W W, Xu Z X, et al. 2023a. Plant functional traits explain long-term differences in ecosystem services between artificial forests and natural grasslands. *Journal of Environmental Management*, 345: 118853, doi: 10.1016/j.jenvman.2023.118853.

Wang Q W, Robson M T, Pieriste M, et al. 2020. Testing trait plasticity over the range of spectral composition of sunlight in forb species differing in shade tolerance. *Journal of Ecology*, 108(5): 1923–1940.

Wang Y, Ji H F, Wang R, et al. 2017. Impact of root diversity upon coupling between soil C and N accumulation and bacterial community dynamics and activity: Result of a 30 year rotation experiment. *Geoderma*, 292: 87–95.

Wang Y F, Xue K, Hu R H, et al. 2023b. Vegetation structural shift tells environmental changes on the Tibetan Plateau over 40 years. *Science Bulletin*, 68(17): 1928–1937.

Yeom D J, Kim J H. 2011. Comparative evaluation of species diversity indices in the natural deciduous forest of Mt. Jeombong. *Forest Science and Technology*, 7(2): 68–74.

Yuan Z, Jiang Q Q, Yin J. 2023. Impact of climate change and land use change on ecosystem net primary productivity in the Yangtze River and Yellow River Source Region, China. *Watershed Ecology and the Environment*, 5: 125–133.

Zeng J B, Wang Y M, Wu G, et al. 2024. Comparative transcriptome analysis reveals the genes and pathways related to wheat root hair length. *International Journal of Molecular Sciences*, 25(4): 2069, doi: 10.3390/ijms25042069.

Zhang C B, Li D R, Jiang J, et al. 2019. Evaluating the potential slope plants using new method for soil reinforcement program. *CATENA*, 180: 346–354.

Zhang G Q, Yao T D, Xie H J, et al. 2020. Response of Tibetan Plateau lakes to climate change: Trends, patterns, and mechanisms. *Earth-Science Reviews*, 208: 103269, doi: 10.1016/j.earscirev.2020.103269.

Zhang H W, Yang S P, Wei X Q, et al. 2023a. Forecasting the favorable growth conditions and suitable regions for chicory (*Cichorium intybus* L.) on the Qinghai Plateau under current climatic conditions. *Ecological Informatics*, 78: 102343, doi: 10.1016/j.ecoinf.2023.102343.

Zhang M X, Zhao L Y, Hu J P, et al. 2023b. Different grazers and grazing practices alter the growth, soil properties, and rhizosphere soil bacterial communities of *Medicago ruthenica* in the Qinghai-Tibetan Plateau grassland. *Agriculture, Ecosystems and Environment*, 352: 108522, doi: 10.1016/j.agee.2023.108522.

Zhao Y N, Wang H M, Li Z G, et al. 2024. Anthropogenic shrub encroachment has accelerated the degradation of desert steppe soil over the past four decades. *Science of the Total Environment*, 946: 174487, doi: 10.1016/j.scitotenv.2024.174487.

Zheng H, Wang Q F, Li Y N, et al. 2013. Characteristics of evapotranspiration in an alpine shrub meadow in Haibei, Qinghai of Northwest China. *Journal of Applied Ecology*, 24(11): 3221–3228. (in Chinese)

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