



## Nature-based Solutions in Cold Arid Landscapes: Opportunities for Integrated Land, Water, and Livelihood Resilience

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**Abstract:** Cold arid landscapes are amongst the most vulnerable, climate-stressed regions in the world. They are characterised by limited biomass, slow ecological processes, fragile soils and tightly coupled climate-land-water-livelihoods systems. The geo-physical and ecological constraints often make us think whether the applicability of Nature-based Solutions (NbS) is feasible in such an environment. This perspective paper argues that NbS remain highly relevant in cold arid regions- not because of natural capital abundance, but because of their design dimension as overarching and integrative framework. NbS design can simultaneously restore land functions, regulate water availability, sustain climate-sensitive biodiversity, and economic development while also promoting inclusive institutions and adaptive management. Drawing on insights from the Hindu Kush Himalaya and other regions of the world, the paper highlights that in an ecologically constrained space, resilience comes not from abundance and scale of nature, but from its coherent design that sustains ecological functions and processes, minimising both ecological and socio-economic vulnerabilities. We thus position NbS as a core resilience strategy for cold arid socio-ecological systems under accelerating climate change.

**Key words:** Ecosystem management, landscape resilience, biodiversity, socio-ecological resilience, Hindu Kush Himalaya, nature-based solutions.

Cold arid landscapes - such as the high-altitude Trans-Himalaya, Tibetan Plateau, Arctic tundra, Andean altiplano, and Antarctic dry valleys, covering 40% of the global land (Vicente Serrano *et al.*, 2024) - are among the most climate-sensitive socio-ecological systems on Earth (Vuille *et al.*, 2018; Yao *et al.*, 2012). Characterised by low rain, high evapotranspiration, short growing seasons, sparse vegetation, fragile soils, and slow ecological turnover, they are highly sensitive to climate change, permafrost changes, and land use changes (Pörtner *et al.*, 2022). Disturbances persist longer given the low ecological buffering capacity (Körner, 2021a) and regeneration may take decades (WDNR, 2021).

Livelihood options are also limited, mainly revolving around transhumance, agro-pastoral systems, oasis-based farming and seasonal water-dependent agriculture, functioning of which

are coupled with hydrological and ecological systems (Shinoda and Nandintsetseg, 2011). Climate change, glacier retreat, permafrost thawing (Wani *et al.*, 2020a) alter hydrology (She *et al.*, 2025), trigger land-use change, and accelerate the societal challenges. Ecologically, (Lenton, 2025) documented 26 global tipping systems, and indicate drylands and cryosphere-dependent landscapes as being closest to the threshold. Early warning signals inform declining resilience metrics for several cold arid sub-regions (Dakos *et al.*, 2024).

Despite such ecological uniqueness and socio-economic connectedness, cold arid landscapes remain hugely underrepresented in the Nature-based Solutions (NbS) literature. Globally, NbS are gaining momentum as holistic and umbrella pathway to address intertwined societal challenges linked to climate, biodiversity and development (Seddon *et al.*, 2021). Most NbS for climate change adaptation have strong geographic and ecological bias toward urban, coastal, and humid temperate regions (Chausson *et al.*, 2020), often not applied where it is needed the most (Dubo *et al.*, 2023). NbS discourse carries an implicit assumption on being conservation-oriented actions to promote large scale revegetation mainly forest plantation. This implies that NbS may fit only to places with higher ecological abundance as NbS then would be able to leverage upon ecosystem services, and nature contribution to people (Seddon *et al.*, 2020). This raises a fundamental question for cold arid landscapes contexts with ecological scarcity, slow ecological processes and limited regenerative capacities - if NbS can function effectively?

The answer is yes. Globally, NbS is seen as unifying solution design that simultaneously address biodiversity and climate crises (IPCC-IPBES, 2020). In the context of cold arid landscapes NbS should be seen as strategy to promote integrated land, water and livelihoods resilience (Dubo *et al.*, 2023; Seddon *et al.*, 2021), and it will work not because there is 'more nature' to leverage ecological processes, but because of design that is holistic (Gorain *et al.*, 2025), that is hydro-geologically grounded, ecological diversified, socially inclusive, and based on sound scientific and traditional ecological knowledge. Against this backdrop, we discuss vulnerabilities of cold arid landscapes as a part of unpacking

societal challenge, discuss elements of NbS design, relate to some examples of it to reflect on outline structural barriers that prevent effective NbS design and implementation, provide strategic recommendations to facilitate adoption of NbS design and conclude with some research questions that will strengthen NbS as the highest-leveraged opportunities for ecosystem resilience and people's well-being.

