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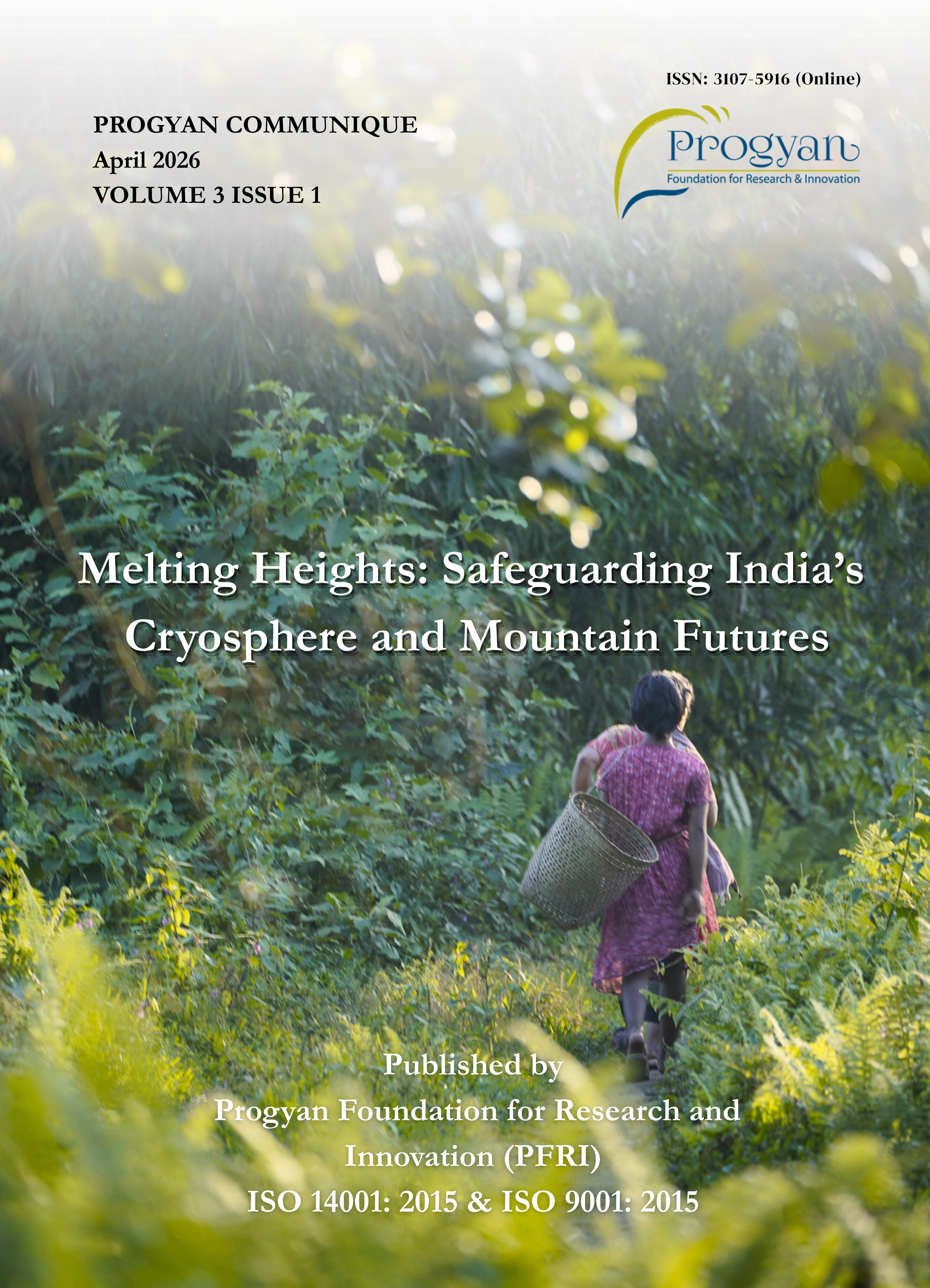

Melting Heights: Safeguarding India's Cryosphere and Mountain Futures

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CURRENT CONTEXT

THE CASE OF KODAIKANL

ELEVATE

ECOLOGICAL LIMITS, EVIDENCE-BASED VERNACULAR ADMINISTRATION, AND TERRITORIAL EQUITY IN MOUNTAIN GOVERNANCE

Mr. Rajib Das, Research Assistant (PFRI)

ABSTRACT

Fragile mountain ecosystems like Kodaikanal in India's Western Ghats face converging threats from geomorphic sensitivity, climate volatility, and human activities. This paper examines socio-ecological vulnerabilities, using the mercury contamination crisis and tourism overload as case studies. Drawing on biophysical analyses, carrying capacity assessments, and governance critiques, we advocate for decentralized, ecologically literate interventions integrating vernacular knowledge. Findings underscore the need for institutional reforms to enforce evidence-based limits, fostering resilience in coupled human-environment systems.

Keywords: mountain governance, carrying capacity, socio-ecological vulnerability, Kodaikanal, Western Ghats, vernacular knowledge

INTRODUCTION

Mountain ecosystems represent intricately coupled socio-ecological systems where geomorphic sensitivity, climatic volatility, and anthropogenic pressures amplify vulnerability (Jha et al., 2021). Kodaikanal, located in the Palani Hills of the southern Western Ghats at over 2,000 m above mean sea level, exemplifies this dynamic. Its montane shola-grassland complexes, orographic rainfall, and role as a headwater for peninsular rivers are increasingly strained by land-use changes and governance gaps.

Strengthening local governance demands epistemically robust, decentralized, and ecologically informed strategies.

This paper analyzes Kodaikanal's biophysical traits, environmental conflicts, and reform pathways, emphasizing evidence-based limits and vernacular integration.

Biophysical Characteristics and Anthropogenic Pressures

Kodaikanal's landscape features steep gradients, immature soils, and fragmented forests, which heighten the risks of erosion, landslides, and hydrological disruptions. Plantation monocultures, urban sprawl, and tourism infrastructure have altered hydrology, reduced soil moisture, and increased sediment loads. These changes, combined with extreme weather, push the ecosystem toward irreversible thresholds. Land-use transformations exacerbate hydro-geomorphic instability, underscoring the need for governance that internalizes ecological externalities.

Case Studies in Environmental Conflict

Mercury Contamination from Industrial Activity

The Hindustan Unilever thermometer factory released mercury, contaminating soils and biota with elevated concentrations and bioaccumulation risks (Karunasagar et al., 2006). This incident revealed regulatory failures, surveillance deficits, and accountability gaps—critical flaws in mountains with slow recovery rates and low assimilative capacity.

Tourism-Induced Overload and Carrying Capacity Assessment

Tourism exceeds infrastructure, waste, water, and slope stability limits. A consortium including IIT Madras, IIM Bangalore, and civil society (Progyan Foundation for Research & Innovation, 2023) conducted a multi-criteria study using geospatial analytics, traffic simulation, water modeling, and load indices. These efforts highlight systems science over ad-hoc administration.

Methods for Evidence-Based Governance

Assessments employed integrated frameworks:

- **Geospatial and hydrological modeling:** ArcGIS for land-use change detection; SWAT for water balance.
- **Carrying capacity metrics:** Physical (traffic flow), ecological (waste assimilation), social (crowd tolerance), and infrastructural indices.
- **Qualitative integration:** Vernacular knowledge from local communities via participatory mapping.

Data sources included satellite imagery (2010–2025), field sampling, and stakeholder surveys (n=500+).

Discussion: Institutional Reforms and Vernacular Integration

Technocratic insights require local empowerment. Panchayati Raj Institutions need juridical powers, fiscal resources, and technical training to enforce zoning, construction rules, and tourism protocols. Integrating generational ecological knowledge enhances monitoring and adaptation (Progyan Foundation for Research Innovation, 2023). Governance must address non-linear dynamics and feedback loops for resilience.


Image: Rajiv Das, (PFRI)

Conclusion

Kodaikanal's sustainability depends on confluent reforms: scientific inquiry, decentralized stewardship, and environmental justice. Implementing carrying capacity limits and vernacular epistemologies can mitigate conflicts and preserve ecological integrity.

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Image: Rajiv Das, (PFRI)

SCIENCE OF SUSTAINABILITY

Adaptation and Maladaptation in High-Altitude Agriculture:

Navigating Water Scarcity and Crop Shifts in the Indian Himalaya

Dr. Aritra Mukherjee, Research Assistant (PFRI)

Abstract

As the Indian Himalayan cryosphere recedes, high-altitude agricultural systems face a dual crisis of shifting climatic envelopes and profound hydrological change. This article examines adaptation pathways through the lens of water availability and crop suitability. It analyzes the phenomenon of "Peak Water," the utility of engineered interventions like ice stupas, and the concurrent shifts from traditional agro-biodiverse systems to water-intensive cash crops. The central argument posits that sustainable adaptation requires a synergistic approach: leveraging localized water-harvesting innovations while privileging climate-resilient, traditionally adapted crops, thereby avoiding maladaptive trajectories that trade short-term economic gain for long-term ecological and hydrological security.

Introduction

The Indian Himalaya sustains unique agricultural systems that have evolved over centuries to navigate the region's steep terrain, fragile ecology, and harsh climatic conditions. These systems, deeply intertwined with traditional ecological knowledge (TEK), traditionally prioritised agrobiodiversity, soil conservation, and climate resilience to ensure subsistence security and ecological balance (Gururani et al., 2021; Saxena et al., 2005; Negi et al., 2025). Today, they face unprecedented pressures from two interconnected dimensions of climate change: profound shifts in temperature and precipitation regimes (Rana et al., 2011; Sahu et al., 2020), and a fundamental transformation in the hydrological cycle driven by the recession of the cryosphere, the region's snowpacks and glaciers (Nie et al., 2021; Nüsser et al., 2019). This convergence of climatic and hydrological stressors is forcing communities to adapt their farming practices, water management, and crop choices, often within a context of evolving market incentives and policy frameworks.

The Upward March: The 'Apple Line' as a Climate Indicator

The most visible agricultural fingerprint of this warming is the altitudinal migration of commercial crops, epitomized by the shifting 'apple line' in Himachal Pradesh. Once concentrated between 1200-1500 m, optimal apple cultivation has moved decisively upwards, now established between 2500-3500 m in regions like Kinnaur, Lahaul, and Spiti (Sahu et al., 2020; Khan et al., 2023).

This migration is a direct agro-climatic response to declining winter chill, a critical prerequisite for apple dormancy and flowering. Warming temperatures and reduced snowfall at lower elevations have rendered them unsuitable, while previously marginal high-altitude zones now meet the necessary chill-unit thresholds (Rana et al., 2011; Singh & Patel, 2017). This upward march is not merely an anecdotal shift; it is a quantifiable signal of a fundamental restructuring of mountain agro-ecology, forcing the relocation of a major economic activity and displacing traditional land-use patterns.

