



Dynamics of Cold Arid Zones in the Hindu Kush Himalaya and their Implications for Ecosystem Services and Human Well-Being

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Abstract: Mountains cover ~22% of the Earth's land surface and support ~13% of the global mountain population. The Hindu Kush Himalaya (HKH), one of the world's largest mountain systems, provides critical ecosystem services-water, food, bioresources, and energy-sustaining about 240 million mountain people. Cold arid environments in the HKH are governed by interactions among precipitation, atmospheric moisture demand, temperature, and elevation. Analysis of ecosystem classes for 2000, 2010, and 2022 reveals marked spatial and temporal shifts across cold arid zones, including the cryosphere, high-altitude wetlands, and alpine vegetation. Change detection (2000-2022) highlights strong spatial heterogeneity in land-cover transitions, indicating diverse, localized responses to climatic change. Overall, the region shows a coupled pattern of vegetation expansion, cryosphere decline, and wetland formation, reflecting climate-driven restructuring of high-elevation ecosystems. These transformations in cold arid ecosystems-across glaciers, snow systems, wetlands, and alpine vegetation-are increasing risks for downstream populations. Declining ecosystem services are likely to reduce agricultural productivity, heighten disaster risks, and undermine human well-being in both mountain and downstream regions. Cold arid ecosystems are therefore critical in the context of climate and global change, requiring targeted attention and sustained investment to enhance resilience and support sustainable development.

Key words: Alpine vegetation, climate change, high-altitude wetlands, mountains, snow and glacier, spatial-temporal changes.

Global cold arid regions are characterized by extremely low temperatures, sparse precipitation-predominantly in the form of snow (typically precipitation <250 mm annually)-and high levels of aridity. Major cold arid zones occur in the polar regions, the Tibetan Plateau, the Gobi Desert, the Great Basin Desert, and high-altitude areas of the Himalaya.

Mountains occupy approximately 22% of the Earth's land surface and support about 13% of the global population (FAO, 2015). An estimated 915 million people live in mountain

regions, including around 150 million residing above 2,500 m, particularly within cold arid environments. Nearly half of humanity depends directly on mountain resources, especially freshwater. Mountains harbor approximately 25% of the world's terrestrial biodiversity and encompass nearly half of global biodiversity hotspots. In semi-arid and arid regions, they contribute between 70% and 95% of available freshwater resources (Kapos *et al.*, 2000; UNEP-WCMC, 2002, UNEP, 2022). Beyond their ecological importance, mountains provide a wide range of goods and ecosystem services of global significance, including freshwater supply, hydroelectric power, timber, biodiversity, niche products, mineral resources, recreation, and natural hazard regulation such as flood control (Schild and Sharma, 2011; Molden and Sharma, 2013).

The Hindu Kush Himalaya (HKH) is one of the greatest mountain systems of the world. The HKH region is defined by interconnected biophysical features, including elevation gradients, mountain systems, river basins, and ecological zones. It spans approximately 4.2 million km² across eight countries—Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan (Bajracharya *et al.*, 2015; Sharma *et al.*, 2019). The HKH and the Tien Shan together contain the largest expanse of glaciers and permanent ice outside the polar regions. This vast cryospheric reserve spans several countries across South and Central Asia and includes thousands of glaciers, extensive snowfields, and high-altitude permafrost systems. Because of this exceptional concentration of ice, the HKH region is widely referred to as the “Third Pole,” underscoring its global climatic and hydrological significance. This opinion paper focuses specifically on the HKH region.

The region delivers a wide range of ecosystem services—such as water, food, bioresources, and energy—that directly sustain the livelihoods of around 240 million people living in the mountains and hills of the HKH. Its significance, however, extends far beyond these highland communities. Nearly 1.9 billion people residing across the ten major river basins originating in the HKH depend on these resources, both directly and indirectly. In addition, the agricultural productivity supported by these river systems contributes

to food security for more than 3 billion people, underscoring the HKH's critical role in regional and global sustainability (Sharma *et al.*, 2019).

The HKH spans a vast and diverse mountain system, extending from Myanmar in the east to Afghanistan in the west. It encompasses not only the Himalayan range but also the Hindu-Kush, Karakoram and Pamir mountain systems, along with the expansive Tibetan Plateau. This interconnected region forms one of the most significant high-altitude arid landscapes on Earth, characterized by complex topography, rich biodiversity, and critical ecological functions.