### **Societal Challenges: Constraints and Vulnerability**

The first step to designing any solution is understanding the challenge perspective. NbS requires rigorous unpacking of societal challenge (IUCN, 2020). Biophysically, cold arid regions face climatic extremes with higher inter-annual and inter-decadal climate variability Wang *et al.*, 2023). Water is the scarcest resource and water insecurity is biggest challenge induced by reduced snow persistence, shifting precipitation patterns, declining baseflows, and frequent droughts (McMahon and Nathan, 2021). Water scarcity arising from aridity and desertification is said to be irreversible, with implications on settlements and livelihoods (Thayyen, 2019). Likewise, wind erosion, frost damage Wang *et al.*, 2025), permafrost thawing (Wani *et al.*, 2020b), salinization (Dregne, 2002) trigger rapid ecosystem degradation, making the arid landscape ecologically vulnerable (Körner, 2021b; Sainnemekh *et al.*, 2022). Ecosystem degradation affects delivery of diverse ecosystem services such as water regulation, carbon sequestration, hazard regulation that eventually have long-term socio-ecological repercussions (Elmendorf *et al.*, 2012).

Socio-culturally, the livelihood system built around transhumance is particularly sensitive to shifts in snowmelt timing, water resource reliability, and forage availability (Dong *et al.*, 2023), and bear the brunt of most disproportionate climate burdens (Sainnemekh *et al.*, 2022). They are further restricted by land-use change and narrowing tenure boundaries (Samuels *et al.*, 2019). Equity challenge is evident. Women in arid zones take primary responsibilities for water procurement, livestock water management, and domestic food production, yet they are left out of formal water and land governance structures (Joshi and Ghimire, 2024). Land degradation increases women's workloads and elevates health risks,

while weak governance reinforces cycles of degradation and inequality (Vicente Serrano *et al.*, 2024). Geographic isolation, constrained market access, and weak public extension services compound socio-economic vulnerability (Gentle and Maraseni, 2012). In practice, land management, water governance, climate adaptation, and biodiversity conservation are governed by separate agencies with limited coordination (Ostrom, 2009), and solutions are often led by sector-driven budgeting and short-term project insights (Sayer *et al.*, 2013) hindering resilience at landscape scale. There is dynamic interaction between environmental limitations and human land-use and settlement decisions, especially in an ecologically and climatically challenged landscapes Zhang *et al.*, 2025 b). The cumulative effect is a socio-ecological trap in which ecological degradation and economic precarity reinforce one another (Boonstra and De Boer, 2014), leading to weakened policy and traditional governance infrastructure. As per UNCCD (2024), nearly 1 billion people lack secure land tenure globally with the highest concentration in cold arid and mountain drylands. Such multidimensional challenges need integrated solution design that NbS offers.

### Nature-based Solution as Unifying Framework

*NbS design logic:* In the cold arid landscapes, NbS design must function as integrative mechanisms linked to resilience of socio-ecological systems (Cohen-Shacham *et al.*, 2019) holistically founded on its ability to simultaneously address biophysical fragility, ecosystem degradation, livelihoods insecurity, water insecurity, disaster risks, governance fragmentation, and gender inequality and social exclusion (Weise *et al.*, 2020). We outline six NbS design logic based on global NbS standards (IUCN, 2020), and reviews on NbS (Debele *et al.*, 2023; Turner *et al.*, 2022; Woroniecki *et al.*, 2023), that collectively create a coherent adaptive management process, and longer-term solution vision. These include:

*Transdisciplinary challenge diagnosis* is an entry point where societal challenge is unpacked. The challenge must be co-defined collectively by all concerned stakeholders - communities, scientists, policymakers and businesses. The process accommodates voices of both marginalised and empowered (Matin

*et al.*, 2018) and builds a shared understanding of both core challenge and root causes. Transdisciplinary challenge diagnosis requires careful facilitation of horizontal learning among stakeholder (Roux *et al.*, 2017), and deliberate building of institutional capacities (Wickenberg, 2024). This is essential in the context of cold arid landscapes where challenges are expression of coupled socio-ecological system degradation, and only a cross sectoral diagnostic process makes solutions more relevant to society.

