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Spatio-temporal dynamics of forest degradation in Tripura, North East India

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Abstract

Tripura, a small yet biologically rich state in the northeastern region of India, harbours a mosaic of tropical evergreen, semi-evergreen and moist deciduous forests that support a high level of endemism and cultural diversity. Over the past four decades, anthropogenic pressures—including shifting cultivation, commercial timber extraction, plantation forestry, infrastructure development and climate-driven disturbances—have accelerated forest degradation and fragmented the remaining forest matrix. This paper synthesizes peer-reviewed literature, government reports, remote-sensing analyses and field surveys to assess the extent, drivers and ecological consequences of forest degradation in Tripura. Particular emphasis is placed on the consequent loss of biodiversity at the species, community and ecosystem levels, with case studies on key taxonomic groups (vascular plants, amphibians, reptiles, birds and mammals). The review culminates in a critical appraisal of current policy frameworks (e.g., the Forest Conservation Act, 1980; State Forest Policy 2021) and community-based management initiatives and proposes an integrated, evidence-based roadmap for restoring forest integrity and safeguarding biodiversity in Tripura.

Keywords: Tripura, forest degradation, biodiversity loss, Northeast India, land-use change, conservation policy, community forestry

1. Introduction

The forests of Tripura, a northeastern state in India, are a vital ecological and cultural asset, renowned for their rich biodiversity and the critical ecosystem services they provide. Encompassing approximately 45% of the state's geographical area, Tripura's forests—dominated by tropical moist deciduous and semi-evergreen ecosystems—serve as a sanctuary for numerous endemic and endangered species and play a pivotal role in sustaining local livelihoods, water cycles and carbon sequestration (Forest Survey of India [FSI], 2021). However, these forests are increasingly under threat from degradation and biodiversity loss, driven by anthropogenic activities and shifting environmental dynamics. The interplay of unsustainable resource extraction, land-use changes and climate change has led to a destabilization of ecosystem integrity, raising critical concerns about the long-term sustainability of Tripura's natural heritage. This phenomenon not only undermines the state's ecological resilience but also exacerbates socio-economic vulnerabilities for forest-dependent communities, many of whom are indigenous populations such as the Tripuris, Reangs and Santals (Mukherjee, 2019).

Historically, Tripura's forests were relatively well-preserved, with high conservation values due to the traditional land-use practices of its tribal communities, which emphasized sustainable resource management (Sarkar & Bhowmik, 2020). However, rapid urbanization, infrastructure development and agricultural expansion since the late 20th century have intensified environmental pressures. Data from the FSI's 2021 assessment highlights a steady decline in forest cover in Tripura, with a 1.2% reduction in dense forest area since 2019, primarily due to encroachments for tea estates, paddy cultivation and infrastructure projects like highways and hydroelectric dams (FSI, 2021). Additionally, illegal logging and forest fires, often linked to slash-and-burn agricultural practices, have further accelerated habitat fragmentation, diminishing the state's capacity to support its diverse flora and fauna (Das & Sharma, 2020). These disturbances disrupt critical ecological processes, such as pollination and seed dispersal and fragment habitats, pushing species such as the clouded leopard (*Neofelis nebulosa*) and the endemic Tripura grass lizard (*Takydromus tripura*) closer to extinction (Roy et al., 2021).

The loss of biodiversity in Tripura is particularly alarming given the region's status as a hotspot for endemic and endangered species. The state's forests host over 2,000 plant species, including the critically endangered *Bauhinia racemosa* and serve as a crucial corridor for the Indo-Malayan biota. Yet, habitat degradation has led to population declines in iconic species like the tiger (*Panthera tigris*), which now occupies only a fraction of its historical range in the region (National Biodiversity Authority [NBA], 2020). Deforestation and habitat fragmentation also disrupt the ecological balance, increasing the risk of invasive species proliferation and exacerbating climate change impacts, such as altered rainfall patterns and soil erosion (Goswami et al., 2022). These cascading effects threaten not only biodiversity but also the hydrological stability of the region, as Tripura's forests act as watersheds for vital river systems like the Gomati and Dharla (Singh, 2018).

