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Ideas and perspectives: soil cracking should be given great attention in the collapse of *Kobresia* ecosystems on the Tibetan Plateau

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Abstract. The *Kobresia* meadow in the Tibetan plateau is the world's largest and most unique pastoral alpine ecosystem, forming dense and closed 'lawns' mainly dominated by *Kobresia* species. Soil cracking induced by overstocking is an important feature of degraded alpine *Kobresia* meadows: it cuts the closed, intact rangeland and alters microtopography. However, soil cracks in alpine grasslands of the Tibetan plateau have rarely been reported and the importance of cracking in relation to livestock overgrazing for the degradation and collapse of alpine rangelands has not been taken seriously. In this Perspectives article, we explain the mechanisms of soil crack formation in *Kobresia* meadows under overgrazing; the ways in which the soil cracks affect the dynamics of hydrological processes and trigger the erosion of *Kobresia* turfs; and finally the effects on plant community composition and distribution. We outline the importance of recognizing soil cracks as visual indicators and early warning signs of degradation in order to recover alpine *Kobresia* meadows by reducing stocking rate. The purpose of this article is to emphasize that researchers and managers of alpine rangelands should pay more attention to crack phenomena in an effort to promote sustainable practices and restoration in *Kobresia* meadow-livestock systems.

Keywords. Tibetan Plateau; Overgrazing, Soil cracking; Grassland degradation; Preferential flow, Eroded turf

1. Introduction

The Tibetan Plateau supports various alpine ecosystems, most of them categorized as alpine grasslands under a tundra-like vulnerable environment (Harris, 2010;Niu et al., 2019b). The *Kobresia* meadow in the Tibetan highland, with an area of about 450,000 km^2 (Niu et al., 2019b), is the largest pastoral alpine ecosystem on earth. It is globally unique in its formation of dense and closed 'lawns' dominated by *Kobresia* spp. characterized by cold-and drought-tolerance and a vegetation height of less than 10 cm (Fig.1B) that extends from 3000 m a.s.l. to nearly 6000 m elevation (Miehe et al., 2019). In recent decades, due to accelerated warming in high-altitude areas (Pepin et al., 2015) and the large increase in livestock numbers (Squires and Limin, 2010a;Shang et al., 2014), the *Kobresia* ecosystem has been degraded on a large scale (Niu et al., 2019b). Today, alpine pastures are frequently grazed at higher stocking densities than they were traditionally with nomadic pastures due to the increase in the number of people who, directly or indirectly, rely on these grasslands for their livelihoods (Squires and Limin, 2010b;Kemp et al., 2013). This has led to an intensifying loss of biodiversity since the 1980s, resulting

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in serious damage and degradation of the structure and function of the alpine ecosystems. Fragmented, degraded alpine meadows are the most direct manifestation of *Kobresia* ecosystem degradation on the Tibetan Plateau (Fig.1). This system is difficult to restore because it is constrained by slow pedogenic processes (Kaiser et al., 2008), low nutrient utilization, limited recruitment from seed, and short growing season (De Boeck et al., 2018;Baumann et al., 2009). The grazing-induced degradation is not spatially uniform in the Tibetan Plateau; the most accepted assessment states that 30% of the alpine rangelands are degraded (Miehe et al., 2019). A growing body of research has addressed the issue of alpine rangeland degradation from a soil or vegetation perspective (Li et al., 2013). However, previous studies focused on the patterns of rangeland degradation without including turning points or driving factors, likely due to the gap in our understanding of the transition from intact *Kobresia* turfs to isolated turf patches (Fig.1). Niu et al. (2019b) proposed that the overgrazing-induced soil cracking stage is the tipping point during the course of alpine meadow degradation.

Although soil cracking is a common occurrence across overgrazed *Kobresia* meadows (Niu et al., 2019b), the underlying formation mechanisms are poorly understood. Few researchers are studying the soil cracking phenomenon in the Tibetan Plateau. This Perspectives article aims to communicate the importance of soil cracking in the degradation of *Kobresia* ecosystems though the alteration of hydrological processes and the acceleration of turf erosion.