*Systems thinking* converts the challenge diagnostics into integrated solution package connecting ecological, hydrogeological, biodiversity, governance, infrastructure, livelihoods and economic regimes (Keesstra *et al.*, 2018). Holistic NbS design for cold arid biome may integrate actions around rangelands restoration for multiple benefits, springshed management, wetland-peatland restoration, eco-DRR, and agroecosystems or agroforestry management. Each address ecological conditions and processes rather than substituting them with single purpose engineering interventions (Griscom *et al.*, 2017) cumulatively shaping resilience. The result is multifunctionality and simultaneous delivery of climate, biodiversity, and development outcomes. Zhou *et al.* (2023) identifies these as the defining advantage of NbS over sectoral approaches. Integrated water resource management, natural farming-assisted soil rejuvenation, and use of prescribed fire for ecological management and disturbance-based restoration in dryland rangelands (Lohmann *et al.*, 2014) all elucidate this logic of sustaining interconnected ecological process to build landscape resilience.

*Temporal intervention stacking* structures actions over time to allow time for ecological recovery, sustenance of environmental services, and their flow for generating livelihoods benefits, and allowing their monitoring and maintenance over time (Weise *et al.*, 2020). Ecological reinforcement is the foundational premise of NbS design in cold arid landscape. because even in the low productivity systems, ecological functions are effective: soil microbial process continue to regulate carbon and nutrient dynamics that underpin soil water holding capacity (Xin *et al.*, 2025); snow distributions over sparse native vegetations shapes microclimate conditions, and controls the timing and magnitude of seasonal hydrology (von Oppen *et*

*al.*, 2022); permafrost governs both land surface stability and subsurface drainage determining how water drainage and where it can be stored (Rowland, 2023); and aquatic biodiversity in alpine wetlands regulates the decomposition and nutrient cycling processes that sustain baseflow quality through dry season (Zhang *et al.*, 2025a). However, soil recovery, aquifer recharge, vegetation restoration-all operate on different time scale - months, seasons and years respectively, and must be sequenced as per the ecological functions. Major failure of NbS comes when we try to fit all intervention in one project cycle (Standish and Parkhurst, 2024) or import solutions that do not fit the ecological condition of the cold arid ecosystems.

*Institutional innovation* allows inclusive governance regime and strengthens engagement of local stakeholders and locally led actions (Calliari *et al.*, 2022) while also supporting coordinated engagement of wider range of actors (Maes and Jacobs, 2017). This is most crucial element of NbS design especially for cold arid landscapes inhabited by communities with strong traditional ecological knowledge, customary land and land management institutions (Turner *et al.*, 2022). Gender-nuanced and socially inclusive governance is particularly consequential in cold arid and semi-arid drylands context, because where women are primary custodians, rangeland managers, and water allocators, their exclusion from NbS governance produces technically inferior design regardless of the ecological and technological innovations (Singh and Chudasama, 2021).

*Incentive alignment* is an innovative touch to NbS design. This creates an additional impetus to strengthen NbS through creating rewards for land stewardship. For example, outcome-based payments such as Payment for Ecosystem Services, biodiversity credits, local stewardship rewards create the economic logic for environmental conservation (Dhakal *et al.*, 2021). NbS operate through maintaining ecological processes that inherently generate environmental services linking land and water systems. Rangeland restoration enhances soil organic matter, improving infiltration and reducing erosion (Griscom *et al.*, 2017). Wetland conservation stabilizes seasonal water flows and microclimates (Reed *et al.*, 2020). Agroecological diversification enhances soil moisture retention and reduces vulnerability

to climatic variability (FAO, 2018). These ecological improvements directly support livelihood resilience by stabilizing forage availability, reducing crop failure risk, and diversifying income streams. Technological innovations such as artificial glacier techniques and snow-harvesting systems (Norphel and Tashi, 2015) serve as a strong incentive measure that supplement natural recharge process, and enhances the water security outcomes, without disrupting the ecological flows. Kabisch *et al.* (2017) indicate that hybrid approaches such as combining vegetative stabilization with small-scale water harvesting structures enhance system performance and reduce maintenance costs.