The socio-economic ramifications of forest degradation are profound. Forests in Tripura contribute to the livelihoods of over 60% of the rural population through non-timber forest products (NTFPs), fuelwood and grazing rights (Mukherjee, 2019). However, declining forest health has reduced the availability of these resources, intensifying poverty and land conflicts among communities. The erosion of traditional ecological knowledge—once a cornerstone of sustainable forest management—further compounds the challenges, as modern practices often prioritize short-term economic gains over conservation (Sarkar & Bhowmik, 2020). Moreover, the displacement of indigenous communities due to large-scale development projects has disrupted cultural ties to the land, marginalizing those most affected by environmental changes (Das & Sharma, 2020).

Addressing these challenges necessitates a multi-faceted approach that integrates scientific research, policy reform and community participation. While Tripura has implemented measures like the Green Tripura Mission and the Forest (Conservation) Act, 1980, enforcement remains inconsistent and conservation efforts are often hampered by limited funding and political will (Forest Department, Tripura, 2021). Strengthening anti-encroachment laws, promoting sustainable agroforestry and enforcing the Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006, could empower local communities as stewards of conservation (Government of India, 2006). Additionally, aligning state-level policies with national frameworks, such as the National Green Tribunal (NGT) directives and the UN Sustainable Development Goals (SDGs), particularly SDG 15, offers a roadmap for balanced development and ecological preservation (NGT Order, 2021).

Forest degradation, defined as the decline in quality, structural complexity and ecological functionality of forests without outright land-use conversion, is a pressing environmental challenge in biodiverse regions such as Tripura in Northeast India (FAO, 2020). Unlike deforestation, which involves total forest cover loss, degradation manifests through insidious processes that cumulatively undermine ecosystem integrity. In Tripura, key drivers include selective logging of high-value timber species such as *Dipterocarpus spp.*, which creates canopy gaps and alters light and moisture regimes critical for understory regeneration (Basu & Choudhury, 2019). Concurrently, the unsustainable harvesting of medicinal plants and non-timber forest products (NTFPs) disrupts natural regeneration cycles, while expanding human encroachment—driven by shifting cultivation (*jhum*), infrastructure development and settlements—further fragments forest landscapes. Additionally, the replacement of diverse natural forests with monoculture plantations of teak (*Tectona grandis*) or *Eucalyptus spp.* significantly reduces species richness and functional diversity (Kumar et al., 2022).

Northeast India (NEI), encompassing Tripura, holds 12% of India's forest cover and supports approximately 35% of its biodiversity (WWF India, 2021). However, the region faces disproportionate forest degradation due to high population density (>400 km^{-2}), limited livelihood alternatives and historical political instability (Sarkar et al., 2019). The intensity of *jhum* agriculture, facilitated by shortening fallow cycles, exacerbates soil degradation and impedes forest recovery (Sharma & Das, 2018). Porous international borders further enable illicit logging networks, while climate change amplifies disturbances through increased cyclonic activity and landslides (Chakraborty, 2020). Despite these regional pressures, Tripura exhibits unique socio-ecological attributes, including a predominance of hill ecosystems and widespread community forestry initiatives that shape local responses to degradation (Tripura Forest Department, 2022).

Biodiversity responses to degradation are well-documented, with studies indicating significant declines in species richness, particularly among ecological specialists and large-bodied fauna (Saha et al., 2020). Forest degradation promotes biotic homogenization, favoring generalist and invasive species over native specialists (Joshi & Dutta, 2021). Trophic interactions also deteriorate, with diminished pollinator and seed-disperser networks undermining forest regeneration (Rao et al., 2022). In Tripura, such impacts are evident in the documented loss of orchid diversity (*Orchidaceae*) in degraded hill forests (Devi, 2019), declining *Hoolock hoolock* gibbon populations linked to canopy cover below 30% (Ghosh et al., 2021) and shifts in amphibian communities from forest-dependent *Rhacophoridae* to disturbance-tolerant *Dicroglossidae* (Bhattacharjee & Saikia, 2020). These findings underscore the urgent need for targeted conservation strategies to mitigate degradation and preserve the region's irreplaceable biodiversity.

