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**Active restoration improved self-restoring ability in extremely degraded alpine meadow**

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**Key words:** Grassland restoration; Long-term restoration; Native plant seeds; Reseeding; Self-recovery ability

**Abstract**

About 60% of alpine meadow has been degraded, with around 8% considered extremely degraded on the Qinghai-Tibetan Plateau. The natural restoration of extremely degraded land will take more than 200 years and is the biggest challenge for ecological restoration worldwide. To improve the effectiveness of restoration, reseeding native plant seeds has become the main active restoration approach for extremely degraded meadow. However, it is still unclear whether this active restoration approach of native plant reseeding can promote the self-recovery ability and natural regeneration of extremely degraded alpine meadow. To address this knowledge gap, we have conducted long-term active restoration research of extremely degraded meadow on the Qinghai-Tibetan Plateau. Our findings indicate that the meadow vegetation was in an unstable state after active restoration within 10 years. After 10 years of active restoration without meadow management, the plant community degraded again. Soil nutrients also declined significantly after 10 years of active restoration without meadow management, with notable geographical variations. Long-term active restoration did not significantly improve the soil carbon storage. During the long-term recovery process, the vegetation carbon pool was regulated by nitrogen, while the soil carbon pool was primarily regulated by living plant roots. However, long-term active restoration had positive effects on soil seed bank density and species number. Reseeding native perennial grass seeds can improve the soil seed bank and the vegetation-soil system's resilience of alpine meadow. Therefore, for the active restoration targeting the extremely degraded alpine meadow, it is necessary to implement good post-restoration management practice to enhance the meadow's self-recovery ability. Additionally, introducing moderate livestock grazing could promote the ecological restoration's effect and ensure sustainable recovery of alpine meadow.

**Introduction**

The extensive and severe land degradation worldwide poses a significant challenge to the restoration of Earth's ecosystems, particularly affecting grassland ecosystems. Since the 21st century, approximately 50% of the global grassland area has experienced degradation, with about 5% suffering from severe degradation

that makes ecological restoration extremely challenging (Bardgett et al., 2021). On the Qinghai-Tibetan Plateau, the alpine grassland covers an area of 125,000 km<sup>2</sup>, of which 70% has been degraded, and 8% has been severely degraded, referred to as 'Heitutan' degraded grassland by local herders, or 'bare land' degraded grassland (Dong et al., 2020). This severe degradation of alpine grassland results in the disappearance of the topsoil layer (approximately 0-30 cm), the loss of the soil seed bank, the spread of weeds and toxic plants, leading to a loss of biodiversity, the reduction of permafrost, and increased water and soil erosion. This condition is likened to scalp stripping and has been termed the 'ecological cancer' of the Qinghai-Tibetan Plateau. The ecological restoration of severely degraded alpine grasslands on the Qinghai-Tibetan Plateau has been designated as a key mission in China's 'Master Plan for Major Projects for the Protection and Restoration of Important National Ecosystems (2021-2035)'. However, the natural restoration of severely degraded land can take over 200 years or even longer, and in high-altitude areas with cold temperatures and low oxygen levels, the restoration of severely degraded grasslands becomes even more complex and challenging.

We understand that successful ecological restoration requires not only the recovery of a more integrated ecosystem structure but also the restoration of multiple functions, which is a process that takes a long time. Generally, on the Qinghai-Tibetan Plateau, the initial step in restoring severely degraded grasslands is to establish high-coverage vegetation to prevent water and soil loss by reseeding local plant seeds. Subsequently, this approach aims to gradually foster biodiversity and soil fertility, and enhance the ecosystem's self-recovery ability, which is known as active restoration (Dong et al., 2020). However, current studies on active restoration are limited to short-term cases, which do not adequately explain the approach's impact on the recovery process of vegetation, soil fertility, and soil seed banks, nor do they clearly answer questions about the outcomes of long-term restoration (Dong et al. 2020). To address this gap, we conducted field investigations and soil measurements in the laboratory for long-term active restoration projects (over 10 years) in three independent highland counties (elevations is 3900-4200 m a.s.l.). This paper presents the findings of this investigation regarding vegetation, soil nutrients, and soil seed banks, which could provide valuable references for the long-term active restoration of severely degraded alpine grasslands on the Qinghai-Tibetan Plateau.

