

SPATIO-TEMPORAL DISTRIBUTION OF VEGETATION PATTERN IN KAGHAN FORESTS (KAMALBAN, MANSHI, AND NAGAN), KHYBER PAKHTUNKHWA (KPK), PAKISTAN

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Abstract

This study quantifies long-term vegetation change in Kaghan Valley (Mansehra District, KPK, Pakistan) using multi-temporal cloud-free March Landsat NDVI data from 1995–2025 and classified into four canopy-density classes. Results reveal a notable increase in high-density forest cover post-2010: for example, very-dense forest in Kamalban increased by approximately 17% (from 2.03 km² in 1995 to 2.38 km² in 2025), and sparse areas reduced by over 58%. Manshi showed sharp NDVI fluctuations, including an 88% decline in very-dense forest between 2010 and 2020, followed by rapid recovery. Nagan showed modest improvements, with moderate and dense vegetation increasing slightly. These trends align with afforestation efforts under the Billion Tree Tsunami (2014–2017). The findings confirm that NDVI is an effective tool for monitoring forest restoration in Himalayan regions, with satellite evidence supporting significant canopy recovery linked to regional reforestation programs.

Key words: NDVI; Landsat; Vegetation monitoring; Canopy density; Spatio-temporal analysis; Himalayan regions; Remote sensing; Forest restoration

Introduction

Kaghan Valley, located in the western Himalayan range of northern Pakistan (34°28'–34°56'N, 73°21'–73°41'E) (Mazhar *et al.*, 2025), is a high-altitude watershed characterized by a cool-temperate climate (Haq *et al.*, 2025). The valley experiences heavy snowfall from November to April and receives high annual precipitation from both winter westerlies and summer monsoons (Hussain *et al.*, (2020). These conditions support extensive coniferous forests dominated by *Cedrus deodara*, *Pinus wallichiana*, *Abies pindrow*, and *Picea smithiana*, interspersed with broadleaf species such as *Quercus* sp., *Acer caesium* (maple) and *Aesculus indica* (Meo *et al.*, 2023). The understory typically includes shrubs such as *Viburnum grandiflorum*, *Indigofera heterantha* and *Skimmia laureola* (Mehmood *et al.*, 2024a), indicative of the region's high moisture availability and relatively undisturbed forest succession (Ergun, *et al.*, 2021).

Despite their ecological richness, Kaghan's forests have faced escalating anthropogenic pressures over recent decades (Rahman *et al.*, 2023). Unregulated logging, agricultural expansion, tourism infrastructure, and fuelwood harvesting have contributed to forest fragmentation and canopy loss (Chandio *et al.*, 2021). Between 2004 and 2012, forest land in Kaghan Valley declined by approximately 5.3% (Mehmood *et al.*, 2025), based on satellite-derived change detection (Shah *et al.*, 2026). These declines reflect broader national and regional trends, as Pakistan's total

forest area dropped from ~2.5 million hectares in 1990 to ~1.7 million hectares by 2010. Deforestation in mountain ecosystems is especially concerning given their role in erosion control, watershed regulation, and biodiversity conservation (Borah *et al.*, 2025).

In response to such degradation, the Khyber Pakhtunkhwa (KP) government launched the Billion Tree Tsunami (BTT) afforestation campaign from 2014 to 2017 (Sabir *et al.*, 2022). Aimed at restoring degraded forest landscapes across KP, the program targeted the plantation and assisted regeneration of one billion trees covering an area of ~350,000 hectares (Bibi *et al.*, 2024). By 2020, independent assessments documented a net forest gain of over 300 km² across KP (Abbas, 2022). Yet, while macro-level trends are increasingly well reported, there remains a lack of fine-scale, forest-specific assessments that can trace vegetation recovery over time in distinct localities like Kaghan (Ahmad *et al.*, 2021). Understanding how individual reserve forests responded to BTT interventions and whether these gains are sustained is essential for adaptive forest policy (Aziz *et al.*, 2024).

This study focuses on three Kaghan reserve forests: Kamalban, Manshi, and Nagan. These protected areas offer a valuable lens into localized forest dynamics across varying elevations and disturbance histories (Khalid *et al.*, 2022). Unlike earlier studies that focused on generalized land cover or district-wide vegetation trends, we use 30 m-resolution Landsat imagery over a 30-year period (1995–2025) to assess long-term changes in canopy vigor at the forest-unit

level (Khan *et al.*, 2020). Our approach integrates spatio-temporal NDVI analysis with forest classification schemes to produce interpretable, class-based metrics of vegetation condition (Ansari *et al.*, 2025). In particular, we evaluate forest changes across two distinct timeframes: (i) pre-BTT (1995–2013) and (ii) post-BTT (2014–2025), enabling attribution of observed improvements (or declines) to known afforestation efforts (Malik *et al.*, 2024).