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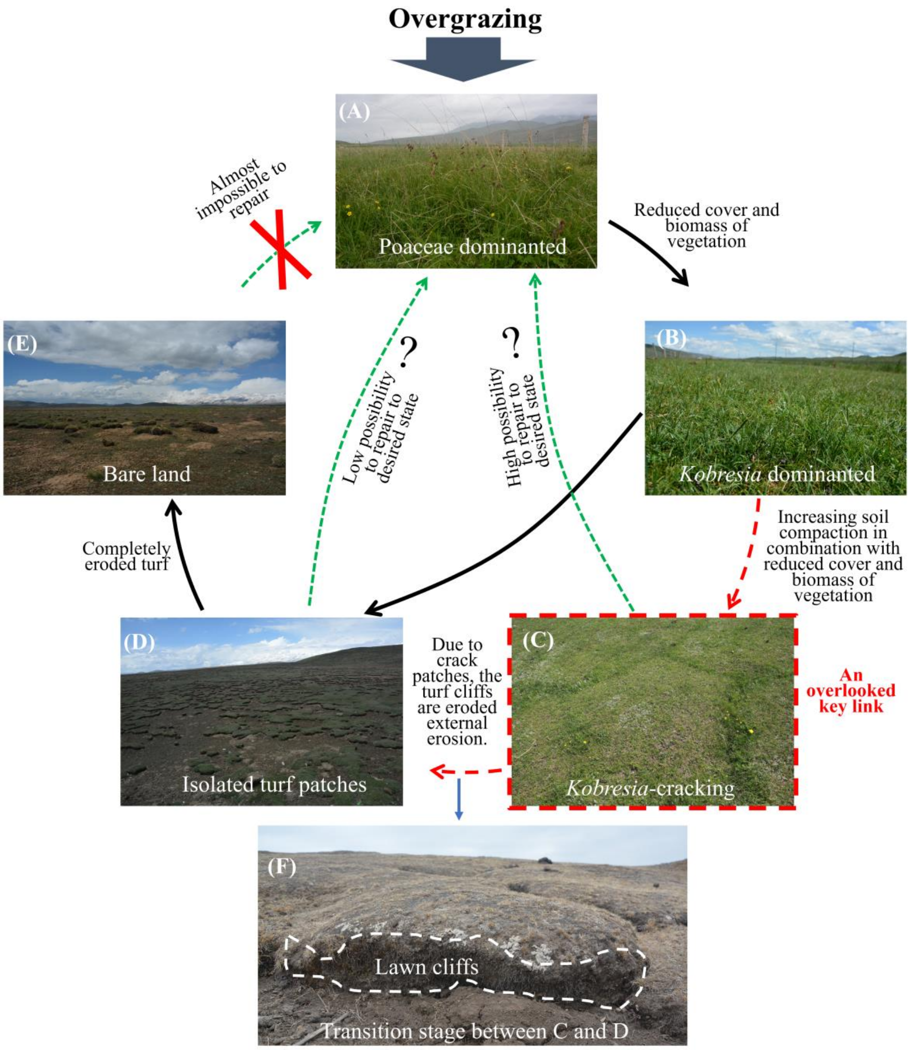

Figure 1. Adding soil cracking to the degradation and restoration loop of alpine *Kobresia* meadows. (A). Poaceae-dominated alpine meadows with 20-50 cm vegetation height (*Kobresia* species as the sub-dominant plants) under low grazing pressure. (B). Closed grazing *Kobresia* turfs with very low vegetation height which form dense and closed lawns covered by *Kobresia* species (mainly *Kobresia pygmaea* and *Kobresia humilis*), which develop a felt-like and dense root mat. (C). Under persistent overgrazing, mosaic soil cracks form in a polygonal pattern during winter. The cracks heal during summer, making them easily overlooked. At this stage, it is still possible to restore the cracking *Kobresia* ecosystem to a desired state by excluding grazing. (D). A quintessential view of alpine *Kobresia* ecosystem degradation: polygonally fragmented and eroded alpine grassland. At this stage, the possibility of restoring to the desired state is very low. (E). Bare land after the complete erosion of the turf. It's almost impossible to restore the bare ecosystem to desired state. (F). Turf cliffs owing to mosaic crack patches become the transition stage between C and D. Photos by Y. Niu.