The 'Peak Water' Paradox and Irrigation Reliability

The hydrological foundation of high-altitude agriculture is undergoing a more insidious, yet ultimately more consequential, transformation. Himalayan glaciers act as natural reservoirs, releasing meltwater during the critical pre-monsoon dry season. For the Upper Indus basin, this melt contributes up to 60% of irrigation withdrawals during this period, supporting millions of farmers (Biemans et al., 2019).

Climate change is driving a non-linear response: initial warming accelerates melt, leading to a transient increase in water availability-a phase termed "Peak Water" (Nie et al., 2021). This temporary surplus is often misinterpreted as abundance. However, as glacier mass depletes, a subsequent phase of severe and permanent decline in dry-season flows is inevitable. Modeling for the Indus and similar basins projects this decline occurring in the latter half of this century, fundamentally threatening the viability of irrigated agriculture (Calvo-Gallardo et al., 2025; Abdullah et al., 2025).

Communities dependent on cryosphere-fed kuhl systems are already experiencing this volatility, facing recurrent water scarcity that forces the abandonment of fields and shifts in cropping patterns (Nüsser et al., 2019; Rashid et al., 2020). The paradox is clear: the current glut of meltwater is a fleeting resource, masking a future of acute scarcity.

Image: Communication Department (PTRI)

Synergizing Engineering with Agronomic Wisdom

Adaptation strategies must address both the timing of water availability and the crop portfolio's resilience. On the water front, ice stupas or artificial glaciers represent an innovative fusion of local knowledge and simple engineering. These structures store winter streamflow as ice, which melts in spring, providing water 4–8 weeks earlier than natural glacial melt, thus bridging the critical irrigation gap (Nüsser et al., 2018; Kumar & Saizen, 2023). Successful implementations in Ladakh have demonstrated their ability to enable earlier sowing and support crop diversification *(Dar et al., 2017)*. However, their storage capacity is modest (typically 1,000–3,200 m^3), and their efficiency variable, meaning they are a supportive adaptation, not a standalone solution (Balasubramanian et al., 2022).

The true test of adaptation lies in what is cultivated with this carefully harvested water. Here, Traditional Ecological Knowledge (TEK) offers a vital repository of agronomic wisdom. TEK-based systems, such as *barahnaja* (twelve-seed mixed cropping) in the Central Himalaya or the cultivation of hardy traditional crops like barley, black pea, buckwheat, and millets, are inherently adapted to marginal conditions because they require minimal external inputs and conserve soil and water (Gururani et al., 2021; Jaggi et al., 2025; Saxena et al., 2005). These crops possess deep-rooted genetic resilience to climatic stressors and form the core of biodiverse, nutritionally secure farming systems (Tula & Karlsson, 2024). The logical adaptation pathway is thus a synergy: using engineered solutions like ice stupas to secure early-season water, and allocating this precious resource to proven, resilient traditional crops rather than to water-intensive substitutes.

The Maladaptive Rush for Cash Crops

In stark contrast to this synergistic model, a dominant on-ground response has been a shift towards high-value *cash crops* like apples, green peas, and potatoes. In Lahaul and Spiti, for instance, traditional barley and black pea are being rapidly replaced by green pea, driven by market access and perceived profitability (Sharma & Chauhan, 2013; Jaggi et al., 2025). While this shift may constitute an "economic adaptation," it risks becoming a profound case of *maladaptation*. These cash crops are often more water-demanding, require chemical fertilizers and pesticides, and promote monocultures that erode agrobiodiversity and increase vulnerability to pests and market shocks (Negi et al., 2018; Behera et al., 2015).

In the context of the impending "post-peak water" decline, cultivating water-guzzling crops in a cold, arid landscape is ecologically unsustainable. It represents a short-term livelihood strategy that mortgages long-term hydrological security, effectively trading a temporary water surplus for permanent ecological degradation. This approach fails the intergenerational equity test central to just adaptation.

Image: Communication Department (PERI)

Towards Just and Ecologically-Sound Mountain Futures

Climate adaptation in high-altitude agriculture must be re-framed as an exercise in ecological justice for the mountains, their hydrological systems, and the communities that depend on them. This requires a paradigm that prioritizes water security and ecological resilience over maximized, short-term cash returns. Policy and practice must actively promote:

- **Water-Smart Infrastructure:** Supporting and optimizing community-led interventions like ice stupas within integrated water management plans.
- **Crop Sovereignty:** Incentivizing the conservation and commercial integration of climate-resilient traditional crops through market linkages, value addition, and agricultural policy.
- **Regulating Maladaptation:** Discouraging, through economic and extension instruments, the unchecked expansion of water-intensive monocultures in critically vulnerable, arid high-altitude zones.

The melting heights are a stark warning. A just transition for Himalayan agriculture lies not in replicating the water-intensive models of the plains, but in prudently harnessing fleeting water resources to strengthen the time-tested, biodiverse, and resilient farming systems that have long been the bedrock of mountain life. True adaptation means aligning our agricultural ambitions with the enduring, yet now precarious, limits of the cryosphere.

Image: Communication Department (PFRI)

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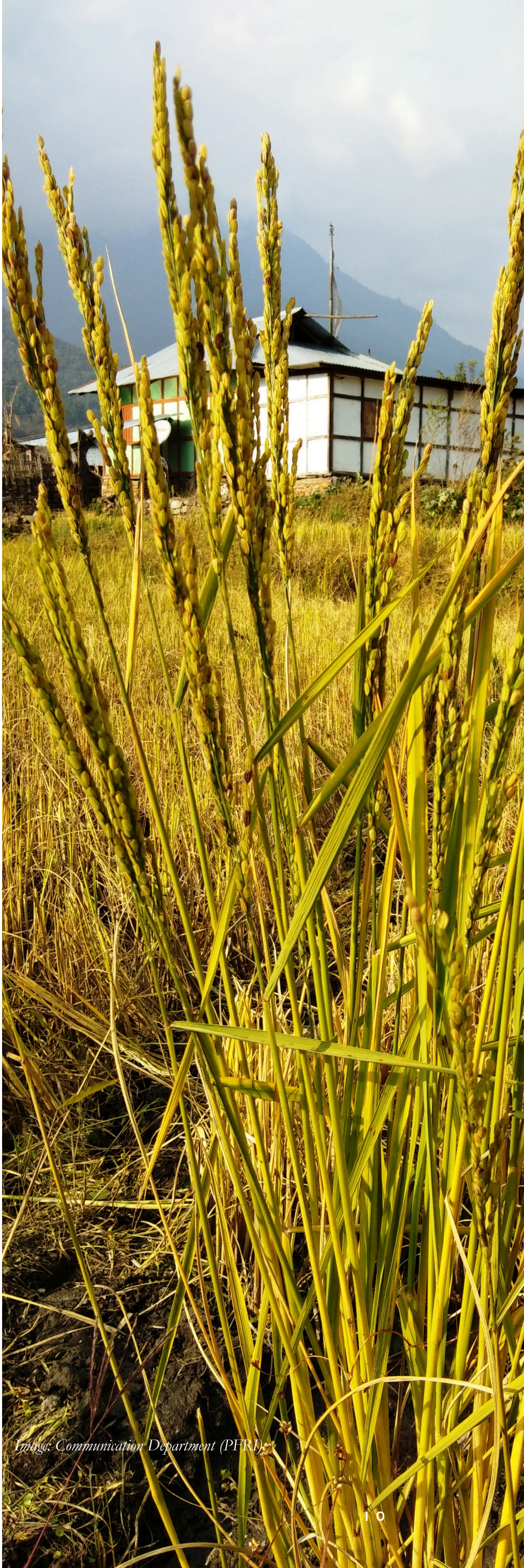

Image: Communication Department (PFRI).

Image: Communication Department (PFRI)

Empowering Tomorrow:

YOUTH-LED ECO-TOURISM AS CATALYST FOR LIVELIHOOD RESILIENCE

Dr. Bhaskar Deb Bhattacharya, Senior Research Officer (PFRI)

The intersection of youth engagement, eco-tourism, and livelihood diversification constitutes a critical nexus in sustainable development science, where socio-ecological systems theory underscores the adaptive capacity of communities to integrate human capital with natural capital for resilience. Amid accelerating anthropogenic pressures such as global biodiversity loss at 1,000 times the background extinction rate and climate-induced disruptions projected to displace 143 million people by 2050, youth-led initiatives leverage demographic dividends to operationalize regenerative tourism models.

This article systematically dissects youth-led eco-tourism's mechanisms for livelihood diversification, quantifying its contributions to ecosystem services valuation, economic multipliers, and social equity indices, with empirical transitions from global archetypes to India's context-specific applications.

Conceptual Foundations

Eco-tourism, rigorously defined by The International Ecotourism Society as 'responsible travel to natural areas that conserves the environment, sustains the well-being of local people, and creates knowledge and understanding through interpretation and education,' operationalizes principles of carrying capacity (e.g., Limits of Acceptable Change framework) and leakages minimization (<20% external profit outflow). Youth leadership - encompassing ages 15-35 per UNESCO metrics (Lelwic-Ojeda & Akintola, 2023) - infuses these with digital-native innovations like AI-driven visitor analytics and blockchain traceability for carbon-neutral operations, enhancing authenticity via participatory action research (PAR) methodologies.

Livelihood diversification aligns with the Sustainable Livelihoods Framework (Scoones, 1998), expanding the asset pentagon- human, social, natural, physical, financial- to buffer shocks. Econometric models show that diversified portfolios reduce income volatility by 30-50% in climate-vulnerable zones (Sithole & Eita, 2025). Youth involvement catalyzes this via skill multipliers such as training in biodiversity monitoring (e.g., iNaturalist protocols) that yields 2-3 times employment gains over monoculture.

Global Empirical Evidence

Globally, youth-led models demonstrate scalable impacts. In Bhutan's Zhemgang, youth-managed ecolodges boosted household incomes by 25% while restoring 500+ ha of degraded land, per net primary productivity metrics (Beal 2025; Narayan et al., 2023). South Africa's Addo initiatives cut poaching by 40% through youth ranger programs, with Gini coefficients improving from 0.65 to 0.55 via tourism revenues (Minnaar & Herbig, 2018). Costa Rica's 25% GDP from eco-tourism (Schultis, 2018) exemplifies policy integration (Payment for Ecosystem Services), where youth enterprises achieve 15% annual returns (Leek, 2023) while sequestering 1.5 MtCO2e yearly.

These cases reveal common metrics: 60-70% local retention rates, biodiversity intactness indices >0.8, and youth unemployment drops of 20% *(Kudrzycki, 2024).*


Image: Communication Department (PURI)

India-Specific Adaptation

India's 600 million youth (UNFPA) and 8% of global biodiversity hotspots position it for analogous scaling (Speidel, 2019), yet face context-specific barriers like 68% rural underemployment. The National Strategy for Sustainable Tourism (2022) endorses youth cooperatives, mirroring global successes (Pathak 2025). For instance, the DAMAMI Siddi homestays in Karnataka (Bettada, 2025) enhanced the resilience of 105 households (HDI uplift 0.15 points) via women-youth treks preserving 2,000 ha mangroves. Also, Meghalaya's Mawlynnong leverages youth for Living Root Bridge tours, diversifying from jhum cultivation with 30% income rise and soil erosion halved.