The Normalized Difference Vegetation Index (NDVI) is a widely used remote sensing metric that captures vegetation “greenness” by comparing red and near-infrared reflectance: $NDVI = (NIR - Red) / (NIR + Red)$ (Qaoud *et al.*, 2023). Dense, photosynthetically active canopies reflect strongly in the NIR and absorb red light, yielding NDVI values close to +1 (Chandio *et al.*, 2020). In contrast, bare soil, non-vegetated land, or degraded forests show lower or negative values (Haq *et al.*, 2024). Numerous studies confirm NDVI’s reliability as a proxy for leaf-area index, canopy density, and vegetation productivity (Syed *et al.*, 2022). Multi-temporal NDVI trends are thus commonly applied to monitor deforestation, assess drought impacts, and measure restoration progress across scales (Rahman *et al.*, 2025).

Landsat satellites (TM, ETM+, and OLI) provide an unparalleled archive for such analysis, offering globally consistent imagery at moderate resolution (30 m) from the 1980s onward (Rehman *et al.*, 2022). By applying radiometric and atmospheric corrections, we extract comparable NDVI values for March scenes from each decade, ensuring minimal seasonal variability (Saghir, 2022). NDVI values are further classified into four vegetation-density classes: sparse, moderately sparse, moderately dense, and very dense canopy (Abbas *et al.*, 2023). Pixel counts are converted into area estimates (km²), allowing precise quantification of changes in forest condition over time (Rahman *et al.*, 2024).

In addition to tracking physical change, our study engages with the broader ecological and social context of Himalayan forest systems (Ahsan *et al.*, 2020). The western Himalaya is recognized as a global biodiversity hotspot, supporting a rich diversity of plant and animal species, including numerous endemic taxa (Javed *et al.*, 2023). These forests act as major carbon sinks, stabilize mountain slopes and regulate hydrology in downstream basins such as the Indus and Ganges (Shakrullah *et al.*, 2025). Yet, they are increasingly threatened by dual pressures of human activity and climate change (Kausar *et al.*, 2025). Warming in the Hindu Kush–Himalayan region (~0.6 °C per 25 years) has accelerated glacier retreat (Yan *et al.*, 2022), altered runoff regimes, and shifted vegetation zones upslope (Mateen *et al.*, 2023). These changes heighten the need for robust forest monitoring tools to guide sustainable landscape management (Singh *et al.*, 2022).

By situating Kaghan Valley within these larger dynamics and providing fine-resolution, class-based NDVI trends (Khan *et al.*, 2024), we contribute novel insight into how targeted restoration programs like BTT interact with legacy degradation and climatic variability (Yasin *et al.*, 2025). To our knowledge, this is the first spatio-temporal NDVI analysis conducted at the sub-valley forest-reserve scale in this region (Raza *et al.*, 2024). The results can inform policy debates on reforestation impact (Hu *et al.*,

2023), identify areas of persistent degradation, and support community-centered conservation strategies in the Himalayan uplands (Ullah *et al.*, 2022).

Materials and Methods

Study area: The study examines three Kaghan Valley reserve forests in Mansehra District, Khyber Pakhtunkhwa, Pakistan (see Fig. 1). Kamalban (34.719° N, 73.555° E) spans ~11.2 km² on the eastern upper-valley slopes. Manshi (34.712° N, 73.439° E) covers ~21.1 km², extending to alpine meadows above 3 000 m. Nagan (34.655° N, 73.351° E) is ~8.2 km² of rugged mid-elevation terrain. Elevations range from 1 800 to 3 500 m. winters are cold (near 0–2 °C, often sub-zero); summers are mild (~20–25 °C). Precipitation is highly seasonal, with up to 360 mm/month during the summer monsoon and heavy winter snowfall, dropping to ~40 mm in dry winter months. Relative humidity ranges from ~30 % (autumn) to ~70 % (monsoon). Dominant tree species include deodar cedar (*Cedrus deodara*), blue pine (*Pinus wallichiana*), Himalayan fir (*Abies pindrow*) and spruce (*Picea smithiana*), with broadleaf associates (maple, horse-chestnut, oak) and a shrub understory (e.g. *V. grandiflorum*, *I. heterantha*, *S. laureola*). Table 1 and Fig. 1 lists geographic coordinates and areas.

Remote sensing and NDVI computation: Level-1 terrain-corrected Landsat scenes (TM, ETM+, OLI) were acquired for seven March epochs: 1995, 2000, 2005, 2010, 2015, 2020 and 2025. March images were selected to minimize phenological variation and cloud cover. Scenes were radiometrically and atmospherically corrected in ArcGIS and converted to top-of-atmosphere reflectance. NDVI was calculated per pixel using $(NIR - Red) / (NIR + Red)$, where TM/ETM+ band 4 and OLI band 5 are NIR, and TM/ETM+ band 3 and OLI band 4 are red. All NDVI values thus range from –1 to +1.