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2. Two mechanisms of soil crack formation associated with grazing management

The formation of soil cracks is directly related to the expansion and shrinkage of soil system consisting of solid-liquid-gas phase (Fig.2), is the combined effect of changes in soil properties (such as minerals, organic carbon, water content, etc.) and environmental conditions (such as drought, freeze-thaw alternation, grazing, fertilization, etc.). We propose two mechanisms for soil crack formation. The first is the freeze-swell crack (Fig.2C). Under low temperature conditions, the water in the soil changes from a liquid to a solid state, the volume increases, the solid particles in the soil shrink to a certain extent during the freezing process (limited shrinkage), and finally the soil expands to form cracks. The second is the drying-shrinkage crack (Fig.2D). When soil is exposed to hot, dry conditions, the water in the soil evaporates, causing the previously water-swelled clay minerals in the soil to shrink, which leads to soil shrinking and thus forming cracks. The shrinkage of soils was significantly correlated with the content of expanding mineral during drying (Greene-Kelly, 1974). The shrinkage capacities of soils varied greatly with different expanding minerals, Gray and Allbrook (2002) concluded that allophane dominated soil had the largest shrinkage, followed by montmorillonite and halloysite dominated soil. In addition to the mineral particles, soil shrinkage was significantly correlated with organic matter content (Peng and Horn, 2013). Bandyopadhyay et al. (2003) concluded crack parameters were significantly positively correlated with soil bulk density, and that the application of manure reduced cracks. Current research on soil cracking mainly focuses on farmland ecosystems, rarely on grassland ecosystems. The grassland soil itself is affected by the interacting effects of grazing system, vegetation type, freeze-thaw alternation and external factors besides the phase change of the individual components of the soil, and the reason for its cracking is more complicated. As shown in Fig.2A, compared with adjacent alpine meadows with the same soil type under low grazing pressure, overgrazing reduced the vegetation cover and height, and increased soil bulk density through the compression of soil particles and reduction of available space for the swelling of water under freezing, leading to crack formation.

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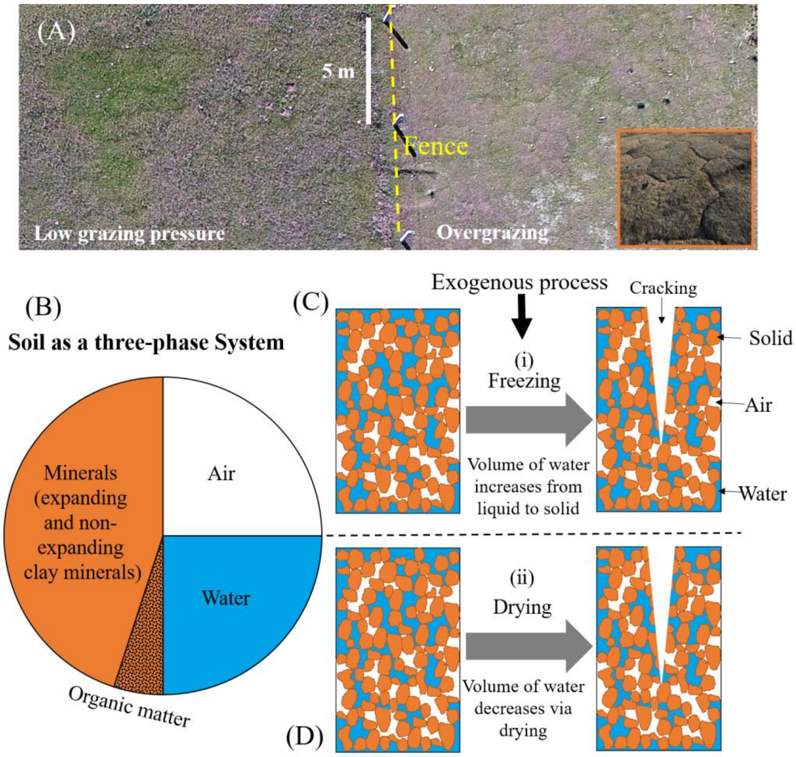

Figure 2. (A). Soil cracking occurs only in overgrazed alpine *Kobresia* meadow, whereas the adjacent, the meadow under low grazing pressure separated by only a fence is crack-free. (B) Soil is a multicomponent open system, formed by solid (including minerals and organic matter), liquid, and gas. (C) In the process of soil freezing, the water phase change from liquid to solid leads to the formation of cracks. (D) In the process of soil drying, the decrease in water content leads to the formation of cracks. Photos by Y. Niu.