In the Western Ghats of Maharashtra and the Sundarban of West Bengal, agroforestry-ecotourism hybrids could valorize NTFP markets (₹10,000 crore potential), aligning with SDGs 8, 13, 15 through youth GIS-mapped trails and carbon credit schemes.

India's Perspective: Prospects for Youth-led Eco-tourism and Livelihood Diversification

India's prospective integration of youth-led eco-tourism into livelihood diversification frameworks leverages its socio-ecological assets, quantified by a youth cohort (15-35 years) comprising 34% of 1.4 billion population and harboring 7-8% of global biodiversity across 4.2 million km^2 of varied biomes. Empirical models from the Sustainable Livelihoods Approach (SLA) project a 25-40% reduction in income vulnerability indices (Knutsson & Ostwald, 2023) when tourism multipliers (1.5-2.0) supplant monocrop dependencies, aligning with IPCC AR6 pathways for adaptive resilience in climate-vulnerable agroecosystems.

Demographic and Entrepreneurial Dynamics

India's demographic bulge - peaking at 10 million annual labor market entrants - fuels entrepreneurial ecosystems *(George, 2024)*, with NASSCOM data indicating 1,200+ green startups by 2025, 15% tourism-linked. Youth ventures exhibit 2.5 times higher innovation rates in digital-native models (e.g., app-based trail mapping), according to NITI Aayog's SDG India Index, yielding self-employment elasticities of 0.3-0.5 in rural cohorts and curtailing NEET rates (17.8%) through venture capital inflows (₹50,000 crore green fund potential).

Demand and Policy Catalysts

Domestic tourism (1.8 billion trips, 2025 projection) and inbound growth (15 million arrivals) favor regenerative niches, with 68% Gen Z tourists prioritizing ESG metrics (WTTC). National Tourism Policy 2022 and Swadesh Darshan 2.0 allocate ₹7,500 crore for eco-circuits, integrating Skill India (PMKA) modules yielding 30% hospitality upskilling; microfinance via SVEP (₹2,000 crore) targets 1 million SHG-youth enterprises, amplifying local retention to 65-75%.

Biodiversity-Driven Opportunities

As a 'megadiverse' nation (ranked 8th globally), India's ecosystems support niche eco-tourism with ecosystem service values (ESV) exceeding $1 trillion annually (Majumder et al., 2021). Himalayan circuits (e.g., snow leopard habitats) sustain 1.2 million ha protected areas for high-value trekking (₹20,000/tourist); Western Ghats/Northeast hotspots (36/220 global biodiversity areas) enable avian endemism tours (1,300+ species); coastal mangroves (4,975 km^2) facilitate blue carbon ventures sequestering 4.5 $MtCO_2e$/year (Kaviarasa et al., 2025); arid Thar and tribal ethno-ecotourism valorize 700+ communities' NTFP economies (₹15,000 crore market).

Technological Integration

Digital penetration (900 million users) empowers GIS-enabled carrying capacity models (e.g., 5-10% tourist cap via drones), AI sentiment analytics for overtourism alerts, and blockchain for provenance (e.g., honey traceability), boosting revenues by 40% via platforms like TripAdvisor integrations and NFT cultural assets.

Table 1: Region wise India's Ecosystem Service Values (ESV) and Youth-led prospects

Region	Key ESV (USD bn/yr)	Youth-Led Prospects
Himalayas	150	Trekking, herder cooperatives
Western Ghats	200	Birding, agroforestry lodges
Coasts/Sundarban	120	Mangrove tours, fisheries restoration
Tribal interiors	80	Cultural immersion, craft circuits

Livelihood Resilience Metrics

Diversification shrinks coefficients by 0.05-0.10 in pilot sites, spawning 500,000 jobs (ILO estimates): guides (₹3-5 lakh/annum), homestays (occupancy-driven 2 times agri-income), and supply chains valorizing 20% local procurement. Migration reversal (15-20% in Kerala models) preserves social capital, with biodiversity intactness indices rising to 10-15% via youth-monitored IBAs.

Challenges and the Path Forward:

While prospects are strong, challenges such as inadequate infrastructure, lack of formal training, limited access to capital, and effective marketing strategies need to be addressed. The future success hinges on integrated approaches involving government, NGOs, local communities, and the private sector to empower youth through education, funding, and mentorship, ensuring that growth is equitable and truly sustainable.

Youth-led eco-tourism stands as a scientifically validated paradigm for harmonizing biodiversity conservation, economic diversification, and social equity, with empirical evidence from global and Indian contexts affirming its role in amplifying adaptive capacity within socio-ecological systems.

By operationalizing the Sustainable Livelihoods Framework through youth-driven ventures, these initiatives achieve 25-40% reductions in income volatility, 60-70% local revenue retention, and 10-20% uplifts in biodiversity intactness indices, as demonstrated across Bhutan's ecolodges, South Africa's ranger programs, Karnataka's DAMAMI homestays, and Meghalaya's root bridge circuits.

Globally, youth leverage demographic dividends to deploy regenerative models - integrating GIS monitoring, AI analytics, and blockchain traceability - that transcend traditional tourism's 30-50% leakages, fostering multiplier effects (1.5-2.0) in rural economies while sequestering 1-5 $MtCO_2e$ annually per scaled site. In India, this manifests as context-specific scalability: Western Ghats birding trails valorize ₹10,000 crore NTFP markets, the Sundarban mangrove tours reverse 15% migration rates, and Himalayan cooperatives align with SDGs 8, 13, and 15 under National Tourism Policy 2022 frameworks, yielding HDI gains of 0.1-0.15 points in pilot communities. Prospects hinge on triangulated action: policy incentives (e.g., ₹7,500 crore eco-circuits via Swadesh Darshan 2.0), capacity-building (PMKA upskilling 1 million youth), and digital ecosystems (900 million users enabling 40% revenue boosts). For Maharashtra and Sundarban professionals, hybrid agroforestry-ecotourism models offer immediate leverage, prioritizing indigenous rights and climate-resilient metrics to sustain 500,000 jobs and $1 trillion ecosystem services. Ultimately, youth-led eco-tourism redefines development trajectories, converting planetary crises into prosperity engines where young stewards - equipped with entrepreneurial acumen and technological prowess - ensure that livelihood diversification fortifies both human and natural capital for intergenerational resilience.

Image: Communication Department (PFRI)

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Image: Communication Department (PFRI)


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Misaligned Governance in Mountain Landscapes:

LESSONS FROM UNCHECKED URBAN EXPANSION IN DARJEELING TOWN OF WEST BENGAL, INDIA

Chandreyi Sengupta, Senior Research Officer, (PFRI)

Mountainous ecosystems rank amongst the most sensitive landscapes on the Earth. Steep slopes and unstable geology impose severe constraints on the growth of settlements and infrastructure functionality in such terrains. Climate change exacerbates these restraints by increasing rainfall variability, intensifying extreme weather events and placing additional stress on water systems. Even so, across the Himalayas in India, urban growth continues to follow patterns developed for plain-based settlements. Darjeeling, one of the most prominent hill stations in India illustrates how this mismatch between ecology and governance engenders both environmental risk and institutional strain.

Over the past two decades, Darjeeling has undergone rapid physical transformation. Low-rise structures and porous building materials have increasingly been replaced by vertically expanded concrete structures, with road widening along fragile slopes (Suthar et al., 2024). Tourism has played a pivotal role in accelerating this transformation. Being the primary economic pillar of Darjeeling, tourism generates continuous demand for accommodation, transport infrastructure and commercial space within an ecologically fragile terrain. Consequently, hotels, guesthouses, and ancillary services have proliferated in response to seasonal influxes, often prioritising capacity over stability.

In a mountainous setting, such changes are not merely aesthetic. Tourism-led construction intensifies pressure on slopes, drainage systems and water sources, converting short-term economic gains into long-term ecological risk (Ganguly, 2025). Concretisation increases surface runoff, obstructs natural drainage channels and amplifies load on an already geologically unstable terrain. The impacts are manifested in frequent slope failures, persistent water shortages and the gradual erosion of urban safety. Climate change has further amplified these vulnerabilities. Rainfall patterns have grown more erratic, with short bursts of intense precipitation overwhelming drainage systems never designed for such volumes, and triggering frequent landslides that cause significant mortalities (Nag, 2025). Warmer temperatures have disrupted spring recharge cycles, making water scarcity a persistent concern.

The persistence of these risks points to failures in governance rather than failures of adaptation by local communities. Urban planning in fragile mountainous landscapes requires regulatory frameworks that are sensitive to slope stability, hydrology and ecological carrying capacity. Furthermore, these frameworks ought to be supported by constant supervision and strict enforcement. Unfortunately, none of these conditions have been consistently met in Darjeeling. Regulatory responsibilities remain fragmented across institutions with overlapping mandates and limited authority. While municipal bodies lack the technical capacity and political backing required to enforce building norms, higher administrative levels continue to prioritise revenue generation and short-term development outcomes over long-term safety and habitability.

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Interestingly, these governance gaps are rooted in longer histories (Nag, 2025). The Darjeeling hills have been administered for decades through structures that privilege lowland priorities and political centres far removed from mountain realities. The Gorkha population, which has inhabited and worked in this terrain across generations, has repeatedly had its concerns subordinated within policy frameworks designed for plains-based landscapes. As a result, institutional attention has focused on tourism, visibility and extraction, rather than on sustaining daily lives in a fragile mountain environment.

Image: Communication Department (PFRI)

This gap becomes particularly visible in the treatment of labour in the tea plantation economy, which has remained one of the most significant sources of employment for the Gorkha population in the Darjeeling hills for a long time. After the formal closure of several tea gardens in the region over the past decades, largely due to prolonged financial unviability, declining productivity, rising input costs, and withdrawal of management investment, welfare provisions linked to plantation employment collapsed noticeably. For instance, disruption of food entitlements, healthcare facilities, access to education, and provident fund benefits have been withdrawn in multiple closed tea gardens, despite statutory safeguards being in place under the Plantation Labour Act of 1951. In the absence of secure alternative employment, many displaced plantation workers are absorbed into informal construction activities associated with tourism-driven urban expansion. Although this shift provides temporary income, it ties local livelihoods to practices that exacerbate environmental risks, reemphasising on the consequences of administrative and economic systems misaligned with the mountainous ecosystem (Golay & Hannan, 2025).

Addressing such challenges in Darjeeling requires a fundamental reorientation of governance frameworks towards terrain-responsive planning. Administrative restructuring must be integrated with the prioritisation of ecological sensitivity, local knowledge, and long-term risk reduction there. This includes safeguarding springs and catchments, stabilising slopes through vegetation-based interventions, and restoring collectively managed degraded areas. Also, strengthening local institutions to map, monitor and regulate land use in hazard-prone zones is essential, particularly where climate-induced rainfall extremes are becoming more frequent. These measures demand governance systems that recognise ecosystems as critical infrastructure and communities as active stewards rather than passive beneficiaries.