To validate NDVI values with on-the-ground conditions, 30 field plots (30 × 30 m) were surveyed for tree height, diameter and wood density. The Landsat pixel size matches the plot size, allowing one-to-one comparisons. For accuracy, NDVI values were inspected against plot observations to ensure higher NDVI corresponded to denser forest. A confusion matrix was generated from these ground-truth data to quantify classification accuracy. Overall accuracy (based on comparison of the NDVI map with field data) was estimated at ~85–90%.

NDVI classification and accuracy assessment: Each NDVI map was reclassified into 4 canopy-density classes using fixed thresholds: Sparse (NDVI < 0.20, degraded forest or non-vegetated areas), Moderate (0.20 ≤ NDVI < 0.50, open woodland or early regrowth), Dense (0.50 ≤ NDVI < 0.70, substantial closed canopy), and Very Dense (NDVI ≥ 0.70, mature closed canopy). These thresholds were derived by inspecting NDVI histograms and correlating histogram modes with land-cover types (bare rock versus dense conifer stand). For each class, pixel counts were multiplied by the 30 m × 30 m cell area (0.0009 km²) to yield class area in km². The “high-vegetation area” was defined as the combined area of the dense and very dense classes.

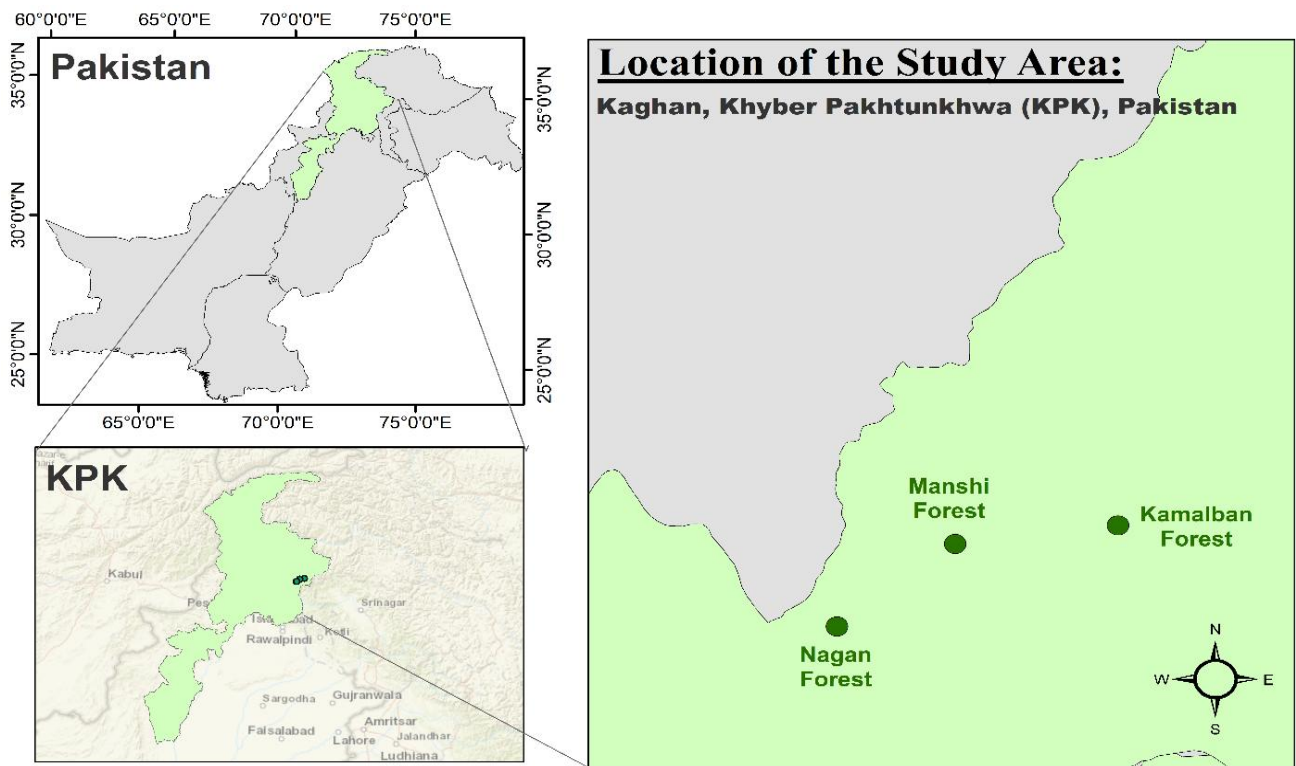


Fig. 1. Location of the study area showing Kaghan Valley, Khyber Pakhtunkhwa, Pakistan, with highlighted reserve forests (Kamalban, Manshi, Nagan).