3. Soil cracks alter hydrological processes

The soil surface is the link between the atmosphere and groundwater, and is a critical interface in the hydrological system. Cracked-soil mosaics play a significant role in water remigration and redistribution, with cracks acting as pathways of preferential flow. Soil cracks affect hydrological processes at the catchment scale in multiple ways (Fig.3), especially in contiguous mountain ecosystems (Niu et al., 2019a). They create channels between surface flows and groundwater, largely decreasing surface runoff and increasing infiltration. They also enhance evaporation due to the increase in soil surface area with cracks and low vegetation cover caused by overgrazing. Finally, they alter soil surface microtopography. Mitchell and Van Genuchten (1993) reported that water infiltration in cracked land was significantly higher than in crack-free land during flood irrigations. Even after soil cracks are closed on the soil surface, they can still remain paths for preferential flow (Sander and Gerke, 2007). Even though soil cracks can heal over the course of a summer, surface flow will continue

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to bypass central areas of polygonal crack units that have more compacted soil and smaller pore space (Fig.3) and preferentially flow laterally towards the healed cracks where water flows downwards very quickly through vertical pathways of large pore space. Consequently, the majority of rain or snowmelt water flows rapidly through the cracks and into the scree and gravel layer below the thin soil layer in these Tibetan grasslands. Hu et al. (2020) performed a hydrological experiment at a hillslope scale in the Tibetan Plateau and found that 95% of the total runoff from a north-facing slope was due to subsurface flow. This high proportion of subsurface flow is likely due to the presence of soil cracks in the hillslope.

3.1 Potential ecological risks caused by preferential flow paths of soil cracks

The uneven and often rapid transport of water and solutes via soil cracks is referred to as preferential flow and allows a range of contaminants, such as pesticides, animal waste, chemical fertilizers, and manurial pathogens, to be transported much faster through the soil matrix. Due to this increased transport of contaminants, preferential flow has significant consequences for the quality of ground-water which is used extensively as a source of drinking water and has direct impacts on human health. More than 1.4 billion people in Asia depend on water from rivers that have their headwaters in the Tibetan highlands (Immerzeel et al., 2010). Soil is the primary filter of drinking water. Water from rain or snowmelt, that flows laterally as surface runoff, or vertically through soil under gravity within a watershed and then into aquifers, is subject to extensive physical filtering by soil layers and purification by metabolic activities of soil microbes that gradually remove contaminants (Timmis and Ramos, 2021). However, contaminants carried by water can directly enter aquifers due to the decreased filtering effects of soil cracks, which may threaten drinking water.