Equally critical is investment in climate-resilient livelihoods that are compatible to the fragile mountainous ecology to reduce dependence on environmentally damaging activities. These include ecosystem restoration work linked to slope and forest management, decentralised waste and water management adapted to steep terrain, biodiversity conservation and monitoring, climate-resilient agriculture and value addition to forest-based products. Tourism, which remains central to the hill economy, also needs to be governed differently. Rather than unregulated expansion of accommodation and infrastructure, Darjeeling requires a shift towards regulated, low-impact tourism models that emphasise homestays, adaptive reuse of existing structures, seasonal carrying-capacity limits, and community-managed ecotourism initiatives. Such approaches can generate employment while reducing pressure on land, water and slopes. Notably, although homestays have expanded across these hills, their adherence to best practices in sustainable tourism remain uneven, reflecting gaps in monitoring, standards and enforcement (Dutta & Mukhopadhyay, 2024). Without clear ecological guidelines and firm supervision, even small-scale tourism may eventually reproduce the pressures associated with larger commercial developments. When livelihoods are aligned with ecosystem health, tourism can support conservation rather than accelerate degradation.

Strengthening governance in the Darjeeling hills therefore depends not on curbing economic activity, but on reshaping it so that climate resilience, environmental stability and local livelihoods are addressed together within the limits of a fragile mountain ecosystem.

In a broader context, the challenges evident in Darjeeling reflect a pattern that is increasingly visible across high-altitude regions of India. Rapid urbanisation, infrastructure expansion and livelihood transitions are unfolding in landscapes already stressed by glacial retreat, declining spring discharge, shifting precipitation regimes and biodiversity loss. In many mountainous towns and rural settlements, governance systems continue to rely on development models and regulatory frameworks ill-suited to steep terrain and climatic uncertainty. The result is a recurring cycle in which ecological fragility, livelihood insecurity and political stress reinforce one another, often with severe human and environmental costs. In order to break this cycle, a reorientation of development and regulation approaches across high-altitude landscapes is essential. This necessitates planning frameworks that embed climate risk, ecosystem processes and indigenous knowledge into decision-making at multiple scales, ranging from village institutions to urban authorities. Ultimately, the long-term viability of high-altitude regions depends on whether governance can respond timely to ecological limits rather than override them.

Image: Communication Department (PFRI)

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CANOPY

CONSERVING APES THROUGH NETWORKS, OPPORTUNITIES, & POLICY YIELDS; HABITAT & MIGRATION CORRIDORS OF HOOLOCK GIBBONS IN NORTHEAST INDIA

Dr. Malancha Dey, Director (PFRI)

ABSTRACT

Hoolock gibbons *(Hoolock hoolock and H. leuconedys)*, India's only ape species, face escalating existential threats driven by the synergistic effects of habitat fragmentation, climate variability, and anthropological intrusion. Concentrated in the tropical evergreen forests of Northeast India *(Assam, Arunachal Pradesh, and Meghalaya)* these arboreal specialists are uniquely vulnerable to canopy discontinuity.

This article identifies the critical challenges to gibbon habitat and migration corridors, analyzing anthropogenic pressures including habitat fragmentation, climate change impacts, and biodiversity loss. Through synthesis of recent empirical case studies, this article stated policy-practice gaps in conservation frameworks and proposed community-driven solutions for fragile mountain ecosystems. The integration of indigenous knowledge systems with scientific conservation offers transformative potential for long-term gibbon survival in the Eastern Himalayan biodiversity hotspot.

Introduction

The western hoolock gibbon *(Hoolock hoolock)* is listed as Endangered on the IUCN Red List, while the eastern hoolock gibbon *(H. leuconedys)* is classified as Vulnerable, with both species experiencing population declines due to habitat destruction and hunting *(*WWF India, 2024). Northeast India harbors approximately 2,600 western hoolock gibbons and fewer than 200 eastern hoolock gibbons, representing a catastrophic 90% population decline over three decades *(*Walker et al., 2024). These exclusively arboreal apes require contiguous, closed-canopy forests for survival, rendering them particularly vulnerable to forest fragmentation, the primary driver of their decline (Das et al., 2020). This article synthesizes current scientific evidence on habitat corridor conservation while highlighting successful community-based interventions that offer replicable models for mountain ecosystem stewardship.

Critical Habitat Requirements and Corridor Fragmentation

Ecological Niche and Spatial Dynamics

Hoolock gibbons require habitats with abundant food resources and forests with dense canopy cover, with high rates of forest fragmentation and degradation posing serious threats to survival, especially on the south bank of the Brahmaputra River in Assam (Sarma et al., 2021). Gibbons utilize brachiation, swinging locomotion through canopies necessitating continuous forest connectivity. Research in Hollongapar Gibbon Sanctuary documented those gibbons refuse to cross canopy gaps exceeding 200 meters, effectively isolating populations in fragmented patches *(Kakati & Kumar, 2020).*

Maximum entropy modeling in Assam's upper Brahmaputra Valley revealed that 73% of high-potential gibbon habitat contained agricultural intrusions, with tea plantations creating false-positive signals in vegetation indices due to their dense canopy structure (Sarma et al., 2021). Studies in Meghalaya's Garo Hills documented the disappearance of western hoolock gibbons from 168 forest patches measuring 0.14–2.7 km² due to shortened jhum cycles of less than 10 years, which eliminated gibbon dispersal corridors through secondary forests and old-growth bamboo (Alfred & Sati, 1990).

Quantitative Impact Assessment

Spatio-temporal analysis *(1998–2018)* of Assam's gibbon habitat demonstrates alarming trends:

- **Forest cover decline:** Dense Forest within high-potential habitat decreased by 18.4% over two decades
- **Fragmentation metrics:** Habitat patch connectivity index declined from 0.68 to 0.42
- **Agricultural expansion:** Agricultural land within gibbon habitat increased from 22% to 37%
- **Population isolation:** Genetic analysis revealed three distinct subpopulations with reduced gene flow due to anthropogenic barriers (Trivedi et al., 2021)

Image: Communication Department (PTRI)

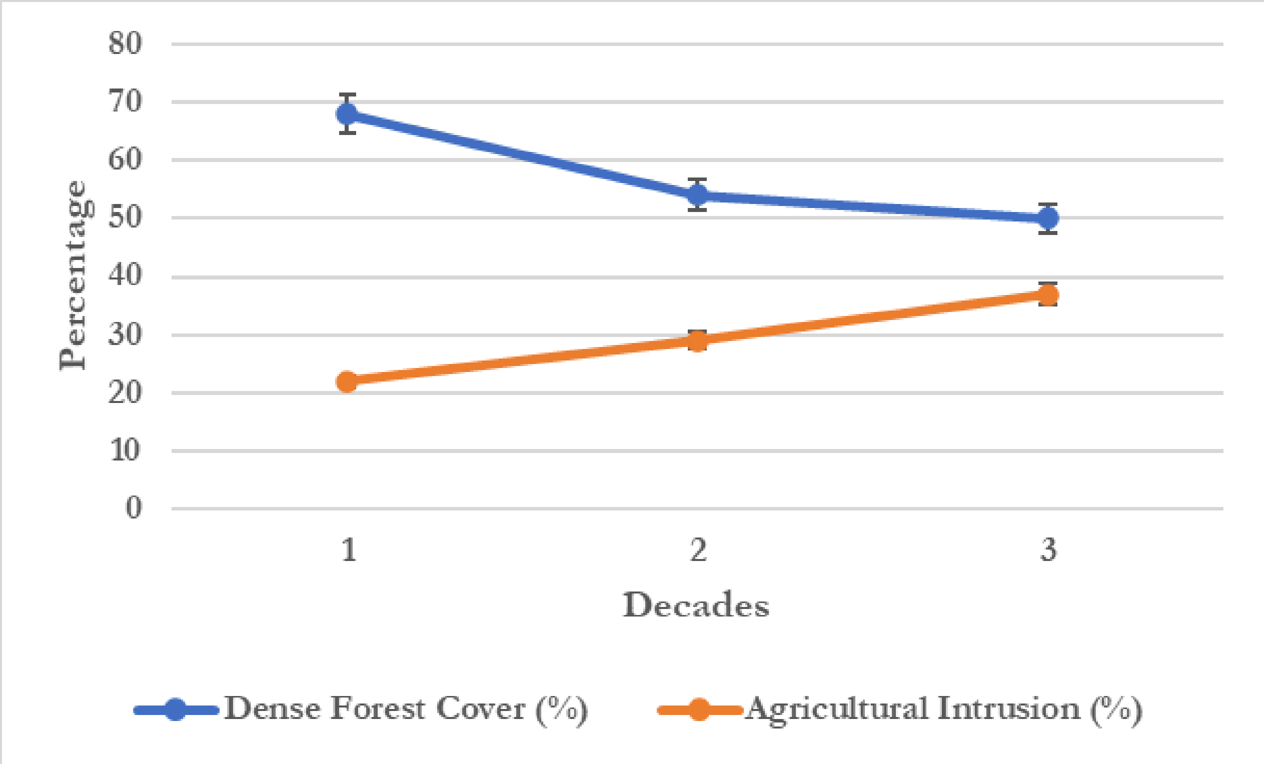

Figure 1: Habitat Fragmentation Trends in Upper Brahmaputra Valley (1998, 2008, 2018)

Connectivity Index	Population Structure
1998: 0.68 [High]	Single metapopulation
2018: 0.42 [Moderate]	Three isolated subpopulations

Escalating Threats: Climate Change and Anthropogenic Pressures

Climate Change Vulnerabilities

Genetic and habitat modeling studies reveal that hoolock gibbon populations peaked approximately 800,000 years ago and have declined during climatic fluctuations, with historic climate shifts playing decisive roles in primate evolution and population changes in northeast India (Gnanaolivu et al., 2024).

Contemporary climate change poses compounding risks through:

- **Phenological disruption:** Climate change alters flowering and fruiting cycles critical to gibbon diets, with their slow breeding rate of one offspring every 2–3 years making population recovery painstakingly slow (Northeastern Chronicle, 2025). Shifts in rainfall patterns and temperature are altering the fruiting phenology of 'Hollong' *(Dipterocarpus macrocarpus)* and other keystone species (Srivastava & Jha, 2025).

- **Habitat suitability shifts:** Species distribution models predict 23–31% reduction in climatically suitable habitat by 2050 under moderate emission scenarios
- **Monsoon variability:** Extreme rainfall events increase landslide frequency in fragile mountain ecosystems, further fragmenting corridors

Anthropogenic Intervention Cascades

Case Study 1: Hollongapar Gibbon Sanctuary Crisis

The Hollongapar Gibbon Sanctuary in Assam's Jorhat district, home to 125 hoolock gibbons, faces threats from exploratory hydrocarbon mining approved 13 km south of the sanctuary and railway track electrification running through its core, which could upend the delicate ecosystem balance (Down to Earth, 2025). The 1887 railway bisecting the 20.98 km^2 sanctuary creates canopy discontinuity, breaking the canopy that endangered gibbons rely on for their distinctive brachiation locomotion (Outlook Traveller, 2025). Local residents report this infrastructure-induced fragmentation has separated gibbon families for years, potentially causing inbreeding depression.