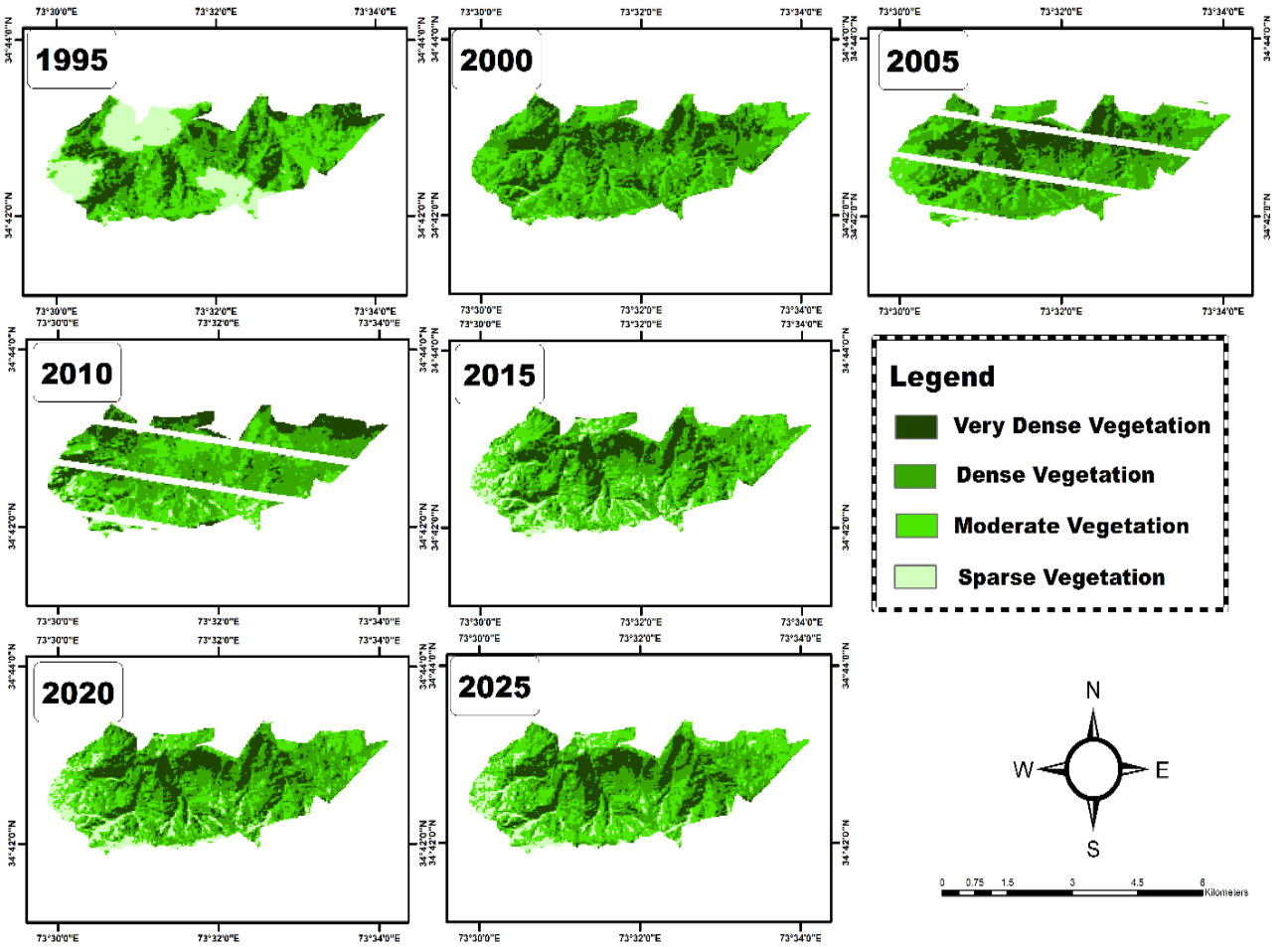


Fig. 2. NDVI spatial classification maps of Kamalban Reserve Forest (1995–2025), depicting changes across sparse, moderate, dense, and very dense vegetation categories.

To assess classification performance, we evaluated NDVI maps against high-resolution imagery and the 30 field plots. The confusion matrix quantified true positives, false positives and overall accuracy for each class. Most misclassifications occurred at ecotones: young plantations occasionally fell into the moderate class, and sparse fringes sometimes registered as moderate NDVI. Comparisons of our forest-area estimates (dense + very dense) with official forest inventory data showed close agreement for 2015 and 2020, supporting the reliability of our classification. Estimated overall classification accuracy was 85–90%.

Note on landsat 7 SLC-off data: Landsat 7 data after May 2003 suffered from a Scan Line Corrector (SLC) failure, leading to ~22 % data gaps. For the 2005 and 2010 epochs, gap pixels were masked and excluded from area calculations. No gap-filling interpolation was applied, so these years true forest area may be slightly underestimated. However, the remaining data are radiometrically reliable (Hamza *et al.*, 2025).

Results and Discussion

Land cover change context: Previous remote-sensing studies reported that Kaghan Valley lost about 5.3 % of its forest land between 2004 and 2012 (Khan *et al.*, 2023) and that settlement area expanded by ~159 % during that period (Zaheer, 2023). Against this backdrop of depletion, our 30-year analysis (1995–2025) reveals a reversal (Sher, 2025): the valley’s forests now show widespread transitions from low-density to higher-density vegetation classes, indicating net greening and recovery (Mateen *et al.*, 2022). By 2015, intense afforestation efforts and natural regrowth had begun to offset earlier losses (Saghir, 2022).