Cold arid environments in the HKH are shaped by the interplay of precipitation, atmospheric moisture demand, temperature constraints, and elevation. The region hosts extensive high-altitude cold deserts, where aridity is driven not only by low precipitation but also by strong thermal limitations and orographic effects.

Analysis of ecosystem classes for 2000, 2010, and 2022 reveals distinct and contrasting trends across cold arid zones, the cryosphere (snow, glaciers, and permafrost), high-altitude wetlands, and alpine vegetation (Table 1). Over this period, the HKH exhibits pronounced spatial heterogeneity in land-cover transitions, reflecting diverse and localized responses to climatic and environmental change.

The multi-temporal maps (2000, 2010, and 2022) reveal clear spatial and temporal shifts in major high-altitude ecosystem classes across the HKH (Fig. 1). Alpine vegetation (green) shows a progressive expansion, particularly across the eastern Himalaya and the Tibetan Plateau, suggesting an upward and lateral spread into previously colder, less vegetated zones. In contrast, snow and glacier cover (white) exhibits a pronounced and continuous decline, most evident in the central and eastern HKH, reflecting ongoing cryospheric loss. High-altitude wetlands (blue), initially more fragmented in 2000, become increasingly extensive and spatially coherent by 2022, especially in the eastern sector, indicating enhanced meltwater accumulation and associated hydrological changes. Meanwhile, cold arid zones (orange) display relatively stable but regionally variable patterns, with slight contractions in parts of the western

Table 1. Dynamics of alpine vegetation, snow and glacier, high altitude wetlands and cold arid zone from 2000, 2010 and 2022

Ecosystems	Year	Area (km ²)	Difference	Change (%)
Cold Arid	2000	772864	-	-
	2010	749952	22912	-2.96
	2022	757108	-7155	0.95
Snow and Glacier	2000	157776	-	-
	2010	147785	9991	-6.33
	2022	121182	26603	-18.00
High Altitude Wetlands	2000	60697	-	-
	2010	63980	-3283	5.40
	2022	74074	-10094	15.77
Alpine Vegetation	2000	1333291	-	-
	2010	1374751	-41460	3.10
	2022	1398344	-23593	1.71

HKH and localized expansions elsewhere. Collectively, these patterns point to a coherent, climate-driven reorganization of high-mountain ecosystems, characterized by declining ice

cover, expanding vegetation, and increasing wetland formation over the past two decades.