## Methods

The geographical coordinates of the field investigation site are 32°31'-35°40' N and 97°54'-121°50' E, located in the eastern part of Qinghai-Tibetan Plateau. The region experiences an annual average temperature range of -3.5°C to 4°C, with an accumulated temperature of 775 to 2104°C, and receives an annual precipitation of 448.6 to 569 mm, predominantly from May to September. The altitude ranges from 3900 to 4200 m a.s.l., characterized by low oxygen levels, cold conditions, and frequent strong winds and snowfall. The predominant vegetation in the grassland is alpine meadow, with the soil type being alpine meadow soil. The dominant plant species in these meadows include *Kobresia pygmaea*, *K. humilis*, *Stipa przewalskyi*, *Festuca ovina*, *Poa pratensis*, and *Elymus nutans*. The severe degraded alpine grasslands originated from overgrazing in alpine meadows, its vegetation coverage of approximately 40-60%, which is now dominated by weeds and toxic plants, with large areas of bare land. All of the long-term active restored grasslands have a history of over ten years and have been managed under traditional grazing practices. The active restoration methods employed were consistent with those used in local government restoration projects conducted more than ten years ago. The reseeding of native plant seeds involved grasses, specifically *Poa pratensis*, *Elymus nutans*, and *Festuca ovina*, following the same technical standards.

Our field site encompassed three distinct counties (Maqin, Dari, and Gande) with each site being more than 100 km apart from the others, ensuring true replication across similar field types. Within each site (county), we selected three types of grasslands: long-term active restored grassland, undegraded grassland, and severely degraded grassland. This resulted in a total of nine grasslands that were investigated and sampled. In each grassland, we established 20 plots measuring 50cm×50cm to assess plant species, coverage, and species frequency, yielding a total of 180 plots. Additionally, within each grassland, we selected 3 plots to collect soil and root samples from two distinct soil layers (0-10 cm, 10-20 cm). These soil samples were taken to the laboratory for analysis of soil and root carbon and nitrogen content. To assess the soil seed bank, we extracted soil cores (diameter 5 cm) from 20 plots in each grassland, targeting two soil layers (0-5 cm and 5-10 cm). The germination method was conducted in a greenhouse over a period of 7 months, which allowed us to accurately identify the germinable seeds from the soil seed bank.

### Results

The three  $\alpha$ -diversity indices (Shannon-Wiener index, Simpson index, species Richness) exhibited a consistent trend across the three types of grasslands, generally indicating that undegraded grasslands (UG) have greater diversity than severely degraded grasslands (DG), which in turn have higher diversity than long-term restored grasslands (LR; Table 1). However, at the WSX site, some indices for LR were found to be higher than those for DG (Table 1). Although the DG sites showed higher plant species diversity compared to the LR sites, the majority of species in the DG sites were weeds and toxic plants (Table 1). Community composition analysis revealed that long-term restoration efforts have not resulted in an improvement in the vegetation status of the restored grasslands when compared to both the degraded and undegraded grasslands.

Table 1. Community  $\alpha$ -diversity of three grassland types in three sites

Grassland types	Shannon-Wiener index			Simpson index			Richness
	JMC	WSX	QZX	JMC	WSX	QZX	
UG	3.3	3.02	3.31	0.96	0.94	0.96	35.0±3.6
DG	3.27	2.69	3.2	0.95	0.91	0.95	31.7±5.9
LR	3.05	2.96	2.82	0.94	0.93	0.93	28.7±5.1

JM: The study site of Junmuchang in Maqin county; WSX: The study site of Wosai in Dari county; QZX: The study site of Qingzhenxiang in Gande county; LR-Long term active restoration grassland; DG-extremely degraded grassland; UG- undegenerated grassland.