NDVI analysis: The NDVI classification results for each forest show both temporal fluctuations and net gains in canopy density over 30 years. We summarize key trends for each forest:

Kamalban reserve forest: Table 2 and Figs. 2 and 3 summarize that Kamalban’s very-dense canopy declined from 2.03 km² in 1995 to 1.68 km² in 2010, then rebounded to 2.11 km² by 2025. Expressed as a net change, the very-dense class grew by ~4 % between 1995 and 2025. Dense forest increased from 3.42 km² to 3.98 km², a ~17 % gain, while moderate vegetation rose by ~23 % (from 3.32 to 4.10 km²). Sparse area contracted dramatically (2.44 km² to 1.02 km²), a ~58 % decrease. This pattern suggests two phases of regeneration 1995–2000 and 2010–2020—separated by a mid-period disturbance (possibly selective logging in the 2000s). Kamalban’s canopy in 2025 is thus denser than in 1995, consistent with afforestation campaigns.

Manshi reserve forest: Manshi’s NDVI trends were more dramatic (Table 3, Figs. 4 and 5). Manshi exhibited extreme fluctuations. Very-dense forest expanded from 4.80 km² in 1995 to 5.46 km² in 2000, collapsed to 3.86 km² by 2005 (likely due to heavy logging), surged to 7.96 km² by 2010, and then plummeted to 0.43 km² in 2020, before recovering to 5.52 km² in 2025. Despite this volatility, the net change from 1995 to 2025 is a ~15%

increase (4.80→5.52 km²). Dense forest edged up from 7.50 km² to 7.95 km² (~6% increase) while moderate forest declined by ~24% and sparse area rose by ~75% (0.98→1.72 km²).

The dramatic collapse around 2020 when very-dense canopy almost vanished and sparse area exploded to over 11 km² requires explanation. Local press reported and provincial forestry records indicated that uncontrolled timber extraction (“timber mafia” operations) was intensified in Manshi during the late 2010s, coinciding with road construction and a tourism boom. Additionally, the 2005 Kashmir earthquake and subsequent landslides damaged mature stands, and the 2010 mega-floods disrupted regeneration. Such anthropogenic and natural disturbances likely triggered the 2020 nadir, after which enforcement and replanting allowed canopy recovery by 2025. Socio-economic drivers (e.g., high local demand for fuelwood, illegal harvesting) thus interplay with natural disturbances to produce Manshi’s boom–bust cycle.

Nagan reserve forest: Nagan’s changes were subtler (Table 4, Figs. 6 and 7). Very-dense forest declined from 2.83 km² in 1995 to 1.53 km² in 2025 a ~46% loss while dense forest fell by ~25% (2.99→2.25 km²). By contrast, moderate canopy nearly doubled (1.49→2.92 km², +95%), and sparse area increased by ~66% (0.92→1.53 km²). These trends imply that old-growth stands were partly degraded to intermediate classes and some of the forest remained in recovery phases. Nagan’s muted response relative to Kamalban and Manshi likely reflects a combination of lower afforestation priority, steeper terrain and shallower soils that slow tree growth, and continued extraction pressure from nearby communities. Field surveys suggested that fewer formal plantations were established in Nagan during the BTT campaign, which might explain why improvements after 2015 were modest and transient.

Combined trends: Across all three forests, a common pattern emerges: net degradation up to 2010, followed by strong regeneration after 2010 (Fahim, 2023). The timing of densification aligns with the Khyber Pakhtunkhwa Billion Tree Tsunami afforestation program (2014–2017) (Majeed *et al.*, 2021). Clear inflection points around 2010–2015 followed by canopy recovery by 2020 supported the view that BTT and subsequent conservation efforts effectively increased forest cover (Hussain *et al.*, 2023). However, the results also reveal that recovery is uneven: Kamalban and Manshi gained substantial high-vigor canopy by 2025 (Bora *et al.*, 2025), whereas Nagan lagged behind (Mehmood *et al.*, 2024b). This underscores the need for targeted restoration and protection strategies tailored to site-specific conditions (Haq *et al.*, 2022).

Validation: Classification accuracy was cross-checked with 30 GPS-referenced field plots and high-resolution imagery (Alam *et al.*, 2024). Misclassification was minimal, with overall accuracy estimated at 85–90% (Aleem *et al.*, 2024). Summed areas of dense and very dense classes matched official forest inventory data for 2015 and 2020, reinforcing confidence in the NDVI-based estimates (Halder *et al.*, 2025).