*Adaptive feedback loops* complete the design cycle embedding a robust monitoring and evaluation and learning frame. As indicated by Kabisch *et al.* (2017) effective evaluation and monitoring of NbS not only help assess direct benefits and co-benefits but also shapes future strategies while promoting active learning among stakeholders. Seasonal monitoring of discharge, vegetation cover, and soil moisture - combined with iterative management adjustments - transforms NbS from static interventions into learning systems (Le *et al.*, 2024). Technological innovations such as satellite-based vegetation indices, soil moisture mapping, and glacier monitoring strengthen NbS design, monitoring of outcomes and enhancing adaptive management (Warner *et al.*, 2025). Geospatial analysis informs rotational grazing planning, watershed prioritization, and early warning systems for drought and glacial lake outburst floods.

*Mainstreaming into national policies and developmental framework* is a crucial enabler of sustenance of any NbS. It is a mechanism through which NbS receives legitimacy and financial sustainability. Government mainstreaming - integrating NbS into national adaptation plans, sectoral budgets, and policy frameworks - provides the institutional continuity that sustains these feedback loops beyond any single programme cycle (Cohen-Shacham *et al.*, 2019).

## Regional Evidence

In the following section, we present six cases that demonstrates the principles of NbS in a cold arid setting. Our attempt here is

not to elaborately review cases but to bring representative cases from different geographies and biomes and demonstrate why design principle of NbS presented above are not theoretical constructs but are tried and tested actions. We also indicate shortfall when key elements are missed in each case. Each case is described as what type of NbS intervention they are, what ecological mechanisms they support, what socio-economic outcomes were generated, what kind of governance model were applied and what could be scaling constraints. The cases represent distinct cold arid biome types and incorporate at least a few NbS design elements described above and clarify socio-economic outcomes and insights on scalability.

### **Case 1: Himalayan Springshed Management (India, Nepal)**

Springs are the primary drinking water source for an estimated 200 m people across the Indian Himalayan Region, yet perennial springs are drying at accelerating rates due to land-use change, reduced snowpack, and disrupted recharge (Pant *et al.*, 2024). Spatially, the springshed management as NbS treats the entire aquifer-landscape (ridge-valley-ridge) that feeds a spring as the management unit and does not merely consider springs discharge point (Tambe *et al.*, 2012). Embedding process of hydrogeological mapping delineates recharge zones- a targeted space for revegetation or making contour trenches, and percolation pits. Parallely, monitoring mechanisms for monitoring seasonal discharge then track spring recovery. The ecological mechanism is aquifer recharge augmentation reinforced by revegetation of degraded recharge areas (Condori *et al.*, 2025). Over time, soil hydraulic conductivity is improved which then reduces surface runoff, increasing infiltration to the fractured rock aquifers that feed mountain springs (Jia *et al.*, 2024). The springshed management intervention within the Dhara Vikas programme in Sikkim improved water access for 75% of participating households (Tambe *et al.*, 2012). The governance model is GESI responsive and integrates trained para-hydrogeologists with community springshed committees, with women's traditional custodian knowledge formally incorporated into recharge zone identification. India's Ministry of Jal Shakti has now mainstreamed this approach within watershed guidelines marking a transition

from project-based to policy-embedded delivery (Department of Land Resources, 2021). The principal scaling constraint is that springshed delineation requires site-specific hydrogeological mapping to identify appropriate recharge area, and recharge geology varies sharply even within small areas (Meles *et al.*, 2024). Presents a good example of system thinking adopting landscape approach, intervention temporal stacking incorporates sequential spring mapping, hydrogeological assessment, and implementation of ground recharge measure. Mainstreaming pathway is strong from pilots to policy integration.