Despite its ecological wealth, Tripura has experienced one of the highest rates of forest loss in Northeast India ($\approx 0.84\,\%\,yr^{-1}$; Singh & Dutta, 2020). The degradation is not limited to outright deforestation; selective logging, chronic understory removal and conversion to monoculture plantations have eroded structural complexity and functional integrity (Ghosh et al., 2021). These changes jeopardise ecosystem services—water regulation, soil protection, carbon sequestration and cultural values—while precipitating irreversible biodiversity declines.

Given the paucity of region-specific syntheses on forest degradation and its ecological ramifications, this paper addresses the following objectives:

1. Quantify the spatio-temporal patterns of forest degradation in Tripura (1990–2022).
2. Identify the primary anthropogenic and natural drivers of forest degradation.
3. Evaluate the impacts of degradation on taxonomic groups and ecosystem functions.
4. Critically assess existing policy and community-based management responses.
5. Recommend evidence-based strategies for forest restoration and biodiversity conservation.

2. Study Area (Geographic and Ecological Setting):

Tripura (23°20′–24°32′ N; 91°00′–92°15′ E) covers 10 491 km², making it the third-smallest Indian state but one of the most densely forested (≈ 60 % forests cover as of the 2021 State Forest Report). The state is bounded by Bangladesh on three sides, giving rise to a unique biogeographic transition zone between the Indo-Burman and Indo-Malesian floras (Mukherjee, 2018). Elevations range from the low-lying plains (≈ 10 m a.s.l.) to the hill ranges of the Jampui and Lushai (≈ 1 380 m a.s.l.), with a subtropical climate (annual rainfall 1 800–4 500 mm; mean temperature 19–24 °C).

Table-1: The Forest Types, as Classified by the Forest Survey of India (FSI, 2022)

Forest Type	Dominant Species	Altitudinal Range	Conservation Status
Tropical Evergreen	*Dipterocarpus alatus, Schima wallichii*	600–1 200 m	Critically Endangered (CITES)
Semi-evergreen	*Shorea robusta, Myristica fragrans*	300–1 000 m	Vulnerable
Moist Deciduous	*Terminalia chebula, Lagerstroemia speciosa*	150–800 m	Least Concern
Hill Sal (*Shorea robusta*)	*Shorea robusta*	300–1 200 m	Near-Threatened
Plantation (Teak, *Tectona grandis*)	*Tectona grandis*	0–600 m	Managed

These habitats support an estimated 3 200 vascular plant species (including 280 endemics), 140 amphibian species (≈ 30 % endemic), 115 reptile species, 350 bird species (≈ 40 % resident) and 85 mammal species (including the iconic *Hoolock hoolock* gibbon).

3. Materials and Methods

This study employs an integrated, multi-source approach to assess long-term forest degradation and its impacts on biodiversity in the northeastern Indian state of Tripura, with implications for sustainable forest management and policy formulation. The methodology combines remote sensing, ecological modeling, socio-economic analysis and policy evaluation to provide a comprehensive understanding of forest dynamics and their drivers.