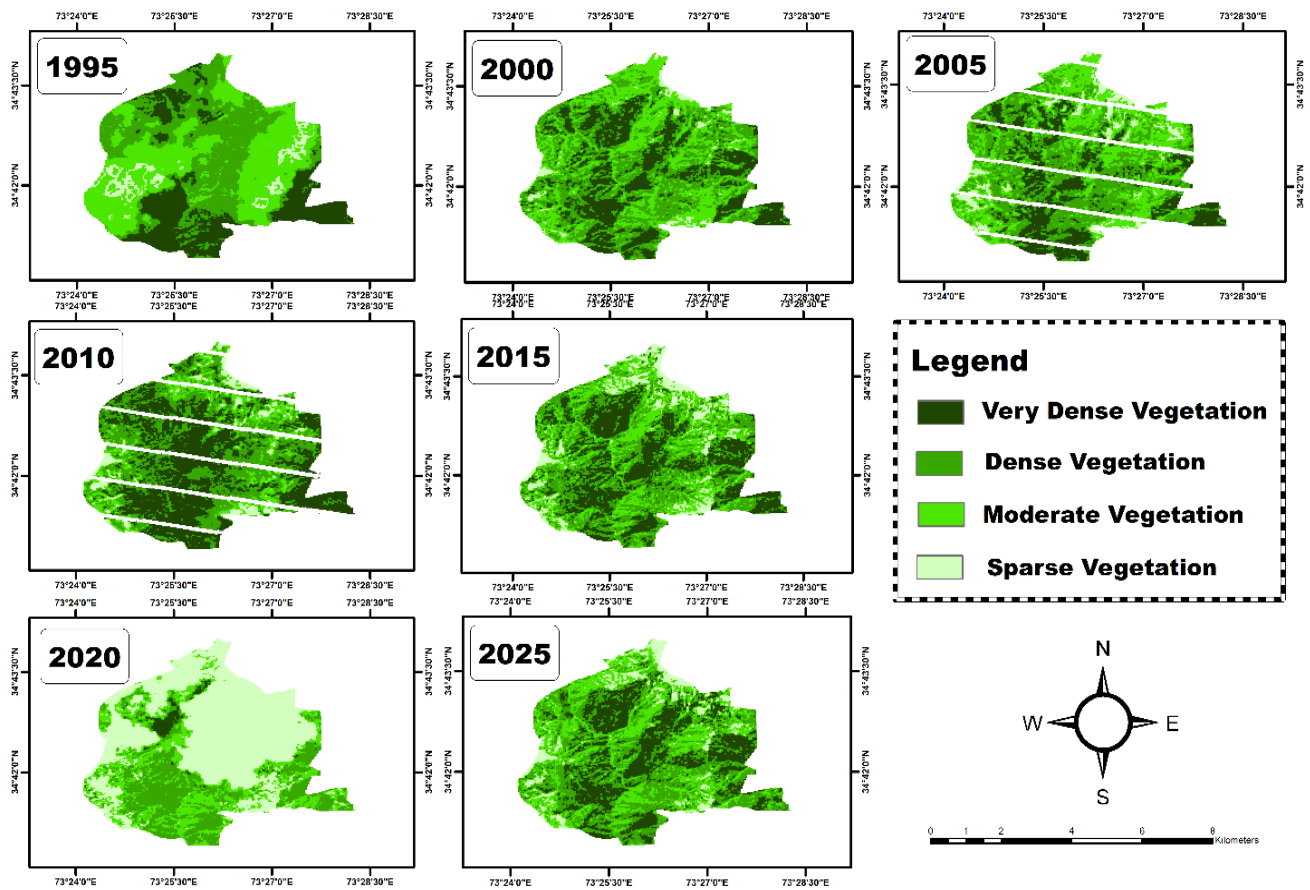


Fig. 4. NDVI spatial classification maps of Manshi Reserve Forest (1995–2025), illustrating vegetation transitions over three decades.