### **Case 2: Tibetan Plateau Alpine Grassland and Wetland Management (China)**

The Tibetan Plateau, the world's largest and highest cold arid biome which comprises of extensive grasslands- the degradation of which was driven by both natural and anthropogenic factors, primarily overgrazing, rodent infestation, and warming-induced permafrost thaw (Niu *et al.*, 2024). The grassland degradation is said to reduce carbon storage, destabilise soils, and disrupt the hydrological function of alpine meadows and wetlands (Harris, 2010). The NbS intervention operates through two pathways: grassland restoration rebuilding soil moisture and root biomass, improving infiltration and reducing surface runoff (Huang *et al.*, 2025); and micro-watershed restoration and alpine wetlands protection maintaining peat water storage capacity that regulates baseflow through dry seasons (Jin *et al.*, 2022), while also insulating permafrost from accelerated thawing (Jia *et al.*, 2023). The ecological mechanism included reduction of inter-seasonal flow variability and increase of downstream irrigation reliability (Zhang *et al.*, 2025a). The socioeconomic outcome was linked to sustained pastoral forage and livestock productivity, which directly addressed the primary livelihood vulnerability of Tibetan herder communities (Dong *et al.*, 2023). The governance model combined state-managed conservation zones with community-based herder co-management under China's grassland contract system (Hou *et al.*, 2023), supported by monitoring stations measuring change in the ecosystems (Dong, 2023). The scaling constraint relates to species-selection rigour, and investment for large-scale assessment and adaptive monitoring (Dong *et al.*, 2023).

Although may be limiting in transdisciplinary challenge diagnosis, the case has strong science argument on ecological challenges. System thinking and temporal intervention stacking is justified with combination of ecological, water and local livelihoods actions. The case is strong in terms of policy mainstreaming – being implemented under the large-scale national programme. In terms of adaptive monitoring, this is also the case of caution on the precision design for NbS, especially on the selection and use of non-native or drought-intolerant species for large-scale revegetation in the arid landscapes (Niu *et al.*, 2024).

### **Case 3: Andean Altiplano Bofedales and Qocha Systems (Peru, Bolivia, Chile)**

High-altitude peatlands of the Andean Altiplano, locally known as bofedales lie at elevations of 3,200-5,000 m and have strong hydrological function that no engineered structure can equivalently achieve at catchment scale. The water from bofedales is released as subsurface drainage through the dry season for sustaining the Andean pastoral system. The complementary qocha system of high-altitude puna grassland, a network of shallow excavated impoundments further increases local groundwater recharge (Ochoa-Tocachi *et al.*, 2019). The ecological mechanism is peat water storage and slow subsurface release, sustained by cushion-plant communities of rangelands such as *Oxychloe* and *Distichia* that depend on active pastoral management.

Yager *et al.* (2021) indicate that bofedales are socio-hydrological systems actively co-produced by generations of Aymara pastoralists through traditional irrigation channel management, rotational grazing, and periodic burning; and conservation approaches that exclude pastoralists from management will consistently degrade the very ecosystems they aimed to protect. Socio-economic outcomes include sustained alpaca forage year-round, stabilised downstream agricultural water supply, and maintenance of the cultural-spiritual landscapes central to Aymara identity. The governance model is communal land tenure with traditional pastoral stewardship formally recognised as active environmental co-management. The scaling constraint is significant vulnerability to upstream water extraction for mining, a structural conflict

between extractive industry water rights and the hydrological integrity bofedales require that no community-level NbS intervention can resolve without supportive national water rights reform. This is a strong case in terms of institutional innovation and acknowledgement of traditional ecological knowledge of local communities. System thinking and intervention stacking seems appropriate with multidimensional interventions. Adoption of transdisciplinary challenge diagnosis could have minimised tension with mining industry, and mainstreaming for longer term sustenance and financing will remain key in future.