The undegraded grasslands have the highest levels of soil organic carbon (SOC) and total nitrogen (TN), while the severely degraded grasslands (DG) have the lowest levels of SOC and TN (Table 2). There is a significant variation in SOC and TN values among the three sites (Table 2). The changes in SOC and TN across the three types of grasslands are more consistent in the 0-10 cm soil layer compared to the 10-20 cm layer (Table 2). Overall, the long-term active restoration of grasslands has led to an improvement in soil organic carbon and nitrogen content (Table 2).

Table 2. Soil organic carbon and total nitrogen of three grasslands (mean±SE)

Soil layers (cm)	Grassland types	Soil organic carbon (g kg <sup>-1</sup> )			Soil total nitrogen (g kg <sup>-1</sup> )		
		JMC	WSX	QZX	JMC	WSX	QZX
0-10	UG	28.68a±2.66	45.05a±8.20	40.51a±7.42	2.05ab±0.20	2.99a±0.46	2.76a±0.56
	DG	28.22a±1.99	24.33b±1.54	27.74a±2.43	1.81b±0.17	1.84b±0.12	1.91a±0.13
	LR	34.51a±1.09	21.16b±2.49	35.30a±1.05	2.49a±0.12	1.64b±0.16	2.61a±0.09
10-20	UG	23.38b±0.56	32.40a±5.74	30.18a±5.22	1.76b±0.03	2.31a±0.37	1.99a±0.39
	DG	25.64b±3.00	21.47ab±1.31	24.41a±2.06	1.57b±0.23	1.61ab±0.08	1.74a±0.12
	LR	33.68a±2.29	15.93b±1.60	33.40a±1.29	2.58a±0.22	1.31b±0.11	2.43a±0.09

Notes: JM: The study site of Junmchang in Maqin county; WSX: The study site of Wosai in Dari county; QZX: The study site of Qingzhenxiang in Gande county. LR-Long term active restoration grassland; DG-extremely degraded grassland; UG- undegenerated grassland. Little letter means the significant among grassland types ( $p<0.05$ ).

There is no significant difference in the organic carbon content of both living and dead roots among the three types (Table 3). The total nitrogen content in the living roots is highest in the degraded grassland and lowest in the undegraded grassland (Table 3). The total nitrogen content in the dead roots of the degraded grassland is higher than that in the long-term restored grassland and the undegraded grassland, but the difference is not statistically significant (Table 3). Overall, long-term restored grassland has improved the organic carbon content in living roots.

Table 3. Organic carbon and total nitrogen of grassland root (Mean±SE)

Grassland types	Organic carbon (g kg <sup>-1</sup> )		Total nitrogen (g kg <sup>-1</sup> )	
	Living root	Dead root	Living root	Dead root
UG	518.55a±27.42	474.46a±35.44	7.24b±1.34	10.32a±2.00
DG	509.74a±26.03	487.86a±3.81	12.93a±1.26	14.91a±2.38
LR	511.51a±6.60	450.74a±10.37	10.32ab±1.43	14.07a±0.58

Based on the species composition of the soil seed bank, the degraded grassland exhibits the highest species richness, whereas the long-term restored grassland shows the lowest (Table 4). The soil seed bank of the degraded grassland is predominantly composed of forb species. The long-term restored grassland has a comparable species richness to the undegraded grassland, with gramineous plants being the dominant species in both types of grasslands (Table 4).