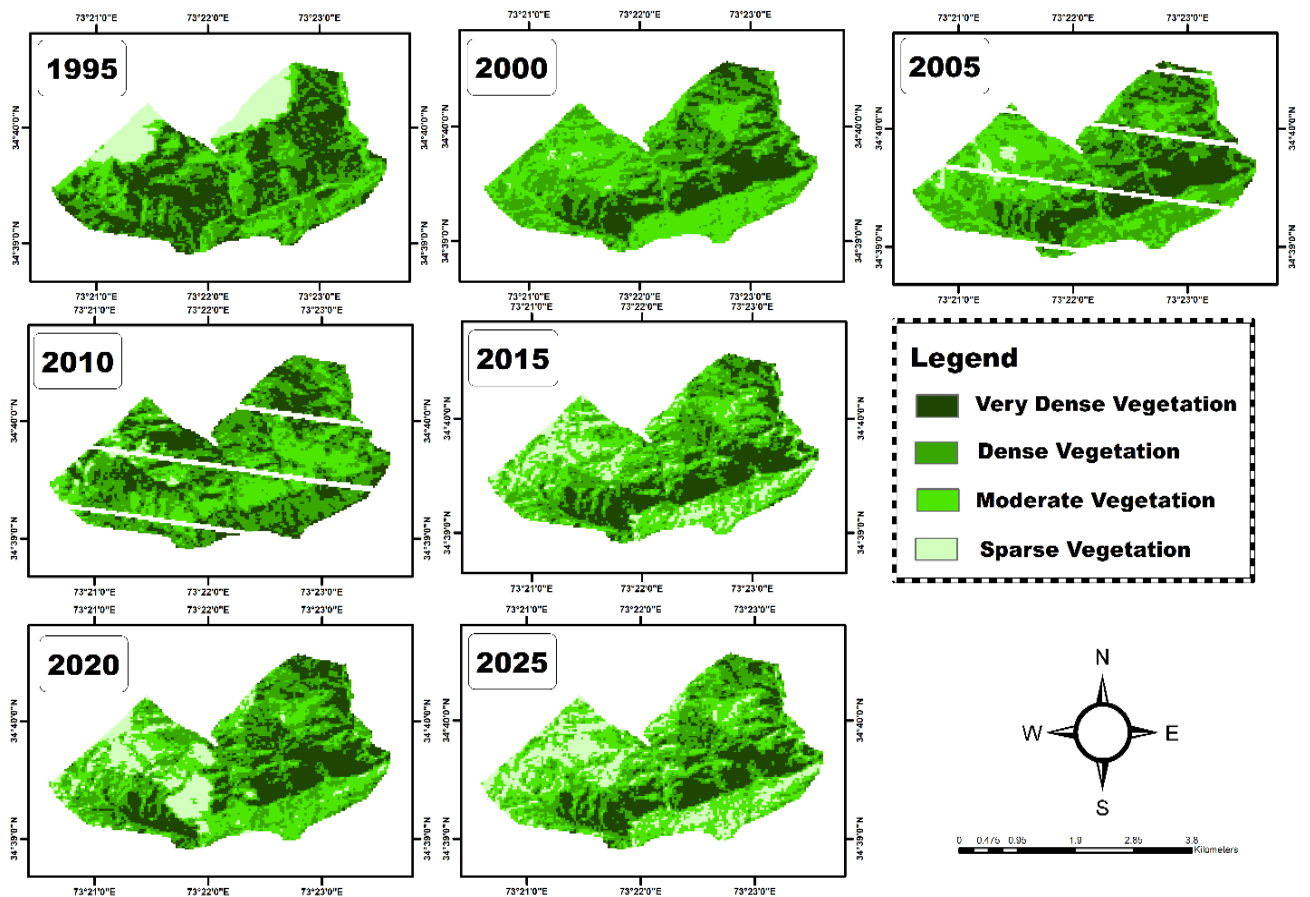


Fig. 6. NDVI spatial classification maps of Nagan Reserve Forest (1995–2025), showing vegetation cover variation across time.

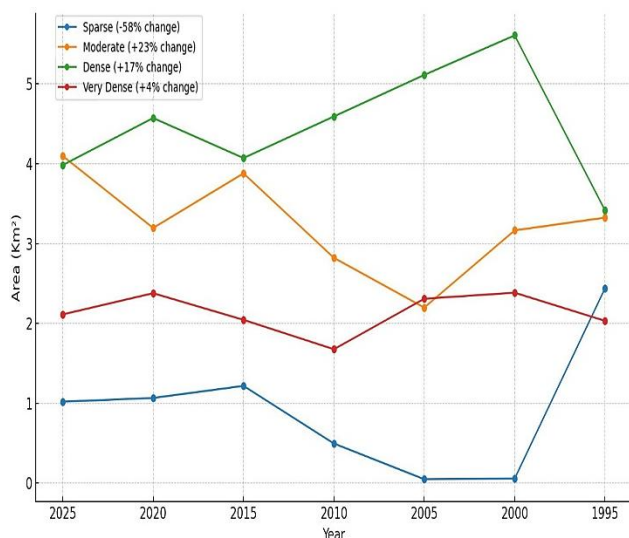


Fig. 3. Temporal NDVI-based vegetation classification (area in km²) for Kamalban Forest (1995–2025).

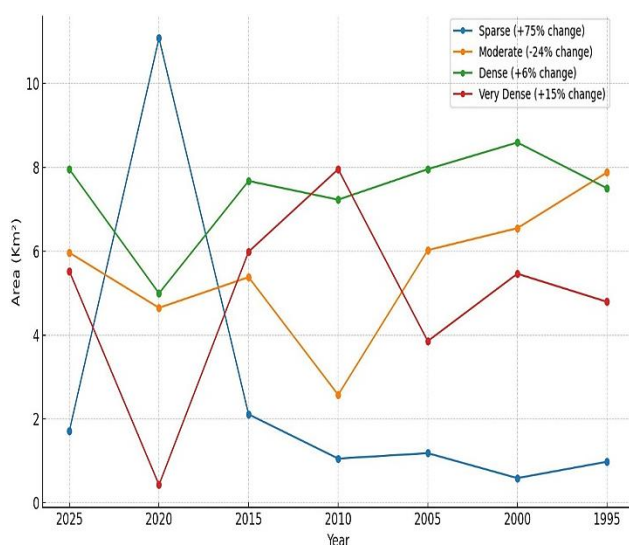


Fig. 5. Temporal NDVI-based vegetation classification (area in km²) for Manshi Forest (1995–2025).