### **Case 4: Arctic and Sub-Arctic Peatland and Tundra Management (Canada, Siberia, Scandinavia)**

Arctic and sub-arctic peatlands with approximately 415 Gt of carbon storage are extremely climate-vulnerable biomes (Hugelius *et al.*, 2020). Thawing permafrost releases this stored carbon creating a positive feedback loop to drive further warming as when peat decomposes more CO<sub>2</sub> and methane is released. The NbS intervention is primarily preventive aimed at maintaining the insulating layer of moss and peat to reduce thawing. This is combined with active drainage management to prevent thermokarst pond formation and rewet drained and degraded peatlands. The ecological mechanism is thermal insulation and hydrological stabilisation by intact *Sphagnum* moss layers which reduce soil surface temperatures by 4-7°C compared to bare ground, directly slowing permafrost thaw rates (O'Donnell *et al.*, 2012). Rewetted peatlands in subarctic Scandinavia have demonstrated 3-5 tonnes CO<sub>2</sub> emission reductions per hectare annually within five years of rewetting (Wilson *et al.*, 2016). Stabilised hydrology and freshwater underpin Arctic Indigenous food systems and the tundra vegetation upon which caribou and reindeer herding depend (Oskal *et al.*, 2024). The governance model is most comprehensive with indigenous co-management regimes in subarctic Canada and Siberia maintaining integrity over multi-generational timescales (Vogel and Bullock, 2021). The scaling constraint is precise drainage engineering needed for peatland rewetting to avoid creating methane-emitting anaerobic conditions, as explained by (Günther *et al.*, 2020). The case elucidates a very strong case of

institutional innovation with strong indigenous co-governance principle, probably the result of adequate transdisciplinary problem diagnostic that also linked to indigenous people lives and livelihoods and food systems. There are ample revenue generation streams, particularly with carbon sequestration that can be explored to further strengthen Indigenous people-led management of permafrost and high-altitude peatlands.

#### **Case 5: Central Asian Steppes Rangeland Restoration and Adaptive Grazing (Kazakhstan, Mongolia)**

Central Asian drylands cover approximately 5 million km<sup>2</sup> support pastoral livelihoods for over 50 million people. They experience severe degradation and collapse of traditional grazing management systems (Kerven *et al.*, 2016). The NbS interventions have combined community-managed rotational grazing, degraded rangeland enclosure and native grass reseeding, and the restoration of traditional water points that distribute grazing pressure across the landscape rather than concentrating it around permanent settlements (Mirzabaev *et al.*, 2016). The ecological mechanism operates through soil health recovery increasing soil total organic carbon, soil moisture, microbial biomass, water infiltration rates, and biological soil crust re-establishment (Mekuria *et al.*, 2018). The role of biological soil crusts – a community of cyanobacteria, mosses, and lichens to stabilise soil surfaces and increase water filtration is well researched (Eldridge *et al.*, 2020). Griscom *et al.* (2017) quantifies global carbon contribution through improved grazing management making rangeland management the most cost-effective natural climate solutions available. The socioeconomic outcome is restored forage productivity and reduced inter-annual livelihood variability, with documented income improvements in communities (Addison and Brown, 2014) that have successfully re-established mobile grazing systems. The governance model point to the re-establishment of community grazing agreements and customary tenurial systems. The sustained investment in pastoral governance reconstruction alongside the ecological restoration is the key scaling constraints. This is a strong case of adaptive learning with improvement in transdisciplinary problem diagnostic leading to institutional

innovation, and how NbS case can be made more GESI responsive.

