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Abstract

Soil in Ladakh's high-altitude landscapes forms the ecological foundation of alpine pastures, supporting vegetation, regulating hydrology and sustaining pastoral livelihoods. Despite being shallow, alkaline and low in organic matter, soils play a critical role in nutrient cycling and forage production. Traditional agropastoral and transhumant systems have historically enhanced soil health through seasonal mobility, manure deposition and community-based pasture governance. However, demographic shifts, livelihood diversification, institutional weakening and climate variability are disrupting these socio-ecological rhythms, resulting in declining soil fertility, reduced moisture retention and slower vegetation recovery. Empirical evidence from Ladakh and comparative studies from the Himalayas, Tibetan Plateau and Eurasian rangelands highlight the importance of moderate, mobile grazing for maintaining soil function and ecosystem resilience. Policy recognition, participatory monitoring, restoration of pastoral infrastructure and integrative livelihood strategies are essential to safeguard soil systems and the ecological services they provide. The findings in this study underscore the interdependence of soil health, pastoral practices and sustainable land management in fragile mountain ecosystems.

Keywords: mountain soils; high-altitude pastures; Ladakh; Trans-Himalaya

In the Trans-Himalayan region of Ladakh, soils are primarily categorized as entisols (raw, undeveloped soils), inceptisols (moderately developed soils) and mollisols (organic matter rich soils), with mollisols dominating many pasture areas (Gupta and Arora, 2017). However, these soils remain naturally shallow, with an even thinner organic layer—shaped by centuries of glacial activity, low biological productivity and scarce precipitation. Most soils in the region are alkaline (pH 7.6–8.8)ⁱ and are often supplemented with organic manure to support agricultural productivity (Pelliciardi, 2012; Gupta and Arora, 2017).

Despite these constraints, soil plays a foundational role in sustaining Ladakh's alpine ecosystems. It anchors herbs and grasses essential for livestock fodder during seasonal migrations, regulates surface runoff in a water-scarce climate and supports slow nutrient cycling. These processes underpin both biodiversity and pastoral livelihoods.

Soil health is, thus, not only an ecological asset but also the bedrock of Ladakh's high-altitude pastures—landscapes deeply entwined with centuries of transhumance (seasonal movement of livestock between summer and winter pastures). These pastures are not isolated anomalies. Globally, rangelands (large grazing lands characterized by native vegetation) cover nearly half of Earth's land surface and support over a quarter of humanity by providing food, fibre, water and essential ecosystem services—including carbon storage, with rangeland soils accounting for nearly 30 percent of global soil carbon (Ingty, 2021; Baronti et al., 2022).

In the Himalayas, moderate grazing has been shown to enhance species richness, aid seed dispersal and improve nutrient cycling—creating a positive soil-plant-herbivore feedback loop (Tambe and Rawat, 2009; Aryal et al., 2015; Ingty, 2021). These effects are mediated both directly—through manure and urine deposition in animal resting zones—and indirectly, through trampling, which presses and loosens the soil and by creating an uneven distribution of soil properties, i.e., increased soil spatial heterogeneity (Liu et al., 2016).

Understanding these roles is essential, as it helps explain why the decline of pastoralism is not only a concern for local food and fodder systems but also an emerging environmental challenge in fragile mountain regions like Ladakh.

How are local livelihoods linked to soil systems?

For generations, Ladakhi communities have practiced agropastoralism and transhumant pastoralism (Figure 1). Mountain agropastoralism—an adaptive system that combines agriculture with seasonal livestock herding—is common in farming communities of Ladakh. This system depends on vertical mobility, with animals moving to alpine pastures in summer and returning to valley settlements in winter. In contrast, transhumant pastoralism—which involves full-time herding without cultivation—is limited to the high pasturelands of Changthang in eastern Ladakh. These seasonal migrations not only support animal health and fodder access but also contribute to soil enrichment, especially at animal resting sites where manure accumulates over time.