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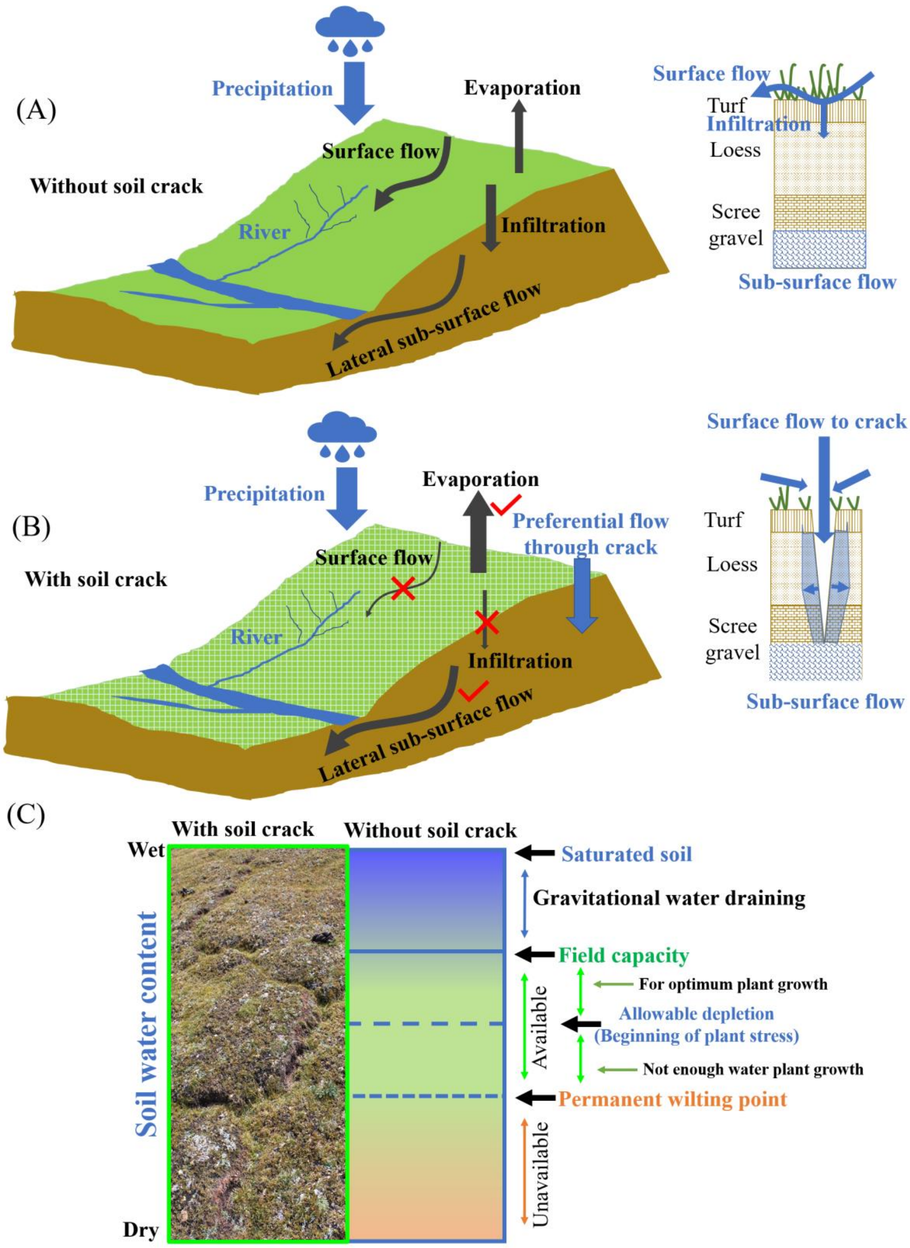

Figure 3. Conceptual model showing the hydrologic process without soil cracks (A) and with soil cracks (B). Soil cracks tend to reduce surface runoff and infiltration, while transferring surface flow to sub-surface flow through the preferential flow in cracks, thus affecting hydrological processes. (C). Alpine plants under chronic drought stress due to soil cracks.

3.2 Plants under chronic drought stress

Even during relatively long periods without precipitation, soil, as the most important water reservoir, retains the moisture necessary for growth of vegetation (Veihmeyer and Hendrickson, 1950). Depending on the actual soil moisture content, the precipitation is either stored in the soil, drains quickly as surface runoff, or slowly percolates through the soil to reach subterranean water. However, the presence of cracks disrupts this balance (Niu et al., 2019b). The increased soil surface area resulting from soil cracking under overgrazing theoretically leads to an increase in potential evaporation. In addition, increased soil compaction, owing to the intensified trampling under overgrazing, reduces total pore volume, and thus soil water storage is reduced even at field capacity (Sharrow, 2007). The combination of water's quick movement through cracks and increased evaporation further dries the soil and reduces the field capacity. Decreases in available water capacity, soil water held between field capacity and permanent wilting point, suppresses root and plant growth (Pan et al., 2020), and can even cause plant death if chronic drought stress persists. Selection induced by lasting drought stress under grazing may increase the frequency of a few trampling-tolerant species with caespitose, matted, rosette, or geophyte morphologies (Cole, 1995), as well as drought-proof species. Long lasting drought is likely to induce catastrophic mortality of poorly adapted species, exposing bare soil, and increasing the risk of turf erosion and long-term degeneration.