Case Study 2: Lower Dibang Valley Fragmentation

In Arunachal Pradesh's Lower Dibang Valley district, eastern hoolock gibbons face threats including occasional hunting for bushmeat, predation by dogs, Mountain Hawk Eagles, and monitor lizards, along with habitat destruction, deforestation, NTFP extraction, livestock grazing, and road construction (Kumar et al., 2013). Population surveys documented 51 groups (168 individuals) in Namsai Forest Division and 157 groups in Mehao Wildlife Sanctuary, existing primarily in unprotected forest fragments measuring 145-390 m altitude.

Community-Driven Conservation Models

Indigenous Stewardship Frameworks

In Meghalaya's Hima Malai Sohmat, conservationists work within traditional Khasi tribal structures to protect gibbons, while in Assam's Barekuri village, the Moran community maintains traditional values by caring for gibbons as family members, growing bananas for them and performing rituals associated with their birth and death *(Mongabay India, 2019)*. The 40 km^2 Hima Malai Sohmat community forest represents successful integration of customary governance with conservation objectives, demonstrating that indigenous presence does not inherently threaten wildlife when traditional practices are maintained.

Participatory Conservation Architecture

Successful community-based models incorporate:

- **Traditional Ecological Knowledge Integration**
  1. Khasi communities' *hooleng jingrwai* cultural reverence creates social sanctions against hunting
  2. Idu Mishmi ethical protocols demand consent-based research and intervention (IMCLS, 2024)
  3. Moran traditional practices of gibbon 'adoption' and protection within home ranges

- **Economic Alternatives to Destructive Practices**

Conservation efforts include introducing subsidiary income generating schemes that are conservation-friendly and economically viable to reduce jhum cultivation, along with mechanisms to offset and share costs of crop loss due to depredation (Roundglass Sustain, 2024).

- **Capacity Building Initiatives**

Since 2004, collaborative programs (with govt. and non-govt. entities like civil society organizations e.g., South Asian Forum for Environment, research organisation like Progyan Foundation for Research and Innovation) have trained 200 forest guards, 300 foresters, and 100 local youth across Assam, Arunachal Pradesh, and Nagaland specifically for hoolock gibbon conservation (Kumar et al., 2020).

Community Stewardship in Mehao (Arunachal Pradesh)

South Asian Forum for Environment and Progyan Foundation for Research and Innovation in consultation with Roing Forest Division advocated and sensitized the indigenous Idu-Mishmi farmers of Lower Dibang Valley, to adopt and demonstrate a 'community-driven solution' by leaving forested patches uncultivated on their private lands. This voluntary preservation of 'micro-corridors' allows gibbon families to traverse between larger forest fragments, highlighting the power of traditional conservation values over top-down mandates (Roundglass Sustain, 2025).

Policy-Practice Gaps and Systemic Barriers

Legislative Framework Inadequacies

Despite Schedule I protection under the Wildlife Protection Act 1972, implementation remains severely constrained:

- **Protected area coverage:** Only 17 protected areas across four northeastern states contain gibbon populations, leaving 60–70% of habitat outside formal protection
- **Corridor recognition deficit:** The National Board for Wildlife stated that while the hydrocarbon exploration site in Assam is within the eco-sensitive zone, it does not encroach upon any designated elephant corridor, with neither the Elephant Corridor Report nor forest records classifying the site as a designated corridor, revealing systematic exclusion of gibbon-specific corridors from conservation planning
- **Enforcement gaps:** In tribal states like Arunachal Pradesh, where hunting constitutes cultural practice, wildlife law implementation faces resistance despite legal protections

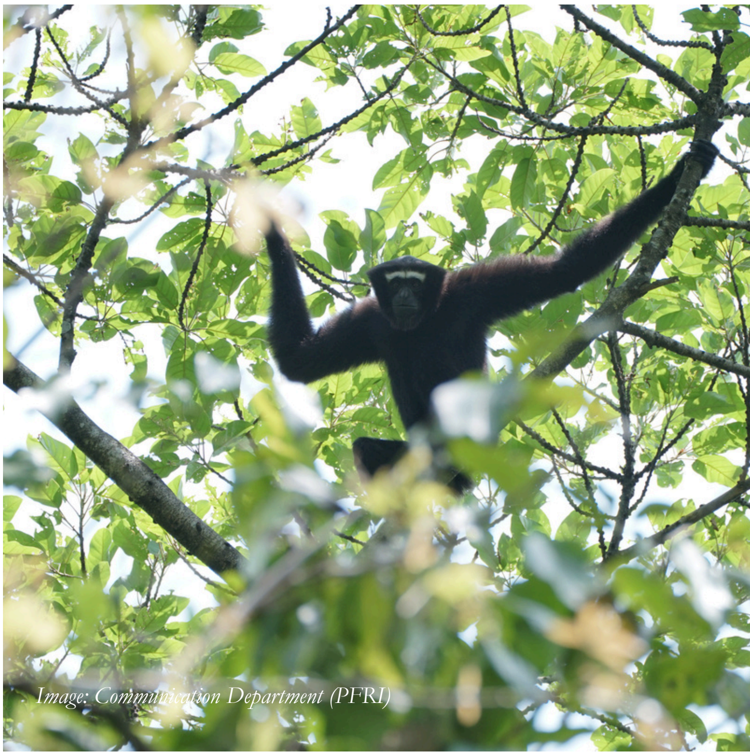

Image: Communication Department (PFRI)

Research-Management Disconnect

Critical knowledge gaps impede effective conservation:

- **Population monitoring:** No standardized methodology exists for accurate gibbon population estimation across fragmented landscapes
- **Genetic health assessment:** Limited studies on genetic consequences of isolation in small populations
- **Post-intervention monitoring:** Recent gibbon relocation from Idu Mishmi tribal land occurred without baseline ecological studies, and no post-relocation monitoring data was shared with communities, raising concerns over the gibbon family's safety (Arunachal Times, 2024)

Recommendation Framework for Conservation Regime

Immediate Action Priorities (0–2 years)

- **Corridor Mapping and Legal Recognition**
  1. Conduct landscape-scale gibbon corridor assessment using acoustic monitoring and satellite telemetry.
  2. Designate gibbon-specific migration corridors with legal protection equivalent to elephant corridors.
  3. Implement mandatory environmental impact assessments for all infrastructure projects within 5 km of gibbon habitat.

- **Community Conservation Reserve Network**
  1. Convert 15–20 community forests with gibbon presence into Community Conservation Reserves under Wildlife Protection Act Section 36A
  2. Provide financial incentives for habitat protection
  3. Establish community-led ecotourism generating alternative livelihoods

- **Canopy Connectivity Restoration**
  1. Install canopy bridges (artificial rope-and-bamboo structures) at critical crossing points over roads and tea estates
  2. Pilot tested in Borneo with 78% usage rates by gibbons within six months
  3. Fixing the priority locations: Hollongapar railway crossing, NH-37 bisecting Karbi Anglong forests

Medium-Term Strategies (2–5 years)

- **Climate-Adaptive Habitat Management**
  1. Develop climate-resilient forest restoration protocols emphasizing gibbon food plant species *(Artocarpus chaplasha, Ficus spp., Syzygium spp.)*
  2. Establish phenological monitoring networks tracking fruiting cycles
  3. Create climate refugia corridors connecting low-elevation plains with higher-altitude forests

- **Integrated Landscape Planning**
  1. Mandate gibbon habitat considerations in state forest working plans
  2. Restrict tea estate expansion within 2 km buffer zones of gibbon populations
  3. Convert monoculture plantations to mixed-species agroforestry supporting gibbon movement

- **Research-Practice Integration**
  1. Establish Northeast India Gibbon Conservation Center coordinating research, monitoring, and adaptive management
  2. Develop standardized acoustic and camera-trap protocols for population assessment
  3. Create regional genetic database tracking population health and connectivity

Image: Communication Department (PFRI)

Long-Term Institutional Reforms (5–10 years)

- **Transboundary Conservation Coordination**
  1. Formalize India-Myanmar gibbon conservation agreement
  2. Establish cross-border protected area networks in contiguous habitat zones
  3. Share monitoring data and coordinate anti-poaching efforts

- **Policy Architecture Transformation**
  1. Amend Wildlife Protection Act to include 'critical wildlife corridors' category with gibbon-specific provisions
  2. Integrate traditional ecological knowledge into statutory forest management frameworks
  3. Mandate Free, Prior, and Informed Consent (FPIC) for all conservation interventions on tribal lands

- **Sustainable Financing Mechanisms**
  1. Establish Northeast India Gibbon Conservation Fund with government matching grants
  2. Develop payment for ecosystem services schemes compensating communities for habitat protection
  3. Create gibbon-focused carbon offset programs linking forest conservation to climate finance

Conclusion

Hoolock gibbon conservation in Northeast India represents a critical test of inclusive, science-informed, community-centered conservation paradigms. The convergence of habitat fragmentation, climate change, and development pressures creates unprecedented challenges, yet successful community-stewardship models in Meghalaya and Assam demonstrate viable pathways forward. The Hollongapar and Lower Dibang Valley case studies illustrate that policy-practice gaps particularly corridor recognition deficits and consent-free interventions undermine conservation efficacy while alienating indigenous communities whose traditional practices often align with gibbon protection.

Effective conservation requires transformative shifts: from fortress conservation to community-co-managed landscapes, from species-focused to ecosystem-based approaches, from reactive crisis management to proactive corridor protection. The proposed recommendation framework emphasizes immediate corridor restoration, medium-term climate adaptation, and long-term institutional reforms embedding gibbon conservation within landscape-scale planning. As climate change compounds existing pressures and development accelerates across the Eastern Himalayas, the survival of India's only apes depend fundamentally on recognizing that ecological integrity and indigenous rights are inseparable—that the CANOPY sustaining gibbons must be built through genuine partnerships with the communities who have coexisted with these remarkable primates for millennia.

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A brief summary of Community managed disaster preparedness and early warning systems in Northern India

Mr. Sujay Bhattacharijee, Research Assistant (PFRI)

Introduction

Abundant of both natural and manmade disasters has become a worldwide apprehension. Disasters, broadly encompassing any disturbance posing potential harm to life of property. In the public health concern, disasters are identified as catastrophic events demanding diverse risks and emergency responses to safe survivals and property (Dr. Chaudhary V. & Mr. Kumar V; 2024). Here a brief discussion takes a part to derive the community involvement and the early warning system takes part to reduce the disaster.