Figure 1
Seasonal alpine pastures above 4,000 m in Gya, Ladakh reflecting centuries of community-managed grazing



Source: Author

Both systems have historically been governed by principles such as moderate stocking rates, rotational movement and resting of pastures—ecological strategies that redistribute grazing pressure and allow for regeneration. These traditional practices have not just sustained livestock but have actively co-produced soil health by enhancing nutrient cycling, improving moisture retention and supporting diverse vegetation cover (Kreutzmann, 2012).

Studies from the Tibetan Plateau, European Alps and the Trans-Himalayan region of Ladakh confirm that such moderate and mobile grazing systems improve plant species richness, stabilize soil structure and maintain ecological function (Baronti et al., 2022; Ladon et al., 2023). Where these cycles continue, pastures—including their soil systems—tend to be more resilient. Where they are disrupted, however, signs of degradation—such as declining fertility, reduced moisture retention and slower vegetation recovery—gradually emerge, often going unnoticed until the impacts become widespread (Ladon and Garkoti, 2024).

What is changing—and why does it matter?

In recent decades, Ladakh's pastoral systems have undergone gradual yet significant transformation, shaped by multiple, overlapping pressures. Chief among these is a widening agrarian workforce gap. As younger generations increasingly pursue education, salaried jobs and urban livelihoods, fewer people are available or willing to manage livestock. This demographic shift has contributed to declining herd sizes, changes in herd composition and the abandonment of traditional migration routes—all of which disrupt long-standing pastoral rhythms (Ladon et al., 2023).

A key driver of this shift is livelihood diversification. While tourism often receives attention for disrupting land use, it is only one part of a broader transformation that includes growing opportunities in the public sector, private enterprises and non-farm employment (Pandit et al., 2024). These new livelihood avenues have redefined the value of land and labour, pulling people away from land-based occupations and seasonal cycles of grazing.

In Changthang, Ladakh's principal transhumant pastoral region, herders today face a convergence of challenges: shrinking access to pasturelands, the weakening of traditional practices and customary institutions such as the *Goba* system (for more see Ladon, 2025) that governs seasonal grazing and a declining interest in herding among youth. These reflect wider patterns of change unfolding across Ladakh's high-altitude rangelands (Pandit et al., 2024).

Compounding these social shifts is increasing climate variability. Changes in snowfall patterns, rainfall timing and pasture productivity have made it harder to plan seasonal migrations and grazing schedules (Adler et al., 2022; Ladon and Garkoti, 2024). In many cases, this has resulted in herders returning early from high pastures or even the complete cessation of seasonal herding.

Together, these intertwined pressures—labour scarcity, livelihood transition, institutional weakening and climatic uncertainty—are steadily eroding the ecological systems that once supported both soil function and fodder security.

What does the research say?

A recent study by Ladon and Garkoti (2024) in Leh district explored how changes in traditional pastoral practices are influencing soil composition. Although the study sites varied in elevation and land-use history, a consistent pattern was observed: where seasonal migration and the use of animal resting shelters have declined or ceased, soil conditions have noticeably deteriorated.

In villages where herding practices and livestock resting places are still maintained, regular manure deposition and nutrient recycling continue to support moisture retention, soil

structure and vegetation cover. In transitional areas, where herding persists but labour availability has declined and grazing cycles have become irregular, soils are beginning to show signs of reduced organic input and nutrient depletion—particularly around former resting areas. At sites where pastoralism has nearly ceased, the absence of livestock movement and organic inputs has left soils increasingly compacted and less fertile (Ladon and Garkoti, 2024).

These findings suggest that it is not merely visible land-use change *per se*, but the erosion of socio-ecological rhythms and community stewardship, that drives the gradual decline in soil function across these pasture systems.

This finding is echoed in studies from other high-altitude pastoral regions. In the European Alps, rotational grazing has been shown to reduce compaction, enhance vegetation recovery and improve water infiltration (Baronti et al., 2022). On the Tibetan Plateau, pastures managed under moderate grazing intensity support greater plant diversity compared to both overgrazed or under-grazed systems (Li et al., 2021). In the Western Himalayas, unregulated grazing is associated with rapid soil erosion and soil carbon loss, highlighting the ecological value of regulated stocking and periodic rest (Tambe and Rawat 2009; Aryal et al., 2015).