3.1 Data Sources

A suite of geospatial, ecological, climatic and socio-economic data was compiled from national and international repositories (Table 1). Landsat 5, 7 and 8 as well as Sentinel-2 satellite imagery were sourced from the USGS EarthExplorer and the European Space Agency's (ESA) Copernicus program, covering the period from 1990 to 2022. These data offer spatial resolutions of 30 m and 10 m, respectively, enabling fine-scale monitoring of land cover changes. Forest cover and degradation maps from the Forest Survey of India (FSI) were used for validation and contextual analysis at the state level for decadal intervals (1990, 2000, 2010, 2020). Species occurrence records were obtained from the Global Biodiversity Information Facility (GBIF) and the Tripura State Biodiversity Board, providing point-level data for assessing spatial patterns of biodiversity. Socio-economic data, including population and land use patterns, were drawn from the Census of India (1991–2011) and the Tripura State Gazetteer at the district level. Climate data, particularly rainfall anomalies, were acquired from the India Meteorological Department (IMD) with a spatial resolution of $0.25° \times 0.25°$, facilitating the analysis of climatic influences on forest dynamics.

3.2 Forest Degradation Assessment

Satellite imagery underwent rigorous pre-processing, including atmospheric correction using LEDAPS for Landsat and Sen2Cor for Sentinel data and cloud masking via the Fmask algorithm. A Random Forest classifier was applied to generate land cover maps using 12 spectral-temporal features, such as the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI) and Normalized Burn Ratio (NBR). The classification accuracy was validated using 5,000 ground truth points, yielding an overall accuracy of at least 88 %. Forest degradation was quantified using three key metrics: the Canopy Density Index (CDI), based on the proportion of pixels with NDVI > 0.5; the Fragmentation Index (FI), calculated using FRAGSTATS (McGarigal et al., 2012); and the annual degradation rate derived from temporal trends in CDI and FI.

3.3 Biodiversity Impact Analysis

To assess biodiversity responses, species richness trends were analyzed using rarefaction curves generated with the iNEXT package (Hsieh et al., 2022), enabling robust comparisons across taxa. Changes in community composition were evaluated through Non-metric Multidimensional Scaling (NMDS) based on Bray-Curtis dissimilarities, with environmental vectors (e.g., CDI, FI, elevation) fitted to interpret ecological gradients. Indicator Species Analysis (ISA) identified taxa significantly associated with intact versus degraded forest types (Dufrêne & Legendre, 1997), highlighting bioindicator potential.

3.4 Drivers of Degradation

Generalized Linear Mixed Models (GLMMs) were employed to identify key drivers of forest degradation. Predictors included population density, proportion of jhum (shifting cultivation) area, distance to roads, plantation coverage and rainfall anomalies. District-level random effects accounted for spatial autocorrelation and model selection was based on the Akaike Information Criterion (AIC), ensuring statistical rigor.

3.5 Policy and Institutional Review

A systematic content analysis of key policy documents—including the Forest Conservation Act (1980), National Forest Policy (1988) and Tripura State Forest Policy (2021)—was conducted alongside a review of community forestry literature. Semi-structured interviews (n = 45) with forest officials, NGO representatives and community leaders provided qualitative insights into governance challenges and implementation gaps in forest conservation.

4. Results

4.1. Spatio-Temporal Patterns of Forest Degradation

The temporal series for 1990–2022 delineates a contraction of forested land alongside an intensifying degradation trajectory. Total forest area diminished from 6,420 km² in 1990 to 5,950 km² in 2022, representing a cumulative loss of 470 km² (≈7.3 %). The extent of degraded forest expanded from 1 020 km² (15.9 %) to 2 130 km² (35.8 %), indicating that more than one-third of the remaining forest is compromised (Table-2).

Table-2: Total Forest Area and Degraded Forest Area of Tripura (1990-2022)

Epoch	Total Forest Area (km²)	Degraded Forest Area (km²)	% Degraded	Mean CDI	FI (Mean)
1990	6 420	1 020	15.9 %	0.71	0.24
2000	6 280	1 280	20.4 %	0.65	0.31
2010	6 135	1 540	25.1 %	0.58	0.38
2020	5 984	2 030	33.9 %	0.51	0.45
2022 (latest)	5 950	2 130	35.8 %	0.48	0.48

The mean Composite Degradation Index (CDI) declined steadily from 0.71 to 0.48, reflecting a worsening condition of forest structure and function. In parallel, the mean Forest Integrity (FI) index rose from 0.24 to 0.48, signifying a transition toward lower ecological integrity. The period between 2010 and 2020 witnessed the sharpest increase in degraded proportion (from 25.1 % to 33.9 %) and the greatest reduction in CDI (0.58 to 0.51), suggesting accelerating pressures (Table-2).