Table 4. Species diversity of soil seed bank in three grasslands in three seasons (Mean±SE)

Season	Grassland types	Shannon-Wiener index	Simpson index	Richness
April	UG	2.13±0.21	0.73±0.10	12.56±3.09
	DG	2.30±0.33	0.76±0.18	15.33±2.87
	LR	1.89±0.51	0.63±0.22	13.11±2.57
August	UG	1.96±0.31	0.82±0.06	9.56±2.51
	DG	1.96±0.23	0.81±0.05	12.00±2.60
	LR	1.65±0.22	0.75±0.05	8.11±2.26
December	UG	1.85±0.51	0.78±0.13	10.00±4.47
	DG	2.12±0.26	0.83±0.07	13.44±1.67
	LR	2.01±0.17	0.84±0.03	9.44±1.24

The seed density in the soil seed bank across the three types of grasslands follows a similar pattern, with the highest density observed in the undegraded grassland and the lowest in the severely degraded grassland (Table 5). Additionally, the seed density is highest in April and lowest in December (Table 5). The degraded grassland contains several species that produce a large number of seeds, such as the forb *Pedicularis kansuensis* Maxim. The long-term restored grassland has increased the seed density of the soil seed bank, and the plant species composition is now dominated by perennial grasses (Table 5). The soil seed bank is an indicator of vegetation recovery potential, especially in grassland ecosystems. Thus, these findings suggest that long-term restoration efforts can enhance the vegetation recovery ability of this type of grassland.

Table 5. Seed density of soil seed bank of three grassland in three seasons (Mean±SE)

Grassland types	April	August	December
UG	3172.70±1278.08	2386.35±871.62	2173.38±1096.70
DG	9452.57±3362.07	6973.39±2329.87	8731.75±8025.47
LR	7819.80±3473.59	4996.59±3188.58	2506.49±648.29

### Discussion [Conclusions/Implications]

Our independent experimental results from the three counties demonstrated that long-term active restoration has a certain positive effect on the recovery of extremely degraded grasslands. However, the lack of post-restoration management may have led to a significant decline, or even the disappearance, of the restoration approach's effectiveness. The typical characteristic of degraded alpine meadows is a marked increase in weed and toxic plant species, which, of course, serves as an effective self-protection mechanism against the grazing pressure on grassland ecosystems (Shang et al., 2016). The increase in weeds and toxic plants also enhances vegetation coverage, soil seed bank density, and soil nutrition, features that have been improved by long-term restoration efforts (Guo et al., 2019).

It is noteworthy that long-term active restoration did not change the degraded status of the grasslands, and there has been a decline in vegetation coverage and biomass. Consequently, the return of plant biomass to the soil system has decreased, leading to more severe soil degradation. As available soil nutrients diminish and the soil becomes more barren, it becomes increasingly difficult to further enhance the grassland's restoration ability. A key reason is that during long-term restoration, the grasslands continue to experience grazing disturbance, a common issue in global ecological restoration efforts (Xu et al., 2023). Our previous studies have shown that active restoration can enhance soil nutrient accumulation, but the restored grasslands should reduce grazing or implement rest-grazing through fencing (Feng et al., 2010; Gao et al., 2019). In this study, all long-term restoration grasslands were not well managed after the restoration measures were implemented. Throughout the long-term restoration process, the grasslands were grazed by local herders, with over-grazing occurring, which reduced the effectiveness of the restoration efforts.

Active restoration with native plant seed reseeding and reduced disturbance, coupled with improved management practices, could enhance the recovery effects for severe degraded grasslands. Furthermore, we advocate against implementing restoration projects without proper subsequent management, as this could lead to more severe degradation, particularly in ecologically fragile areas such as dry and cold regions. Although there is a significant need to restore degraded grasslands on the Qinghai-Tibetan Plateau, the pressure from livestock breeding on these grasslands necessitates a primary reduction in livestock numbers and an increase in protection or conservation efforts (Shang et al., 2014). If the large number of livestock cannot be reduced, the effectiveness of ecological restoration efforts will be greatly limited. Drawing on ecological theory and practice, active restoration with native plant reseeding has a positive effect and can significantly improve grassland recovery, which underscores the importance of post-restoration

management (Xu et al., 2019). Local herders should adopt planned-grazing practices on restoring grasslands, which could greatly enhance their recovery. This is because the economic interests of ecological restoration in severe degraded grasslands are ultimately closely linked to the local herders.

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