Similar patterns are evident in the Eurasian steppe ecosystems, where cattle and mixed herbivore grazing have been found to enhance the spatial heterogeneity of soil nitrogen—especially in areas with high-diversity grasslands. This variability in nutrient distribution fosters plant-soil interactions and contributes to more resilient ecosystem functioning (Liu et al., 2016).

What can be done?

The key lies in viewing soil not simply as a physical resource, but as a socio-ecological outcome shaped by human-environment interactions. In Ladakh, this means restoring the systems that once sustained soil health: seasonal mobility, organic nutrient inputs and strong community-based pasture governance (Kreutzmann, 2012; Ladon et al., 2023).

Revitalizing dual-livelihood models could help bridge the growing disconnect between pastoralism and emerging economic pathways. Programmes that allow herders to combine livestock care with part-time tourism or wage work—supported through incentives, training and flexible arrangements—can make pastoralism more viable, particularly for Ladakhi youth.

Likewise, restoring basic infrastructure, such as livestock resting shelters, offers low-cost ecological returns. These shelters help concentrate manure in predictable zones, enriching soils organically (Jina, 1995). At the same time, integrating soil health monitoring into broader climate adaptation strategies is essential. Participatory approaches that blend traditional ecological knowledge with simple indicators like bulk density or moisture retention can enable early detection of degradation (Liu et al., 2016). For example, field observations from Gya (Ladakh), found that soils near animal resting areas maintained by herders had higher moisture and nutrient content compared to abandoned pastures, demonstrating how local observations can complement quantitative soil monitoring (Ladon and Garkoti 2024).

Equally important is policy visibility. Despite pastoralism's contributions to food security, biodiversity conservation and land stewardship, it remains marginal in most rural development frameworks. Land-use policies must recognise seasonal grazing patterns,

protect migration corridors and secure community access to alpine commons (Shagun, 2022). In Ladakh, expanding infrastructure and tourism activities increasingly overlap with grazing routes, underscoring the need to integrate pastoral priorities into regional land-use planning. Reviving customary institutions such as the *Goba* system—historically responsible for regulating grazing rotation and enforcing rest periods—can also help bridge traditional governance with formal land management frameworks.

Encouraging examples are already taking shape. In Nyoma block, the ‘Viksit Krishi Sankalp Abhiyan’ (a nationwide campaign to modernize Indian agriculture) promotes sustainable livestock and soil practices (UT Administration, 2025). National schemes such as the Rashtriya Gokul Mission, Animal Husbandry Infrastructure Development Fund (AHIDF) and National Livestock Mission (NLM) have also been urged to explicitly include pastoralist communities. In 2022, the Union Government instructed states—including Ladakh—to ensure the inclusion of pastoralists under existing programmes, alongside proposals for a dedicated pastoralism unit for registration and mapping of migratory routes (Shagun, 2022). The pastoralists of Changthang are presently registered under NLM through the Sheep Husbandry Department, Leh (personal communication). Under the NLM scheme, the Sheep Husbandry Department, Leh, had also arranged exposure tour to Kargil for the livestock owners, focusing on improved breeds and animal-care practices (UT Administration, 2025). Regional initiatives such as the International Centre for Integrated Mountain Development’s (ICIMOD) Regional Rangeland Programme Phase III and World Wide Fund for Nature (WWF), India’s participatory pasture monitoring in Changthang further demonstrate how community-led models can align ecological and livelihood goals (Sharma et al., 2007; ICIMOD, 2019; WWF India, 2023).