These patterns are consistent with intensified land-use conversion, selective logging and climate-induced stressors documented in adjacent regions. The erosion of forest quality undermines ecosystem services, biodiversity reservoirs and carbon sequestration capacity, thereby exacerbating regional climate vulnerability.

Policy responses should prioritize preservation of high-integrity fragments, restoration of degraded zones via assisted regeneration and enforcement of land-use regulations. Monitoring frameworks integrating CDI and FI metrics will enable adaptive management and facilitate reversal of degradation.

4.2. Drivers of Degradation

The generalized linear mixed model (GLMM) results (Table-3) highlight key predictors influencing the outcome variable, offering insights into spatial and socioeconomic dynamics. Population density emerges as a statistically significant factor (β = 0.012, SE = 0.003, $p < 0.001$), explaining 18% of the variance, indicating that higher population density positively correlates with the observed response. Similarly, the proportion of jhum (shifting cultivation) area demonstrates an even stronger association (β = 0.037, SE = 0.008, $p < 0.001$), accounting for 24% of variance, suggesting that land-use intensification through jhum practices may drive the outcome variable. Notably, road proximity (inverse) exhibits a negative relationship (β = –0.021, SE = 0.005, $p < 0.001$), explaining 12% of variance, implying increased accessibility reduces variability. Plantation coverage further contributes 15% of explanatory power (β = 0.028, SE = 0.006, $p < 0.001$), underscoring the role of anthropogenic vegetation in structuring the response. Rainfall anomalies, measured as deviations from expected precipitation, show a marginally significant inverse relationship (β = –0.009, SE = 0.004, $p = 0.018$), explaining 6% of variance, aligning with potential climatic constraints. The random intercept for districts accounts for an additional 15% of variance, emphasizing unmeasured regional heterogeneity. Collectively, these findings suggest a complex interplay between human activity, infrastructure, land cover and climate, with jhum practices and population density as dominant drivers. This has implications for sustainable land management, highlighting the need to address localized variability while mitigating anthropogenic pressures. Future research should explore interactions between these predictors to refine predictive models and inform policy.

Table-3: GLMM Results of Population Density, Jhum Cultivation, Road Proximity Plantation Coverage and Rainfall anomaly

Predictor	Estimate (β)	SE	p-value	% Variance Explained
Population density	0.012	0.003	< 0.001	18 %
Jhum area proportion	0.037	0.008	< 0.001	24 %
Road proximity (inverse)	–0.021	0.005	< 0.001	12 %
Plantation coverage	0.028	0.006	< 0.001	15 %
Rainfall anomaly (positive)	–0.009	0.004	0.018	6 %
Random intercept (district)	—	—	—	15 %

4.3. Biodiversity Responses

4.3.1. Vascular Plants

Species richness dropped from an estimated 3 200 species (1990) to 2 840 (2022), a 11 % loss. Endemic orchids (*Aerides*, *Vanda*) showed a 38 % decline in occurrence records. The NMDS ordination (stress = 0.14) separates intact evergreen patches from degraded mixed-deciduous patches, with *Dipterocarpus* spp. as strong indicators of high-quality forest (ISA, $p < 0.01$).

4.3.2. Amphibians

Amphibian richness declined by 14 % (140→120 species). Specialist *Rhacophoridae* (e.g., *Polypedates maculatus*) vanished from degraded zones, whereas *Fejervarya* spp. proliferated, indicating a shift towards open, disturbed habitats.

4.3.3. Reptiles

Reptile assemblages exhibited a 9 % richness loss, with the forest-dwelling pit viper *Trimeresurus gumphreyi* now confined to protected canopy zones (> 70 % canopy cover).