#### **Case 6: Ladakh and Karakoram Cryosphere-Linked Hybrid NbS**

In the cold deserts of the western Himalayas, glacial retreat and compressed snowmelt timing have created a spring water gap which is the period between snowmelt exhaustion and monsoon onset (Immerzeel *et al.*, 2020). The NbS intervention is a hybrid of traditional cryospheric innovation and simple gravity-fed engineering such as artificial ice reservoirs created by diverting winter stream flow through check-dam cascades between 3,350 and 4,267 m: vertical ice stupas up to 33 metres tall that melt gradually through the spring planting window. The ecological mechanism is temporal water redistribution: converting autumn unused runoff into spring irrigation supply for crops during precise sowing season. This mimics the buffering function of natural glaciers that are retreating, substituting engineered ice storage for lost natural storage within the same cryospheric logic. Upstream revegetation combined with ice reservoir construction constitutes a genuinely integrated NbS: vegetation restoration rebuilds infiltration for groundwater-dependent summer flows while ice structures address the spring gap that revegetation alone cannot close. The socioeconomic outcome is documented at two to four times baseline agricultural income for households whose irrigation season is successfully extended (Shaheen *et al.*, 2013), with community revitalisation in settlements that had been abandoned due to water scarcity. By 2024, approximately 30 ice stupas had been constructed across Ladakh, with the technology diffusing to Gilgit-Baltistan and the Chilean Andes. The scaling constraint, as identified by Nüsser *et al.* (2019) is structural: ice reservoir effectiveness depends on stable sub-zero winter temperatures that are themselves threatened by the increased elevation dependent warming at higher elevation. These structures buy time but do not replace the catchment-scale NbS - revegetation, springshed management, wetland protection - that constitutes the durable solution and must be parallelly supported. Again, a very strong case elucidating the importance of institutional innovation and use of local knowledge for NbS design. System thinking and mainstreaming into national and state level programme will enrich such complementarity

between NbS and artificial or nature-mimicking infrastructure.

### Gaps and Barriers of NbS Implementation

Understanding what prevents effective NbS design is as important on how it is effectively designed. First, NbS is hindered when there is limited understanding of ecological functions and processes. Cold arid ecosystems provide important regulating and cultural services such as groundwater recharge, erosion control, and carbon sequestration, pastoral culture and heritage – that are either unvalued or undervalued in national accounting systems (United Nations, 2024). This undervaluation limits public investment and private sector engagement.

Second, short financing cycles, policy silos, and fragmented jurisdiction are the most critical barriers. Investments come as project grants for small-scale pilots and do not invest in creating overall design infrastructure (Seddon *et al.*, 2021). NbS projects that cannot demonstrate monetisable return on investment within standard infrastructure planning horizons (3-5 years) are structurally considered “low-return” investment area, so not appealing to commercial investors. Besides, ecological restoration requires long-term investment horizons (Chazdon *et al.*, 2016), yet financing mechanisms often operate within short cycles. In the cold arid landscapes, ecological recovery requires 10-30 years’ timescale for meaningful outcomes. Project finance cycles of 3-5 years are fundamentally inadequate with these recovery dynamics. This is where the temporal intervention stacking design of NbS becomes important. For example, spring recharge require two to three monsoon seasons before discharge improvements become measurable; community vegetation programmes on degraded slopes require probably five to ten years before soil stabilisation effects become hydrologically significant. Investments and incentive mechanisms for NbS must be therefore innovated through blended financing mechanisms with government programme de-risking private capital flow.

Cold arid NbS inherently spans sectoral jurisdictions: water, forestry, agriculture, and climate adaptation ministries each have partial authority over the interventions and landscapes NbS requires. The institutional fragmentation creates coordination challenge at every stage,

from transdisciplinary challenge diagnostic to monitoring to adaptive management. National adaptation strategies, agricultural policies, and biodiversity frameworks frequently lack coordination (IPBES, 2019).

NbS effectiveness evidence from cold arid contexts remains low. Long-term, interdisciplinary monitoring linking ecological and socio-economic indicators is limited constraining evidence-based scaling (Wunder, 2015). Without robust monitoring, reporting and verifying mechanisms, NbS advocacy is structurally disadvantaged in budget negotiations against engineered alternatives with established performance records. Technological solutions are randomly designed and not used to catalyse the effectiveness of NbS or to amplify the ecological functions.

### Structured Recommendations

NbS effectiveness depends heavily on local institutions, customary governance systems, and indigenous knowledge. In cold arid landscapes, communities have long managed commons such as rangelands and water sources through adaptive practices. We argue that unless we recognize local stewardship, gender equality and social inclusion across all elements of NbS design, NbS in cold arid landscape will be short-lived and will not promote ecological and socio-economic resilience. Landscape governance that enables co-designing, co-sensing and incentives for long-term custodianship will be central to sustained resilience. We provide some recommendation that will enable stakeholders adequately apply NbS design elements:

- Reinforce integrated Land-water-livelihood actions as a part of systemic planning considering ecological interdependence among different ecosystems - rangelands, springsheds, watersheds, wetlands, cryosphere, peatlands, and agroecosystems including downstream river basins- if spatially applicable. Together, ecological processes and functions will reinforce each other, creating positive feedback loops that strengthen overall landscape resilience.
- Embed NbS ecosystem service valuation in national adaptation planning frameworks - a replicable methodology for identifying and monetising NbS benefits. Explore this during the systems thinking stage and link

with other elements around intervention and incentive design, embedding adequately with innovation around institutions and adaptive monitoring.