4. Soil cracks triggers *Kobresia* turfs to be eroded

Turf erosion in grasslands coupled with the direct and physical loss of topsoil and subsequently soil organic carbon (SOC) is one of the world's most pressing environmental issues, especially in montane and alpine zones (Geitner et al., 2021). The eroded *Kobresia* ecosystems on the Tibetan Plateau, known as Heitutan in Chinese, occupy an extensive area of the plateau, with around 49,000 km^2 in the southern Qinghai province alone (Li et al., 2013). Clonal reproduction strategies play an important role in population establishment and maintenance and stabilize plant communities over long periods in alpine regions (Körner and Hiltbrunner, 2021), and are also largely responsible for the formation of root mat turf. The *Kobresia* turf has an insulating effect, buffering the melting of permafrost (Miehe et al., 2019), and protects alpine soils against intensive livestock trampling while also supporting increasing vegetation productivity and the resistance of the dense root system against leaching and other erosions. Niu et al. (2019b) found that development of soil cracks in intact, protected *Kobresia* lawns was correlated to the two-fold increase in soil compaction in *Kobresia* meadows under overgrazing. Under increased stocking, root distribution also becomes shallower and tends to be allocated to the uppermost soil layers (Dai et al., 2019). This can be attributed to the decreased soil porosity and concentration of nutrients in the soil surface due to lower infiltration. The erosion of *Kobresia* turfs directly leads to a large loss of soil organic carbon (Fig. 4)

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because the *Kobresia* root mat makes up approximately half of the total carbon stock (10 kg C/m^2) of soil organic carbon (Unteregelsbacher et al., 2012;Miehe et al., 2019).

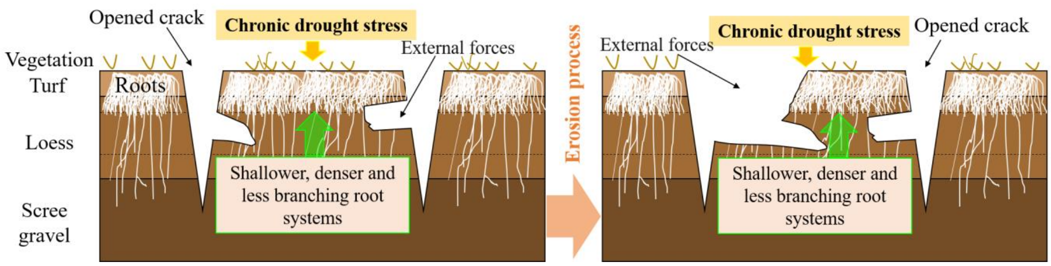

Figure 4. Conceptual illustration of the eroding process of *Kobresia* turfs due to the shallower and denser root systems on Tibetan Plateau.

5. Outlook for an early and visual warning indicator for the degradation of *Kobresia* meadows

From the governmental perspective, destocking, nomad settlements, and pasture fencing are currently the subject of state regulations on grassland management (Squires and Limin, 2010a). There are no clear policies addressing the balance between stock numbers and forage supplies; how to supervise the destocking process (by the local herders or the government); or how to remove excess livestock from alpine pastures (Hua et al., 2015;Squires and Limin, 2010b). From the herder perspective on the Tibetan plateau, pastures have been collectively owned by rural communities and managed by individual households, while nomadic herders have gradually transitioned to settlements (Hua and Squires, 2015). Individual households currently decide where and when to graze their pastures with which kind of livestock. Many other decisions remain about the number of head of livestock to have or to cull and how to feed them over winter. The answers to the above questions are crucial to the success of herd reduction. Determining stocking rate and carrying capacity of pastures owned by individual households is essential for improving grazing management. However, it is challenging for herders, the actual alpine pasture users, to make these estimates due to the complex herd composition (such as the differences in livestock type and size), occasional supplementary feeding, and their traditional lifestyles (Wang et al., 2018). Due to its gradual rather than abrupt nature, the degradation in this ecosystem is difficult to detect. Soil cracking in alpine

Kobresia meadows can be used as a visual indicator and early warning sign of overgrazing and should alert grassland managers to reduce stocking rate. We recommend the encouragement of traditional nomadic pastoralism (seasonal rotational grazing) and modern tourism to ensure that rangelands are not degraded and to safeguard pastoralist livelihoods for the sustainability of *Kobresia* meadow-livestock systems if applicable.

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Declaration of interests

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.

Author contributions

YN designed the research project and conceived the paper; YN finished the first draft; YN, VS, and LH wrote, reviewed & edited the paper.

Availability of data and code

Not applicable

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