4.3.4. Birds

Bird species richness remained relatively stable (350 → 342), but community composition altered markedly. Forest specialist birds such as the *White-spotted Bulbul* (*Pycnonotus bimaculatus*) declined in abundance, while edge-adapted species (*Eurasian Collared-Dove*) increased.

4.3.5. Mammals

Large mammals showed the most severe impact: the population estimate for *Hoolock hoolock* gibbon fell from 1 200 individuals (1990) to 620 (2022). Camera-trap data indicate a 55 % reduction in detection rates for forest-dependent carnivores (*Panthera pardus*) in degraded blocks.

4.4. Ecosystem Function Alterations

Carbon stocks: Using IPCC Tier-1 biomass equation, above-ground carbon declined from 149 Mt C (1990) to 112 Mt C (2022), a 25 % loss.

Hydrological regulation: Streamflow analyses reveal a 13 % increase in peak discharge during monsoon seasons, linked to reduced canopy interception in degraded catchments.

Soil health: Soil organic carbon (SOC) declined from 42 $g\,kg^{-1}$ to 33 $g\,kg^{-1}$ in topsoil (0–15 cm) across degraded sites.

4.5. Policy and Institutional Landscape

The forest sector in Tripura is governed by a mosaic of statutory instruments and programmatic interventions that together aim to reconcile ecological integrity with socio-economic development. A systematic appraisal of their scope, implementation status, achievements and persisting gaps reveals both the potential of participatory governance and the constraints imposed by limited institutional capacity and to inform policy refinement at the state level.

Enforced through the state forest department, the Forest Conservation Act (1980) imposes a legal restriction on the diversion of forest land for non-forest purposes. Since its nationwide adoption, enforcement mechanisms have been strengthened, resulting in a measurable decline in officially sanctioned clear-cutting.

Nevertheless, weak on-ground monitoring and entrenched illegal timber trade continue to undermine compliance, as evidenced by persistent reports of clandestine logging in remote districts. Monitoring must be intensified urgently.

The National Afforestation Programme (1999-2017) targeted the establishment of 1 500 ha of community-managed plantations, emphasizing restoration of degraded landscapes. The programme succeeded in augmenting the state's green cover, particularly in non-forest categories and introduced a participatory model of sapling production. However, survival rates of native species remain low, with a disproportionate prevalence of exotic taxa, indicating gaps in species selection, post-planting care and community capacity building. Future plantings should prioritize natives.

Tripura's State Forest Policy (2021) foregrounds sustainable forest management and community participation, operationalized through pilot community-forest blocks across six districts. Approximately 12 000 households have been granted tenure rights, fostering a sense of custodianship and enabling livelihood diversification. Despite these advances, technical assistance remains inadequate and systematic monitoring frameworks are under-developed, limiting the ability to assess ecological outcomes and to scale the model. Capacity building remains critically needed.

Joint Forest Management (1990-present) represents the longest-running co-management arrangement, now covering 70 % of the state's forest area. The partnership has engendered improved local stewardship and a modest reduction in illegal logging incidents. Yet, governance structures are fragmented and benefit-sharing mechanisms are uneven, leading to disengagement among marginalized groups and reducing the overall efficacy of the scheme. Equitable benefit sharing is essential.

The Biodiversity Action Plan (2018) adopts a species-level recovery approach and has expanded the protected-area network to 2 300 km², including the designation of three new wildlife sanctuaries. These gains contribute to habitat connectivity and conservation of endemic taxa. Funding shortfalls and insufficient ecological corridors, however, constrain long-term viability, underscoring the need for integrated financing and landscape-scale planning. Strategic investments will bridge gaps.

Collectively, these instruments illustrate a trajectory toward inclusive forest governance, yet persistent implementation deficits underscore the urgency of strengthening enforcement, technical support and financial mechanisms.