The change-detection maps (2000–2022) reveal pronounced spatial heterogeneity

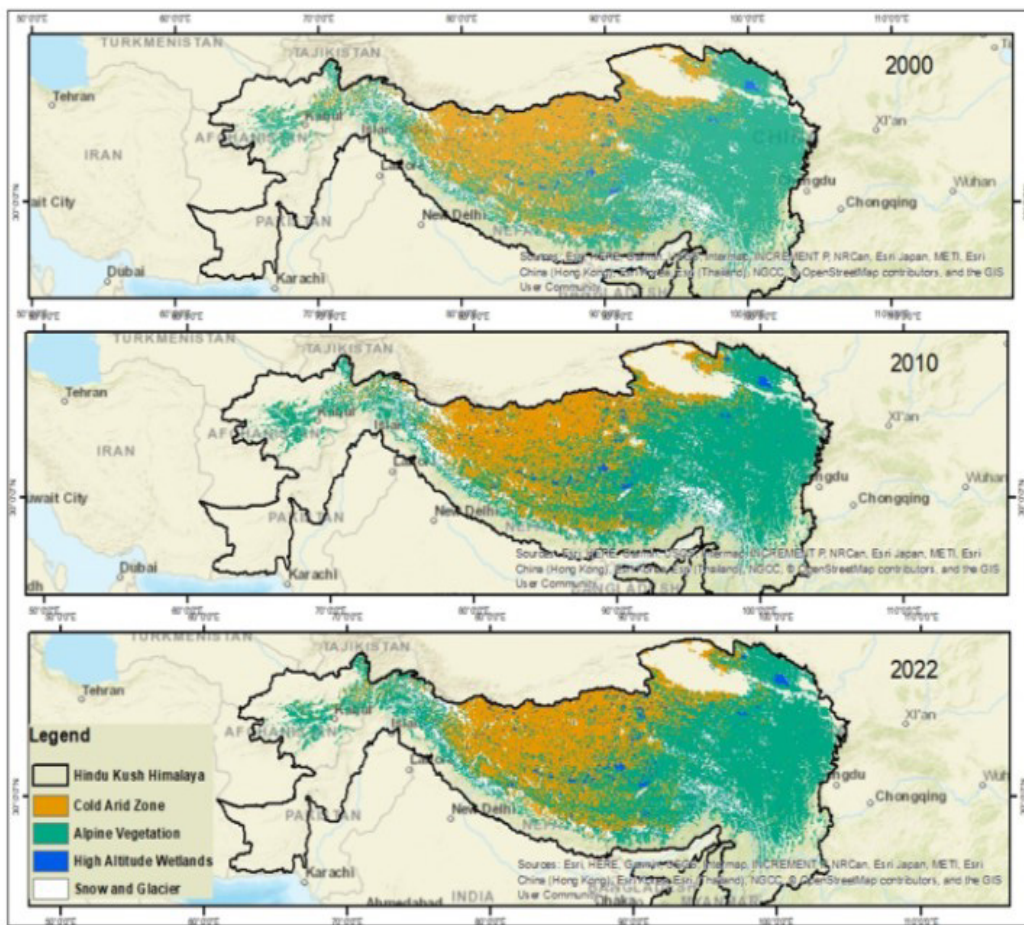


Fig. 1. Multi-temporal representation of major high-altitude ecosystems in the HKH region across 2000 (top), 2010 (middle), and 2022 (Bottom).

in ecosystem transitions across the HKH, highlighting both the direction and magnitude of land-cover dynamics (Fig. 2). Areas of gain (blue) and loss (red) indicate widespread expansion of alpine vegetation, particularly across the eastern Himalaya and the Tibetan Plateau, often at the expense of cold arid or sparsely vegetated landscapes. In contrast, losses in snow and glacier cover are strongly concentrated along the central and eastern high-mountain belts, reflecting extensive cryospheric

retreat. High-altitude wetlands exhibit spatially clustered gains, especially in topographic depressions and downstream areas adjacent to retreating glaciers, suggesting hydrological reorganization associated with increased meltwater availability. Cold arid zones display more diffuse patterns of both gains and losses, indicating localized transitions and relative stability compared to other ecosystem classes. Overall, these patterns point to a coupled process of vegetation expansion, cryosphere