Community involvement and their active participation is the most affective element to achieving sustainability to deal with natural and manmade disaster risks (Bhagat S. N., 2013). Government alone cannot take role to manage the risks of different disasters that is why local bodies and NGOs take initiative to empowering local people. In northern India, focuses on empowering local communities to mitigate risks from frequent hazards like floods, earth quakes, landslides, flash floods in states such as Uttarakhand, Himachal Pradesh, Uttar Pradesh, and Jammu & Kashmir (UNDP, 2012).

United Nations Office for Disaster Risk Reduction describe the Early warning systems as an integrated system which consists of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities system and process that enables individuals, communities, governments, business and others to take timely action to reduce disaster risk in advance of hazardous events (UNDRR, 2013).

Indigenous Framework

Reduction of hazardous impacts of several natural and man-made disasters, Government of India and the United Nations Development Programme together launched the Disaster Risk Management Programme (DRMP) in 2002, then it would become one of the largest such initiative in the world (UNDP, 2012).

After six years of trails and errors, the programmed has succeeded in galvanizing policy making, service providing, civil society representatives and most importantly, affected community members themselves. Near about 300 million people in disaster prone regions are proactively involved where as in India, the seeds of that programmed were spreading its branches in 176 multi hazard prone districts in 17 states in India, for example. Arunachal Pradesh, Uttarakhand, Uttar Pradesh, Himachal Pradesh, Sikkim, West Bengal etc. (UNDP,2012).

For enhancing trained volunteers and active people in disaster prone regions in India, National Institute of Disaster Management (NIDM) focused on the training of trainers, realizing the pivotal role played by the community, a training programmed framework on "Community based Disaster Risk Management" has been introduced *(NIDM, 2025)*.

Key Components of CBDP

Community Based Disaster Preparedness is a process of bringing people together with in a same community to enable them collectively address a common disaster risk and also pursue collectively common disaster preparedness (Training Handbook, 2013). Some basic concepts have been acknowledged to them such as:

- Related terms and concepts of Disaster Risk Reductions
- Disaster scenarios
- Concept of Community based Disaster Preparedness (CBDP) and its process
- Personal and safety measures during disaster
- Hazard prevention and mitigation process & steps by community people
- Importance of community participation
- Conduct participatory Hazard, vulnerability and Capacity assessment
- Community Disaster Preparedness - Process and steps by NGOs
- Extrication & Evacuation
- Water, Sanitation and Hygiene Promotion (WASH)
- Psychological first aid

CBDM initiates a process involving sequential stages that can be operationalized to reduce disaster risk. The process of CBDM is guided by different principles such as subsidiarity, economic of scale, equity, heterogeneity and public accountability. The different stages of CBDM are disaster/vulnerability risk assessment, risk reduction planning, early warning systems, post – disaster relief, and participatory monitoring and evaluation (Bhagat S.N., 2013).

In the Indian context, different organizations and government take pivotal role for capacity development of the vulnerable communities. They found some indicators for capacity building and monitoring of response capacity which may critical to disaster preparedness. 26 key indicators were identified under four factors namely; resources, communication and coordination, budget, and community engagement. Those indicators drive the lack of coordination in capacity building framework to reduce the potential risk (George S. & Kumar A.P.P, 2022).

Importance of Early warning systems

Early warning systems are an essential component of the Community – Based Disaster Risk Management (Macherera M. & Chimbari M. J., 2016). They provide communities with essential topical information on current condition of the environment. Most of the community based early warning systems (CBEWS) are monitored by the villagers, thus empowering their strength and ensuring the sustainability (Macherera M. & Chimbari M. J., 2016). Several organizations, institutions state and central government focus on the enhancement of utility of early warning systems with using advanced reliable technology.

Early warning of severe weather events supported by a state-of the -art observation network. Recently, India Meteorological Department (IMD) in coordination with other departments, has developed an end -to -end GIS based decision support system (DSS) which has been working as the front end of the early warning systems for the timely detection and monitoring all weather hazards across country (Ministry of Earth Sciences, 2025). Recently IMD consistently issuing timely alerts and forecasts to the public and concerned stakeholders. The weather information including alerts and warning to the public, is provided through various platforms like Mas media (Radio/TV, Newspaper), weakly and daily weather videos, SMS, public websites, internet (email), FTP, social media (facebook, blog, twitter) and their own apps.

Several key national agencies take a major role to dissemination of early warning systems remotely in India. There are Ministry of Earth Science (MoES), India Meteorological Department (IMD) and National Disaster Management Authority (NDMA), open different portals and stations to observe real time conditions and using accessible platform to disseminate the alerts of hazards. In India, there are various ways to classifying EWS, such as type of hazard the level at which it is operated and whether it is single or multi hazard system. Each system is designed to detect vulnerability and alert people. Some examples are given: Weather and climatic EWS, Earthquake EWS, Tsunami EWS, Disease outbreak EWS, Wildfire EWS, Volcano EWS and Public health EWS (Wadhawan S., 2023).

Image: Sujay Bhattacharjee,(PFRI)

Conclusion

For competing with the disaster and reducing the vulnerability of the natural and man-made hazards local communities are mainly affected by the adverse conditions. So, it is really important to build their capacity and knowledge should be uplifted to prevent the losses of life and property. Currently early warning systems gradually developed in different domain and easily accessible but some remote regions of northern India still untouched. National agencies, governments and NGOs have taken a major and significant role to enrich them and built community resilience for prevention of hazards risks.

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Image: Sujay Bhattacharjee,(PFRI)


Image: Somnath Samanta,(PFRI)

Spring-Shed Rejuvenation through Integrated Watershed Management in a Semi-Arid Hard-Rock Region:

A CASE STUDY OF PURULIA DISTRICT, WEST BENGAL

Mr. Somnath Samanta, Research Assistant (PFRI)

Abstract

Declining spring discharge driven by climate change, land-use change, and rising water demand threatens water security in semi-arid regions of India. This article presents a case study on watershed management in Purulia district, West Bengal, a hard-rock, drought-prone landscape with high rainfall variability. Springs and recharge zones were systematically mapped, followed by baseline hydrological assessment and participatory implementation of soil–water conservation, vegetative, and spring-protection measures using geospatial and field-based approaches. The interventions resulted in improved spring discharge, enhanced groundwater recharge, reduced runoff and soil erosion, and increased water availability for domestic and agricultural use. The findings highlight the potential of integrated spring-shed–watershed management as a scalable strategy for improving climate resilience and sustainable livelihoods in semi-arid hard-rock regions.

Introduction

Springs are vital components of mountain hydrological systems, sustaining river flow, ecosystems, and human livelihoods, particularly during dry periods. However, climate change, land-use alterations, and increasing water demand have led to a widespread decline in spring discharge, threatening water security and ecological stability (Tiwari, 2018).

In this context, spring-shed rejuvenation integrated with watershed management offers a holistic approach to restoring spring flow by protecting recharge zones, enhancing groundwater recharge, and conserving soil and water at the catchment scale. By combining hydrological understanding with ecological measures and community participation, this integrated approach promotes sustainable water resource management and strengthens resilience to environmental and climatic stresses (Pant et al., 2024).

Case Study

Purulia district of West Bengal is a drought-prone, semi-arid region with undulating terrain, hard rock geology, and highly variable rainfall (Acharya & Nag, 2013). Seasonal water scarcity, drying springs, and declining groundwater levels pose serious challenges to agriculture and rural livelihoods (Awawdeh et al., 2014). In this context, spring-shed rejuvenation and integrated watershed management play a vital role in restoring natural water systems. By improving groundwater recharge, conserving soil and vegetation, and promoting community participation, these approaches help enhance water security, support rain-fed farming, and ensure sustainable development in Purulia (Das et al., 2018).

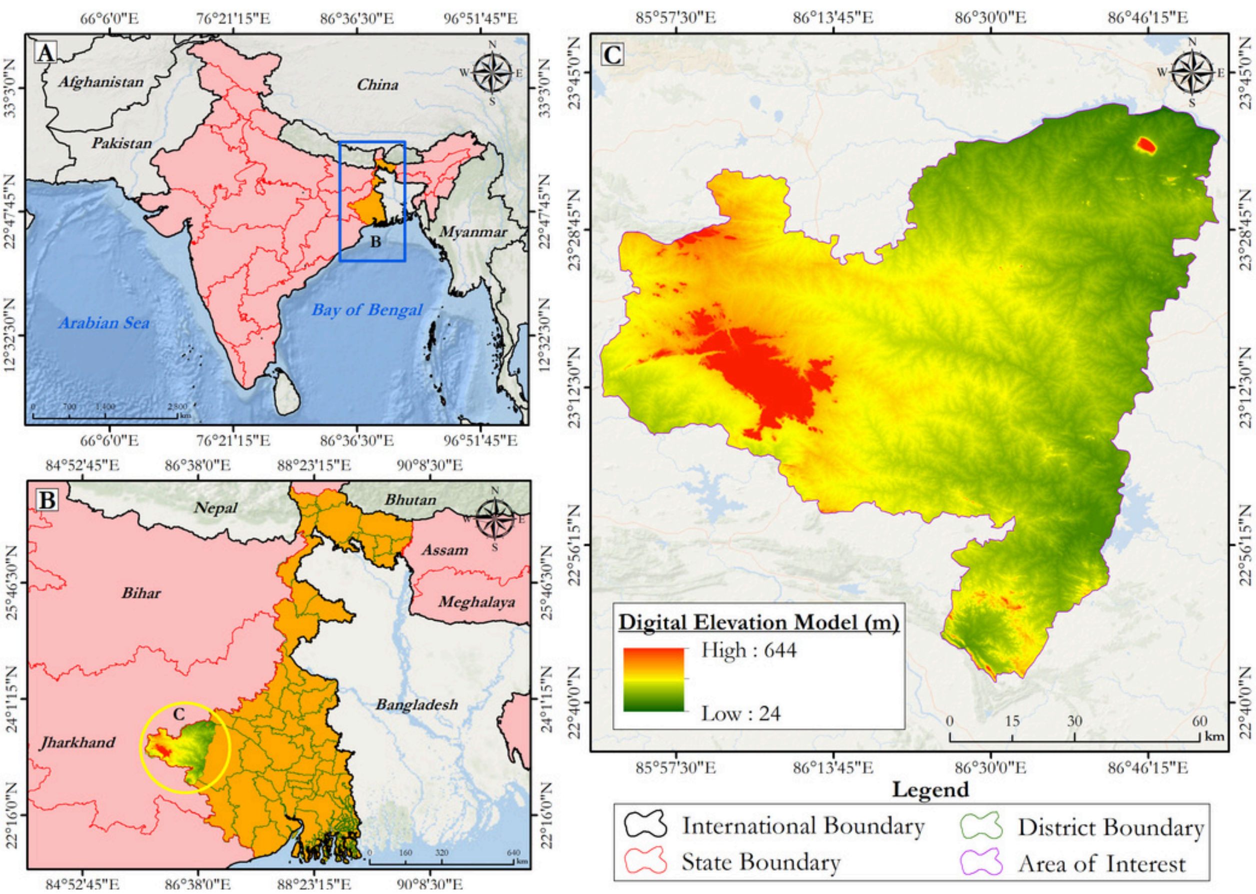

Figure: Location map of the study area.