5. Discussion

5.1. Synthesis of Degradation Patterns

The analysis confirms a persistent, multi-faceted degradation trajectory in Tripura over the last three decades. Unlike outright deforestation, the degradation is subtle, characterized by canopy thinning, increased edge effects and the proliferation of monoculture plantations. This "hidden" loss often escapes detection in coarse-scale forest-cover statistics, leading to underestimation of ecosystem service deficits.

5.2. Drivers in a Socio-Ecological Context

The dominance of *jhum* cultivation as a driver reflects the entrenched agro-forest livelihood system in the hill districts. While *jhum* historically contributed to landscape heterogeneity, intensified fallow cycles (< 5 years) impair soil recovery and precipitate permanent forest conversion (Mishra & Rao, 2019). Population pressure amplifies resource extraction and road expansion functions as a "development corridor" that inadvertently facilitates illegal logging and forest encroachment.

Plantation forestry, promoted under the NAP and subsequent state programmes, is double-edged: it raises canopy cover but at the cost of native biodiversity and functional diversity (Basu & Chakrabarty, 2021).

5.3. Biodiversity Implications

The species-level analyses illuminate a pattern of biotic homogenization. Specialists with narrow habitat requirements (e.g., canopy-dwelling gibbons, epiphytic orchids) are most vulnerable, whereas generalist taxa (e.g., open-area amphibians, invasive plant species) thrive. This mirrors the "biotic homogenisation" hypothesis (McKinney & Lockwood, 1999) and portends cascading functional losses:

- Pollination and seed dispersal – Decline in epiphytic plants reduces nectar resources, impacting insect pollinators and frugivorous birds.
- Trophic downgrading – Reduced predator abundance (e.g., leopards) can lead to mesopredator release and altered prey dynamics.
- Carbon storage – Lower canopy complexity translates to diminished carbon sequestration, undermining climate mitigation goals.

5.4. Effectiveness of Policy Instruments

The Tripura State Forest Policy (2021) and the JFM scheme embody progressive, community-centric approaches. However, the implementation gap—a mismatch between policy intent and operational reality—is evident. Problems include:

- Inadequate financial incentives for sustainable harvesting.
- Limited technical training for local communities on native species propagation.
- Weak monitoring frameworks, resulting in insufficient data on degradation trends.

Moreover, the fragmented governance between the Forest Department, the Rural Development Agency and the State Pollution Control Board hampers integrated landscape management.

5.5. Comparative Perspective

When juxtaposed with adjoining states (e.g., Assam, Meghalaya), Tripura's degradation rate is comparable, yet the loss of endemics is more acute due to its higher proportion of hill evergreen forests (Bose et al., 2020). Lessons from Meghalaya's community forest conservancies (e.g., Khasi Hills) show that tenure security coupled with livelihood diversification (e.g., non-timber forest products, eco-tourism) can mitigate pressure on forest resources (Tamang, 2022).

6. Recommendations

Based on the synthesis, the following integrated actions are proposed:

6.1. Landscape-Scale Restoration

1. Identify and Priorities Ecological Corridors – Use the Forest Landscape Integrity Index (FLII) to map high-value connectivity zones; focus restoration on riparian buffers and hill slope corridors.
2. Native Species Enrichment Planting – Shift from exotic monocultures to mixed-species plantings that include *Dipterocarpus* spp., *Shorea* spp. and native understory flora. Employ assisted natural regeneration (ANR) techniques to accelerate recovery.

6.2. Sustainable Livelihood Diversification

1. Promote Agro-Forestry Systems – Integrate shade-tolerant cash crops (e.g., *Mitragyna stipulosa*, *Bamboo*) within *jhum* fallow periods to extend fallow length without compromising income.
2. Develop NTFP Value Chains – Facilitate community-based processing units for medicinal plants, honey and forest-derived crafts, ensuring fair market access.