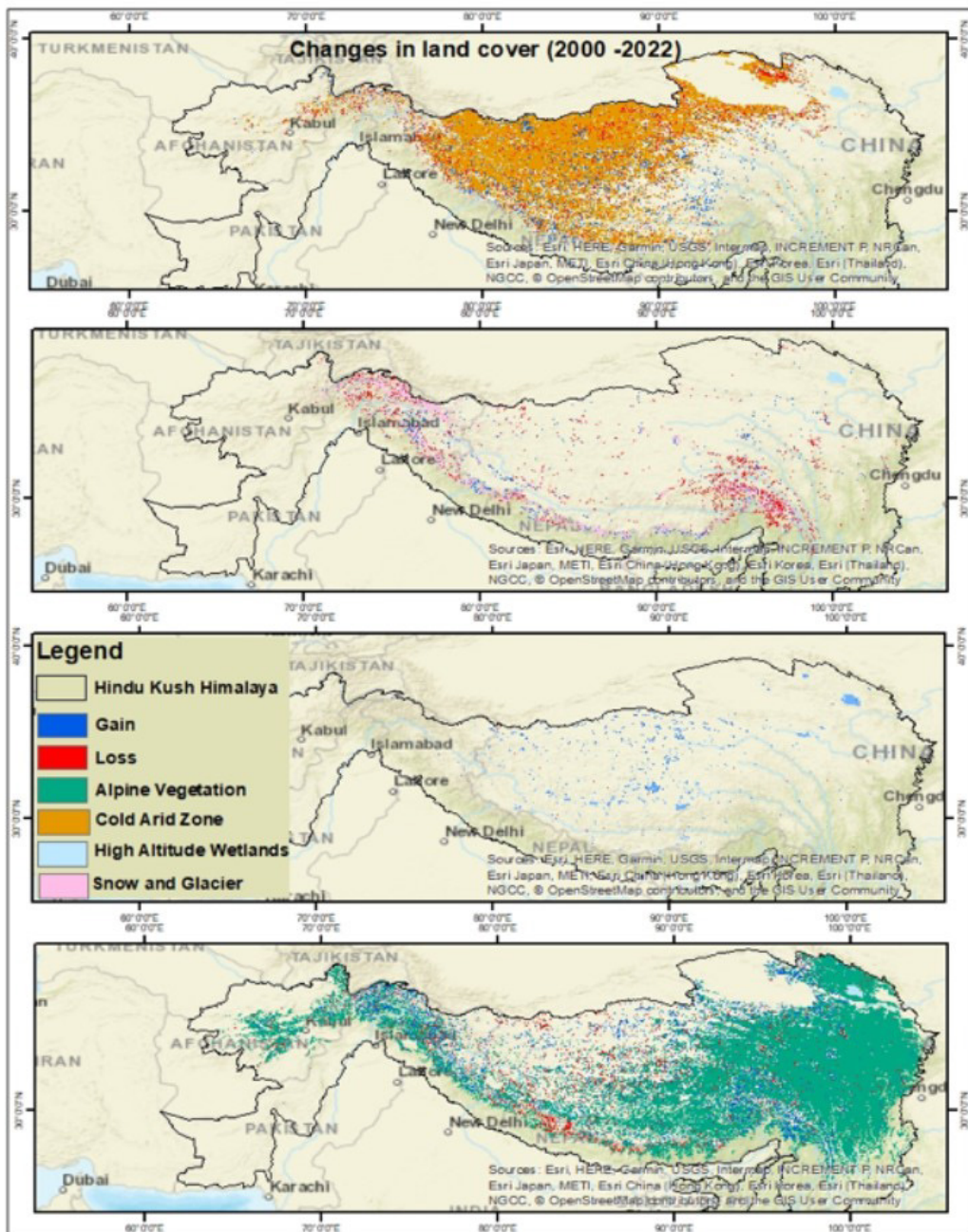


Fig. 2. Spatial patterns of change in major high-altitude ecosystems in the HKH region between 2000 and 2022, derived from change-detection analysis.

decline, and wetland formation, underscoring the influence of climate-driven processes in reshaping high-elevation ecosystems across the HKH over the past two decades.

Cold arid Zone: The cold arid zone experienced a slight overall contraction (-2.75%) between 2000 and 2022, with the largest losses in China, followed by India and Pakistan, while Nepal showed a notable expansion-highlighting contrasting regional dynamics. Temporally, the extent declined during 2000-2010 (-2.96%) and partially recovered during 2010-2022 (+0.95%), resulting in a modest net decrease (~15,757 km²). These trends suggest an initial ecological shift (e.g., towards alpine vegetation or wetlands), followed by localized stabilization or drying. Overall, the cold arid zone remains relatively stable compared to other land cover classes.

Snow and Glacier: Snow and glacier cover declined sharply across the region (-23.19%) from 2000 to 2022, with the largest losses in China, followed by Pakistan, and moderate declines in India, Afghanistan, and Nepal. Bhutan showed small localized gains, but overall cryospheric loss was widespread. The decline was continuous and accelerated over time: -6.33% (2000-2010) and -18% (2010-2022), resulting in a net loss of ~36,594 km². This rapid post-2010 shrinkage reflects intensifying warming in high-elevation HKH areas and poses serious risks to downstream water security and regional hydrology.

High Altitude Wetlands: High-altitude wetlands expanded markedly across the HKH (+22.04%), driven largely by gains in China, with smaller increases in India, Nepal, and Bhutan, while Afghanistan and Pakistan saw minor losses. Expansion accelerated over time: +5.41% (2000-2010) and +15.78% (2010-2022), yielding a net gain of ~13,377 km². This post-2010 surge likely reflects glacier retreat, permafrost thaw, and increased meltwater accumulation, promoting wetland formation in alpine areas.

Alpine Vegetation: Alpine vegetation expanded moderately across the HKH (+4.88%), led by substantial gains in China, with additional increases in Pakistan and India, and smaller rises in Afghanistan and Myanmar. In contrast, Nepal experienced a notable decline, marking the largest contraction in the region. Overall, alpine vegetation showed a steady

increase: +3.11% (2000-2010) and +1.72% (2010-2022), resulting in a net expansion of ~65,053 km². This trend points to an upward shift and densification of vegetation driven by warming and longer growing seasons, though the slower growth after 2010 suggests emerging ecological limits or stabilization.