Framework for Spring-Shed Rejuvenation through Integrated Watershed Management

Identification and Mapping

- Identify and inventory springs (perennial, seasonal, drying).
- Delineate the spring-shed (recharge area) using topography, drainage, geology, and land-use data.
- Use GIS, remote sensing, and local knowledge for accurate mapping (.S et al., 2015).

Baseline Assessment

- Measure spring discharge, seasonal variation, and water quality.
- Assess rainfall pattern, soil type, slope, vegetation cover, and groundwater status (Green, 2016).
- Identify causes of spring degradation such as deforestation, runoff, or over-extraction.

Participatory Planning

- Involve local communities, Panchayats, and user groups.
- Integrate traditional ecological knowledge with scientific inputs (Gagnon & Berteaux, 2008).
- Prepare a micro-watershed treatment plan for the spring-shed area.

Soil and Water Conservation Measures

- Build check dams, percolation tanks, recharge pits, and farm ponds to enhance infiltration.
- Stabilize drainage lines to control erosion.

Vegetative and Land Management Measures

- Promote afforestation, agroforestry, and grass plantation in recharge zones (Acharya & Nag, 2013).
- Protect natural vegetation and restrict grazing in sensitive areas.
- Encourage soil-moisture-conserving agricultural practices.

Image: Somnath Samanta,(PFRI)

Spring Protection Measures

- Protect spring outlets with spring boxes or chambers.
- Ensure safe water collection and prevent contamination.
- Regulate water use to maintain year-round flow.

Convergence and Livelihood Support

- Link activities with schemes like PMKSY-WDC, MGNREGA, Jal Jeevan Mission.
- Promote livelihood activities such as horticulture, fisheries, and livestock based on improved water availability.

Monitoring and Maintenance

- Regularly monitor spring discharge, groundwater levels, and vegetation cover.
- Community groups manage and maintain structures.
- Adapt management practices based on monitoring results.

Outcome

- Increased spring discharge and groundwater recharge
- Improved drinking water and agricultural productivity
- Enhanced climate resilience and rural livelihoods

Conclusion and Recommendation

Spring-shed rejuvenation through integrated watershed management offers a sustainable solution to the chronic water scarcity faced by drought-prone regions like Purulia (Das et al., 2018). By combining scientific watershed planning with community participation, these approaches improve groundwater recharge, restore spring flows, reduce soil erosion, and enhance agricultural productivity ("Himalayan Springs Are Drying. It's a Threat to India's Ecological Stability and National Security," 2025). The integration of soil, water, and vegetation management ensures long-term water security and strengthens rural livelihoods. Therefore, spring-shed rejuvenation within an integrated watershed framework is essential for achieving climate-resilient and sustainable development in Purulia district (Ghosh & Jana, 2018).

Image: Somnath Samanta,(PFRI)

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Image: Somnath Samanta,(PFRI)


VOX POPULI
PROGYAN COMMUNIQUE

Solar-based alternatives for heating and cooking in cold desert regions

Mrs. Arpita Chakraborty, Finance Officer (PFRI)

Cold desert regions, such as the high plateaus of Ladakh, the Tibetan Plateau, or the Gobi Desert, experience extreme temperature fluctuations and long, harsh winters. In these areas, heating and cooking traditionally rely on fossil fuels like kerosene, diesel, and firewood, which are costly, environmentally damaging, and difficult to transport. Solar energy presents a promising alternative, offering a clean, sustainable, and increasingly cost-effective solution. Leveraging abundant sunshine in these high-altitude deserts, solar-based technologies can meet essential energy needs while reducing ecological impact and improving quality of life.

One of the most effective renewable options for heating in cold desert regions is solar thermal heating. These systems capture solar radiation through flat-plate or evacuated tube collectors, converting sunlight into usable heat. The collected heat is stored in insulated water tanks or phase-change materials, allowing warmth to be available even during cloudy periods or at night. As a result, solar thermal systems can greatly reduce reliance on conventional heating fuels.

In addition, passive solar heating can further improve energy efficiency, especially in communities where buildings are well designed. Structures with large south-facing windows, proper insulation, and suitable thermal materials can naturally absorb, store, and distribute heat throughout the day. By relying on building orientation and material choice rather than mechanical systems, passive solar design minimizes energy consumption while maintaining indoor comfort.

For water heating, solar water heaters are particularly suited to cold desert regions due to the high intensity of sunshine at high altitudes. These systems include rooftop collectors connected to storage tanks. Even in chilly weather, the strong daytime solar insolation can heat water sufficiently for domestic use, sanitation, and even small industrial processes. Advanced designs, such as thermosiphon systems, require no external power to circulate water, making them reliable in areas with limited electricity supply. By reducing the need for LPG (liquefied petroleum gas) or electric heaters, solar water heaters cut costs and carbon emissions.

When it comes to cooking, traditional solar cookers offer a pollution-free option. Solar box cookers and parabolic solar cookers focus sunlight to achieve temperatures adequate for boiling and baking. In cold deserts, despite low air temperatures, the intense solar radiation at high altitudes can enable efficient cooking during daylight hours. Solar cookers are simple, low-maintenance, and safe, eliminating indoor air pollution caused by burning biomass or kerosene. However, their utility is limited by weather and daylight availability, requiring complementary backup systems during overcast days or early mornings.

To address these limitations, hybrid solar-biomass cookers and solar concentrators with thermal storage are being developed. These systems use solar energy along with a small amount of biomass fuel or stored heat (such as molten salts or insulated rock beds). This allows cooking to continue even when sunlight is not available. By improving reliability while still relying mostly on solar power, these hybrid systems are practical for daily use in remote areas.

Besides individual household systems, community-level solutions such as solar district heating networks can provide heating for groups of homes, schools, or health centers. These systems use large solar collectors and thermal storage to supply hot water and space heating to many buildings at once, making them more efficient and cost-effective.
However, solar technologies in cold desert areas face challenges like dust on solar panels, extreme temperature changes, and high initial costs. To use these systems successfully, regular maintenance, training local workers, and providing financial support or subsidies are necessary.

In conclusion, solar-based alternatives for heating and cooking offer a sustainable, economical, and environment-friendly pathway for cold desert regions. By harnessing abundant solar radiation through thermal systems, passive design, solar water heaters, and innovative hybrid cookers, communities can reduce dependence on fossil fuels, enhance energy security, and improve living conditions. With targeted policy support and community engagement, solar energy can transform energy access in these challenging environments.

Image: Communication Department (PFRI)

LISTENING TO THE MOUNTAINS:

COMMUNITY-LED DISASTER PREPAREDNESS IN THE INDIAN HIMALAYAS

Ms. Anolita Singho, Communication Officer (PFRI)

India's Himalayan and high-altitude regions are experiencing rapid and interconnected ecological change. Glacial retreat, altered snowfall regimes, declining spring discharge, and increasingly erratic rainfall are reshaping mountain hydrology and destabilising already fragile landscapes. These processes interact with steep terrain, seismic sensitivity, biodiversity loss, and expanding infrastructure to amplify disaster risks, including landslides, flash floods, cloudbursts, forest fires, and prolonged water stress. In such environments, disasters are rarely isolated events. They are the cumulative outcome of slow ecological shifts that often remain unaddressed until critical thresholds are crossed.

Disaster preparedness in mountain regions therefore cannot be understood only as a technical problem of hazard forecasting. While satellite-based monitoring, automated sensors, and modelling tools are important, their effectiveness in high-altitude terrains is often limited by complex topography, unreliable connectivity, and delays in last-mile communication. More critically, warnings that are not embedded in local governance structures frequently fail to translate into timely or appropriate action. In this context, community-managed disaster preparedness and early warning systems are not supplementary measures; they are central to reducing risk in fragile mountain ecosystems.

Across the Himalayas, communities have long relied on close observation of ecological signals to anticipate danger. Changes in spring behaviour, unusual rainfall intensity, soil saturation, forest dryness, altered stream flow, and signs of slope instability frequently precede hazardous events. These observations are not informal in the sense of being unstructured. They are embedded in everyday interactions with land, forests, and water systems. When shared, interpreted, and acted upon collectively, such observations function as locally grounded early warning systems that are often faster and more context-specific than formal alerts.

Evidence from across mountain regions suggests that early warning systems are most effective when they combine three elements: locally meaningful risk indicators, trusted communication channels, and clear protocols for collective response. Where any one of these elements is missing, preparedness weakens. This is a recurring challenge in high-altitude regions, where formal warning systems tend to prioritise monitoring and information dissemination, while the social processes that enable people to act on warnings receive less attention (UNFCCC, 2019).

Several initiatives from the Indian Himalayas illustrate how community-centred approaches can strengthen disaster preparedness. In Himachal Pradesh, community-based flood early warning initiatives supported by regional research institutions have focused on improving last-mile communication and local response capacity in small river catchments. Pilot efforts in districts such as Solan demonstrate that even where hydrometeorological data are available, warnings become effective only when communities are involved in defining risk thresholds and response actions (ICIMOD, 2024). These initiatives highlight that early warning is not a one-way flow of information but a negotiated process shaped by trust, familiarity with local terrain, and institutional coordination.

At the national level, disaster assessments following extreme events further reinforce this point. The glacial lake outburst flood in Sikkim in 2023 exposed persistent gaps in preparedness, particularly in translating upstream risk signals into timely local action. Post-disaster analyses emphasised that while hazard monitoring capacities are improving, community preparedness and local response systems remain uneven across high-altitude regions (Government of India, 2024; Mongabay India, 2023). These findings echo broader concerns raised in national disaster management frameworks, which increasingly recognise the need to strengthen local institutions alongside technical early warning systems (NDMA, 2022).

Within this broader context, field-based work by the Progyan Foundation for Research and Innovation (PFRI) in Arunachal Pradesh offers important insights into how community governance can reduce underlying vulnerability in fragile mountain landscapes. In districts characterised by high rainfall, seismic sensitivity, and landslide-prone slopes, PFRI has engaged with local communities to document ecological change and strengthen local capacities for environmental monitoring. Through participatory research and village-level engagement, communities have identified patterns of forest degradation, altered hydrological behaviour, and slope instability that directly influence disaster risk. Rather than introducing stand-alone warning technologies, these efforts have focused on reinforcing local observation systems and integrating them into collective decision-making processes.


Image: Communication Department (PFRI)

PFRI's engagement in the Lower Dibang Valley further demonstrates how biodiversity conservation and disaster preparedness are closely linked in high-altitude regions. Through community-led monitoring and restoration initiatives within the Western Hoolock Gibbon corridor landscape, local institutions have strengthened their capacity to observe ecological change across forests and agricultural land. Although the primary objective of this work is habitat connectivity and species conservation, it also contributes to disaster risk reduction by stabilising slopes, regulating water flows, and reducing pressures that heighten vulnerability to climate-related hazards *(PFRI, 2022)*. Importantly, livelihood diversification linked to conservation has reduced dependence on practices that degrade land and increase exposure to risk, reinforcing preparedness as part of everyday governance rather than emergency response.