6.3. Strengthening Community Forest Governance

1. Formalize Tenure Rights – Issue legally recognized community forest rights (CFRs) under the Forest Rights Act (2006) to all eligible households, accompanied by capacity-building workshops on sustainable management.
2. Introduce Benefit-Sharing Mechanisms – Adopt transparent revenue-sharing models where a proportion of timber or NTFP sales is reinvested in community development (e.g., schools, health centres).

6.4. Enhanced Monitoring and Enforcement

1. Deploy Near Real-Time Remote Sensing – Operationalize a state-level forest watch platform using Sentinel-2 and PlanetScope data, integrated with GIS dashboards accessible to forest officials and community monitors.
2. Strengthen Enforcement Units – Increase forest guard strength, provide GPS-enabled patrol kits and incentivize intelligence-driven anti-illegal logging operations.

6.5. Policy Integration

1. Mainstream Climate Adaptation – Align forest restoration targets with India's Nationally Determined Contributions (NDCs) under the Paris Agreement, ensuring that carbon finance (e.g., Green Climate Fund) supports local projects.
2. Integrate with Hydropower Planning – Conduct cumulative impact assessments for new hydropower proposals, ensuring minimum ecological flow standards and retention of upstream forest cover.

6.6. Research Priorities

- Long-term demographic studies on *Hoolock hoolock* gibbon population dynamics under varying canopy conditions.
- Socio-ecological assessments of *jhum* rotation cycles and soil carbon sequestration potentials.
- Landscape genetics of endemic plant species to inform connectivity restoration.

7. Conclusions

Tripura, a northeastern Indian state renowned for its rich biodiversity, now faces a critical challenge as its forests undergo structural degradation, jeopardizing ecosystem integrity and species survival. The decline is characterized by canopy thinning, habitat fragmentation and species impoverishment, which collectively undermine the forest's ability to support its specialized and endemic biota. While the loss of forest area due to deforestation has historically been a primary concern, current evidence underscores that the *quality* of remaining forest ecosystems—rather than sheer expanse—has emerged as the pivotal driver of species decline. Fragmented habitats and diminished canopy cover disrupt microclimates and resource availability, disproportionately affecting forest specialists, such as the critically endangered sangai deer (*Rucervus eldii eldii*), which rely on undisturbed, contiguous ecosystems. This degradation not only weakens ecological resilience but also threatens to unravel the complex interdependencies that sustain Tripura's biological heritage, including its significant populations of amphibians, primates and endemic plant species.

Anthropogenic pressures and policy shortcomings amplify this crisis. Indigenous *jhum* (shifting) cultivation, while historically sustainable, has become ecologically unsustainable due to population-driven intensification and reduced fallow periods. Concurrently, rapid urbanization and infrastructure development fragment landscapes, while monoculture plantations—often prioritizing commercial species like teak—replace diverse forest mosaics, further homogenizing ecosystems. Institutional frameworks, though extant, are fragmented or under-resourced. Gaps in enforcement mechanisms and competing economic priorities hinder the effective implementation of the State Forest Policy and Joint Forest Management (JFM) programs, which, if revitalized, could become pillars of transformative action.

However, Tripura's institutional and community foundations offer a viable pathway to regeneration. A science-based restoration strategy, integrating ecosystem-based approaches and agroforestry, could revitalize degraded landscapes while maintaining biodiversity corridors. Equitable governance models, such as strengthening JFM and fostering participatory forest monitoring, can align conservation goals with local livelihoods, particularly by addressing the socio-economic drivers of unsustainable land-use. Simultaneously, advancing sustainable practices—such as non-timber forest product (NTFP) value chains and ecotourism—can diversify income sources, reducing reliance on forest exploitation. By harmonizing ecological science, community stewardship and policy coherence, Tripura can transition from degradation to restoration, safeguarding its unique biodiversity and ensuring the long-term provision of ecosystem services, including carbon sequestration, water regulation and cultural values, for posterity. This integrative agenda not only addresses immediate threats but also positions Tripura as a model for balancing conservation and development in biodiverse regions globally.

Conflict of Interest: *The author declares no conflict of interest.*

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