Climate change is driving profound biophysical and socio-economic impacts in the Hindu Kush Himalaya (HKH), including biodiversity loss, accelerated glacier melt, and increasingly uncertain water availability-directly affecting livelihoods and well-being. The region, particularly its cold arid zones, has warmed faster than the global average, with strong evidence of elevation-dependent warming (Wester *et al.*, 2019).

Mountains act as climate change hotspots, where warming intensifies with elevation. At current emission rates, HKH temperatures could rise by ~5°C by 2100, accelerating glacier melt and reducing ice reserves. In cold arid zones, snow cover and volume are projected to decline further, with rising snowlines and earlier, more intense snowmelt runoff. These changes will alter streamflow regimes, with major implications for nearly two billion people who depend on HKH water resources for agriculture, hydropower, ecosystems, and cultural services.

Environmental, sociocultural, and economic changes in the HKH are tightly interconnected, shaped by governance, demographic shifts, resource use, economic growth, and context-specific vulnerabilities, alongside climate change. Transformations in cold arid ecosystems-including glaciers, snow systems, high-altitude wetlands, and alpine vegetation-are increasing risks for downstream populations. Declining ecosystem services are likely to reduce agricultural productivity, heighten disaster risks, and undermine human well-being across both mountain and downstream regions.

Cold arid ecosystems are therefore critical in the context of climate and global change, requiring targeted attention and sustained investment to support resilience and sustainable development.

Competing Interests

The authors declare no competing interests.

References

- Bajracharya, S.R., Maharjan, S.B., Shrestha, F., Guo, W., Liu, S., Immerzeel, W. and Shrestha, B. 2015. The glaciers of the Hindu Kush Himalayas: current status and observed changes from the 1980s to 2010. *International Journal of Water Resources Development* 31(2): 161-173.
- FAO. 2015. *Mapping the vulnerability of mountain peoples to food insecurity*. Food and Agriculture Organization of the United Nations, Rome, Italy.
- Kapos, V., Rhind, J., Edwards, M., Price, M.F. and Ravilious, C. 2000. Developing a map of the world's mountain forests. In M.F. Price and N. Butt (eds.), *Forests in Sustainable Mountain Development: A State-of-Knowledge Report for 2000*, CAB International, Wallingford: 4-9
- Molden, D. and Sharma, E. 2013. ICIMOD's Strategy for Delivering High-quality Research and Achieving Impact for Sustainable Mountain Development. *Mountain Research and Development* 33(2): 179-183.
- Schild, A. and Sharma, E. 2011. Sustainable Mountain Development Revisited. *Mountain Research and Development* 31(3): 237-241.
- Sharma, E., Molden, D., Rahman, A., Khatiwada, Y.R., Zhang, L., Singh, S.P., Tandong, Y. and Wester, P. 2019. Introduction. In Wester, P., Mishra, A., Mukherji, A. & Shrestha A. B. (eds), *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*. Springer Nature, Dordrecht.
- UNEP-WCMC. 2002. *Mountain Watch: Environmental Change and Sustainable Development in Mountains*. UNEP - World Conservation Monitoring Centre, Cambridge, UK
- UNEP. 2022. *A Scientific Assessment of the Third Pole Environment*. United Nations Environment Programme, Nairobi.
- Wester, P., Mishra, A., Mukherji, A., Shrestha, A.B., editors. 2019. *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*. Cham, Springer Nature, Dordrecht.

About the Authors

Eklabya Sharma, a Padma Shri awardee, is Strategic Advisor and Director of The Himalaya Initiative at ATREE, Bengaluru, and President of the International Society for Tropical Ecology. An ecologist with over 45 years of experience, he is internationally recognized for pioneering research in the Himalaya, advancing science diplomacy, and shaping the global mountain agenda. His work spans biodiversity conservation, natural resource management, climate change adaptation, nature-based solutions, and strengthening resilience in mountain socio-ecological systems. He has held several key leadership positions, including Head of the Sikkim Regional Centre at the G.B. Pant National Institute of Himalayan Environment, Deputy Director General at the International Centre for Integrated Mountain Development, and Vice-Chancellor of TERI School of Advanced Studies.

Avantika Thapa is an interdisciplinary conservation researcher in the Himalayan region, integrating socio-ecological systems, GIS, and remote sensing to understand landscape change and human-wildlife coexistence. Her work examines how climate change, land-use transitions, and conservation policies reshape everyday interactions between people and wildlife in mountain systems. It is grounded in community-informed perspectives, critically exploring how the Himalaya is changing and what these shifts mean for people and biodiversity.