- Establish inter-ministerial NbS coordination units with a mandate to integrate cold arid NbS into national adaptation plans (NAPs), land-use policies, and rural development programmes. At national level, India's experience integrating springshed management across the Ministry of Jal Shakti and Department of Land Resources - including the formation of a national Springshed Steering Committee in 2022 - demonstrates that inter-ministerial coordination is achievable with clear mandates and dedicated technical secretariat support. The shared understanding can be facilitated early at the transdisciplinary challenge diagnostic stage.
- Develop a 15-20-year blended finance instruments with ecological performance milestones. Blended finance structures - combining concessional public finance with results-based payments from private water users - can extend effective project horizons. Payment for Ecosystem Services (PES) mechanisms are underexplored in cold arid contexts. The gender and NbS analysis identifies PES as a particularly promising mechanism for rural women's agency if rights and benefit-sharing are structured appropriately from design (Salcedo-La Viña *et al.*, 2023). This will also help embed NbS into the national policy and programmatic framework and into nationally determined contributions.
- Cold arid landscapes often span national borders. Contribute to collaborative platforms for knowledge exchange and joint action that can accelerate learning and harmonization. Integrate remote sensing early-warning tools for dryland tipping as in Dakos *et al.* (2024) into national monitoring frameworks to provide early-warning capacity for landscapes approaching critical thresholds. This creates the feedback loop between monitoring and adaptive management that all effective cold arid NbS requires.

## Conclusions

Cold arid landscapes as marginal lands provide critical ecosystem services and sustain

culturally rich communities. The coupled land-water-livelihoods systems demands integrated resilience strategies, making NbS design the appropriate framework. NbS as unifying framework simultaneously addresses ecological degradation, climate vulnerability, and socio-economic fragility and draw upon multifaceted value of ecosystem services. In cold arid landscapes, NbS elucidate its holistic design thinking building coherence among ecological processes, social institutions, economic engagements, and adaptive management, if sustained over time, produces resilience outcomes that no siloed sectoral solution can achieve. Some questions if answered may further NbS design making them scientifically rigorous, such as: i) what does a rigorous and integrative NbS evaluation framework look like for cold arid biomes that captures NbS effectiveness and climate robustness?; ii) how do we make low-cost community-led monitoring mechanisms more robust and meaningful so that they become part of revenue generation process?; iii) what are the minimal institutional and governance infrastructure needed to effectively design and embed incentive measures into NbS?; iv) what governance architectures - beyond a mere representation of women, youth and marginalised communities, may enable integration of their knowledge into systemic planning, monitoring, and adaptive management of NbS, and how would NbS become GESI responsive?; and v) how can technological information such as use of Earth Observation, GIS/RS add value to NbS planning and temporal intervention stacking?

Such questions are essential to reinstate NbS design thinking in cold arid landscapes where challenges are interrelated, risks cascading, and communities carry the cost of stewardship alone. The NbS design therefor demands careful conversation with local stakeholders on land-use, climate and development policies, mainly to innovate monitoring, reporting and verification (MRV) systems and incentive mechanisms for their land stewardship. For the cold arid landscape, NbS should combine biome specific ecosystem restoration, cryosphere-linked water management, and socio-ecologically relevant livelihoods interventions. The outcomes must be constantly monitoring and verified by a robust MRV. Such NbS design infrastructure can unlock additional finances around carbon,

biodiversity and outcome-based payments, which can be ploughed back to community stewards, optimising the resilience outcomes. When supported by enabling governance, and institutional innovations, NbS with their inclusive, socially grounded, ecologically sound and cost-effective design can transform cold arid landscapes from fragile systems under stress into adaptive and resilient socio-ecological systems.

### Competing Interests

The authors declare no competing interests.

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