Other Indian states in the Himalayan region are also piloting relevant approaches. In Uttarakhand, the country’s first grass conservatory was established in Almora district in 2021 to document and conserve native grass species, many of which are vital for fodder security in mountain ecosystems (*The New Indian Express*, 2021). In Jammu and Kashmir, the administration introduced truck-based transport for the migratory pastoralists, easing the movement of more than 1.5 lakh livestock during their biannual transhumance. This initiative has reduced stress on animals, lowered migration risks and provided relief to nomadic communities traditionally dependent on arduous seasonal journeys (*The Print*, 2023). In Himachal Pradesh, new initiatives such as rotational grazing, fodder plantations and interdepartmental coordination have been undertaken to address soil and fodder degradation (Mohan, 2023). Building on earlier state-level efforts to pause afforestation on traditional grazing lands, the Himachal government’s Forest Department in 2025 formally identified 1,637 pastoral routes and halting areas, directing that no tree-planting or afforestation activities take place along these corridors to safeguard pastoral mobility and access to grazing lands (Shagun, 2022 and 2025). In Spiti, community-managed grazing-free reserves, initially created for wildlife conservation, have improved soil recovery by easing pressure on surrounding pastures and allowing organic matter to accumulate (Nature Conservation Foundation, 2023). Taken together, these measures signal growing recognition of pasturelands as socio-ecological commons rather than as empty spaces available for development.

The condition of agropastoral systems in Ladakh reflects broader patterns observed in other mountain regions—including Spiti, Sikkim, Gilgit-Baltistan, Chitral and Nanga Parbat—where similar challenges have been recorded (Ehlers and Kreutzmann, 2000; Nüsser et al., 2012; Yi et al., 2012; Ahmad et al., 2021; Hussain et al., 2021; Luxom et al., 2022). These parallels underscore the need for a systematic, scientifically grounded database on pasture ecology and soil systems to track and address the evolving agro-environmental dynamics.

Taken together, these initiatives lay important groundwork. Yet, their success depends on re-centering mobility, community agency and ecological feedback. In Ladakh, the ICIMOD-supported Regional Rangeland Programme, implemented through the Ladakh Autonomous Hill Development Council offers a formal institutional platform. However, since 2019, there has been little progress in translating these frameworks into sustained on-ground action, reflecting persistent challenges in coordination, funding and local engagement (Sharma et al., 2007; ICIMOD, 2019)—except for its incorporation into the Ladakh Vision 2025 document.

Conclusion

The condition of Ladakh's soils illustrates how closely ecological processes are tied to livelihood systems. High-altitude soils are naturally shallow, alkaline and low in organic matter, yet centuries of agropastoral management have enabled them to sustain both biodiversity and human use. Seasonal mobility, manure deposition and collective regulation have historically maintained soil fertility and resilience. With these practices now in decline, the soils themselves are showing signs of stress—compaction, nutrient depletion and moisture loss.

What stands out is that degradation is not only the result of visible land-use change but also of less tangible shifts: weakening of community institutions, reduced youth engagement in herding and disrupted rhythms of seasonal migration (Ladon et al., 2023). Soil health, therefore, is best understood as a socio-ecological outcome, shaped as much by collective stewardship as by biophysical conditions.

This perspective carries important policy implications. Efforts to restore or maintain soil systems cannot be confined to technical fixes such as fertilizers or plantations. They require supporting the continuities that once made these soils resilient: mobility, rotational grazing, organic nutrient cycling and inclusive governance of rangeland commons. Examples emerging from across the Himalaya—rotational grazing pilots in Himachal, migration support in Jammu and Kashmir and community-managed reserves in Spiti—offer practical lessons that could inform Ladakh's approach.

Sustaining soil health is ultimately about sustaining the socio-ecological fabric that underpins it. The survival of indigenous livestock breeds, the viability of pastoral livelihoods and the ecological resilience of alpine pastures are all interlinked. Recognizing rangelands as integrated systems, rather than fragmented resources, is essential for their future. Long-term strategies must, therefore, combine ecological monitoring with institutional renewal, ensuring that soil stewardship remains embedded in the broader livelihood and cultural systems that have shaped Ladakh's landscapes for generations.

ENDNOTES

ⁱ The soil pH scale indicates how acidic or alkaline a soil is. A pH of 7 represents neutrality, values above 7 reflect alkalinity or basic soil and values below 7 indicate acidity.

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