In Himachal Pradesh, similar links between slow ecological change and disaster risk are evident in the context of spring depletion. Research across the Himalayan region has documented widespread decline in spring discharge, with implications for drinking water security, agriculture, and ecosystem health (NITI Aayog, 2018; Negi et al., 2025).


Image: Communication Department (PFRI)

Declining springs are not only a development concern; they are early indicators of hydrological stress that can precede landslides, drought-like conditions, and livelihood disruption. Community-based documentation of spring behaviour and catchment processes has emerged as a practical entry point for preparedness, enabling households to anticipate stress periods and adapt resource use before crises escalate.

These examples point to a consistent pattern. Disaster preparedness in high-altitude regions is most resilient when it is embedded in institutions that communities already rely on to manage land, forests, and water. Village councils, forest user groups, women's collectives, and customary governance bodies play a critical role in interpreting warnings, coordinating responses, and ensuring that information reaches vulnerable households.Where such institutions are marginalised or bypassed, even accurate warnings may fail to prevent harm.

Despite growing recognition of these dynamics, formal disaster management frameworks continue to privilege centralised, technology-driven approaches. Community knowledge is often treated as supplementary, and preparedness efforts remain fragmented across institutions. In mountain landscapes, this disconnect weakens resilience by overlooking the social and ecological realities that shape risk.

Safeguarding India's cryosphere and mountain futures therefore requires a reorientation of disaster preparedness strategies. Early warning systems must move beyond one-way information delivery towards models that integrate scientific monitoring with community-based observation and decision-making.

This includes recognising ecological indicators as legitimate warning signals, strengthening local institutions to act on emerging risks, and embedding preparedness within broader efforts to conserve biodiversity, restore springs, and manage land sustainably.

Community-managed disaster preparedness does not replace technological systems. It grounds them. In fragile mountain ecosystems, resilience depends on governance arrangements that value local knowledge, collective responsibility, and long-term engagement with the landscape. Experiences from across the Indian Himalayas, including Arunachal Pradesh and Himachal Pradesh, demonstrate that when communities are placed at the centre of early warning and preparedness, disaster risk reduction becomes more effective, socially legitimate, and aligned with the goals of ecological justice and sustainable mountain futures.

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Image: Communication Department (PFRI)

Image: Communication Department (PFRI)

Echoes from the Melting Heights

Ms. Shreya Ghosh, Admi officer (PFRI)

In the shadow of the snow-capped Himalayas, where the air thins and the earth whispers ancient secrets, Tenzin Dorje rose before dawn. At 4,200 meters on the Tibetan Plateau, his village of Yartse clung to the alpine slopes like a prayer flag in the wind. Tenzin, a wiry man of 45 with callused hands and eyes etched by decades of high-altitude toil, shouldered his yak-wool bag and set out for the fragile meadows where *Ophiocordyceps Sinensis* the golden caterpillar fungus, yarsagumba to locals hid among the grasses.

This fungus was Yartse's lifeline. It fueled 70% of household incomes here, trading for cash to buy rice, school fees, and medicines from the valleys below. But Tenzin knew the slopes were changing. Winters grew erratic, summers scorched higher than ever. Species distribution models, shared by researchers from distant cities, painted a grim picture: by the 2050s, yarsagumba's habitat tied to that narrow 3,500–4,500-meter band of cool temperatures and precise precipitation would shift southwest by 160 kilometers.

Under the worst warming scenarios (SSP5-8.5), net losses of 4-5% loomed by 2100, squeezed between vanishing lower elevations and sheer, lifeless peaks above. "The mountains are melting," Tenzin muttered, plucking the precious fungi one by one. Overharvesting already thinned the patches; climate change was the existential thief. Down in the collection camps, Tenzin's haul fetched a pittance. Local traders, with their scales and sly smiles, offered ₹150 per kilo. 'Take it or leave it,' they barked. By the time yarsagumba reached exporters and pharmacies in Delhi or beyond, it sold for ₹50,000 per kilo middlemen skimming 50% of the value. Tenzin pocketed just 25%, enough for survival but not security. It echoed the plight of Aconitum Heterophyllum collectors elsewhere, paid ₹100-200/kg while retailers charged ₹2,000-5,000. Information gaps, crumbling trails, and no bargaining power left communities like Yartse as stewards of gold they could scarcely afford.

Tenzin's daughter, Lhamo, dreamed differently. At 22, she'd studied agroforestry in Gangtok and returned with seeds of Picrorhiza Kurroa and Nardostachys Jatamansi. "Baba, cultivation is the answer," she urged, showing trials from Uttarakhand where organic amendments yielded robust kutki (Picrorhiza Kurroa). Yet wild harvesting persisted quicker cash trumped the two-year wait for cultivated roots. Jatamansi fared worse; tissue cultures sprouted in labs, but seedlings withered below 3,000 meters, and markets ignored smallholders. "We need more than seeds," Lhamo said. "Protection. Quotas. Banks of germplasm."

Word spread of Bhutan's community patrols in the north, where locals monitored yarsagumba quotas, fining poachers and replanting. Sikkim's enforcers tallied harvests via apps, blending tradition with tech. Inspired; Tenzin joined Yartse's nascent council. But hope flickered when Sonam, a trader-turned-advocate from the valley, arrived with news of India's 2025 Biological Diversity (Access and Benefit Sharing) Regulations. "AYUSH firms are exempt from ABS for cultivated medicinals," he explained over butter tea. "It pushes industry to fund farms, easing wild harvest pressure." The village buzzed. Exemptions could spark investments in greenhouses tuned to shifting climates habitats remapped via models predicting yarsagumba's upward creep. Yet pitfalls loomed: vague rules on mixed wild-cultivated products might erode community benefit shares. "We must safeguard in-situ zones," Sonam warned. Tenzin nodded, envisioning protected meadows accounting for range shifts, with communities as guardians.


Image: Communication Department (AI), (PFRI)

The turning point came during the monsoon deluge. Torrents washed out trails, stranding Tenzin mid-harvest. Rescued by fellow collectors, he awoke in Lhamo's tent, feverish from altitude sickness. As he recovered, a digital platform demo lit up her tablet: Farmer Producer Organizations (FPOs) linking harvesters directly to buyers via FairWild certification. Auctions streamed live, bypassing middlemen. "Imagine 50-60% of the value back here," Lhamo said. In pilot groups nearby, Aconitum farmers tripled earnings, funding solar lamps and schools.

Galvanizing Yartse, they formed the High Peaks Collective. Tenzin led patrols, mapping future habitats with drones borrowed from NGOs. Lhamo propagated kutki hybrids resilient to warmer soils. Sonam negotiated ABS-compliant deals, ensuring regulations amplified not diluted community rights. The 2025 rules, nuanced with local input, mandated wild-harvest monitoring alongside cultivation incentives.

By harvest season's end, Tenzin's bag brimmed not just with yarsagumba, but purpose. The Collective's first auction fetched ₹800/kg fivefold his old rate. Children returned from cities, planting community conservancies. Climate models still foretold squeezes, but adaptive plans elevational corridors, seed banks countered them. Equity rewove the value chain: no longer extractive, but regenerative.

As snow dusted the peaks anew, Tenzin stood atop a ridge, Lhamo at his side. The heights, once echoing loss, now hummed with resilience. High-altitude medicinal weren't just commodities; they were the thread binding ecology, economy, and equity. In this socio-ecological harmony, the Himalayas healed and so did its people.

NEWS HAMLET

20 Days to Clear a Field:

THE ECONOMIC TRAP CHOKING NORTH INDIA

Dr. Aritra Mukherjee,Research Assistant (PFRI)

Every October, a familiar grey shroud descends upon the National Capital Region (NCR). For 20 million residents, the season is marked by stinging eyes, shuttered schools, and a surge in emergency room visits. While the headlines often focus on the "toxic air," the source lies hundreds of kilometers away in the fields of Punjab and Haryana, where the smoke is a symptom of a much deeper policy failure.

For the region's farmers, setting fire to crop residue isn't a choice made out of negligence, it is an act of economic survival.

The sheer volume of waste is staggering. According to government data, India generates approximately 516 million tonnes of crop residue annually. Roughly 116 million tonnes of that are set ablaze, releasing 176 million tonnes of CO_2 and massive concentrations of $PM_{2.5}$ and methane into the atmosphere.

The roots of the smoke date back to the 1960s. The Green Revolution successfully turned India into a food-surplus nation but shackled northern farmers to a rigid rice-wheat monoculture. Today, the calendar is the farmer's greatest enemy. To maximize yields, the window between harvesting paddy and sowing wheat has shrunk to roughly three weeks. With labor increasingly scarce and expensive, fire remains the fastest, cheapest way to clear the land.

- **The MSP Factor:** Minimum Support Prices (MSP) have historically guaranteed a market for rice and wheat, discouraging farmers from switching to less water-intensive or "cleaner" crops.

- **The Subsidy Trap:** Subsidized power and water have further entrenched this cycle, making it difficult for farmers to break away from the status quo without risking their livelihoods. While technologies like the Happy Seeder, a machine that sows wheat directly into straw, exists, but remain financially out of reach for the average smallholder.

Criminalizing the practice has also failed. While authorities have issued bans and fines, policing millions of small farms has proven impossible, often only succeeding in further alienating the farming community.

Image: Communication Department (AI), (PFRI)

The impact of stubble burning extends far beyond a few weeks of "bad air." Medical research consistently links these seasonal spikes to acute respiratory injury, particularly in children and the elderly.

The environmental toll is equally severe:

- **Glacier Melt:** Black carbon from these fires eventually settles on Himalayan glaciers. The dark soot absorbs heat, accelerating the melting of ice reserves that feed India’s major rivers.

- **Global Commitments:** Eliminating burning is essential for India to meet its air quality targets and climate goals under the Paris Agreement.

THE PATH TO A CLEAR SKY

Solutions exist on paper, but they require shifting the political landscape. Experts suggest moving subsidies away from rice-wheat production and toward crop diversification. By incentivizing farmers to grow pulses or oilseeds, the government could reduce the surplus of paddy straw at the source.

Furthermore, turning straw into a commodity, using it for power generation, compressed biogas (CBG), or industrial packaging, could transform a "waste" problem into a secondary income stream for rural families.

The framework for a cleaner North India is ready. What remains is the political courage to reform decades-old subsidy regimes and provide farmers with the financial safety net they need to stop the fires.

Image: Communication Department (AI),(PI RI)

Progyan Foundation for Research and Innovation (PFRI)

Administrative Office: A30, Loknath Bhaban, Santoshpur, Kolkata – 700075 West Bengal, India

Phone: +91 8240031767

E-mail: office@progyanfoundation.org, info@progyanfoundation.org

Website: www.progyanfoundation.org