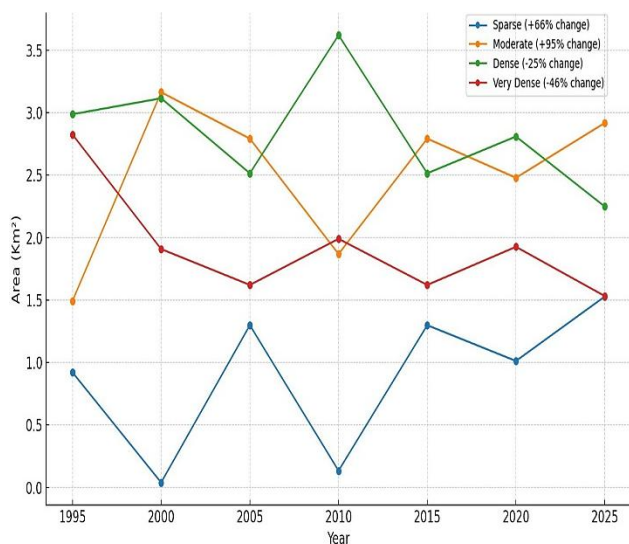


Fig. 7. Temporal NDVI-based vegetation classification (area in km²) for Nagan Forest (1995–2025).

Conclusion and Recommendations

Our 30-year NDVI analysis indicates that Kaghan Valley's reserve forests have experienced significant regeneration since 1995, particularly after 2010. By 2025, the Kamalban and Manshi forests both exhibit larger areas of high-vigor canopy and markedly reduced sparse land relative to 1995, whereas Nagan shows only modest overall improvement. The timing of these gains aligns closely with Khyber Pakhtunkhwa's Billion Tree Tsunami (BTT) afforestation initiative (2014–2017). Our findings therefore corroborate regional estimates of ~300 km² net tree-cover gain and demonstrate that sustained reforestation can reverse decades of degradation.

Actionable Recommendations

Establish an annual NDVI monitoring program: We recommend conducting NDVI-based vegetation assessments at least once per year using Landsat or quarterly using MODIS imagery. Annual analyses will capture both short-term disturbances and regrowth cycles, enabling managers to respond quickly to illegal logging or natural disasters. Results should be archived to build a continuous time series and disseminated through open-data platforms to support transparency and community engagement.

Integrate socioeconomic surveys with remote sensing: NDVI trends alone cannot explain why forests are lost or restored. We advocate pairing annual satellite monitoring with biennial socioeconomic surveys of local communities. Household questionnaires, focus groups and market assessments can identify drivers such as fuelwood demand, tourism pressure or grazing intensity. Combining spatial NDVI data with human–land use information will enable targeted interventions such as providing alternative livelihoods or improving fuel-efficient stoves to reduce forest dependence.

Strengthen enforcement and community-based forestry. To prevent relapse into decline, local forestry departments should intensify patrols against illegal logging and ensure that harvesting quotas (if any) are enforced. Establishing community and forestry agreements where villagers receive controlled harvesting rights in exchange for protecting forest stands can create incentives for stewardship. Such co-management arrangements have been successful in other Himalayan regions of Pakistan (e.g., community forestry initiatives in Khyber Pakhtunkhwa) and merit pilot testing in Kaghan.

Adopt mixed-species, native plantations for resilience: Reforestation efforts should prioritize mixed plantings of native conifers (e.g., deodar, blue pine, spruce) and broadleaf species (oak, maple, *Aesculus indica*). Diverse stands are less susceptible to pests, disease and climate stress than monocultures and provide better habitats for wildlife. Seedlings should be sourced locally to preserve genetic adaptation to site conditions. In degraded riparian zones, incorporate nitrogen-fixing species and understory shrubs to accelerate soil recovery.

Enhance post-planting maintenance and monitoring. Successful afforestation requires more than planting; saplings need protection from grazing, weeding and occasional watering. We recommend training local youths in post-planting care, offering stipends tied to seedling survival rates, and conducting five-year survival audits to evaluate planting success.

Overall, our analysis demonstrates that sustained management combining systematic monitoring, socioeconomic engagement, strict enforcement and ecologically diverse plantations can restore degraded Himalayan forests. Continued annual NDVI assessment will ensure early detection of degradation and help lock in the gains achieved since 2010.

Table 1. Geographic coordinates and area of the selected forest sites in Khyber Pakhtunkhwa, Pakistan.

S. No.	Forest area	Forest type	Forest name	X	Y	Area
1.	Kaghan	Reserve Forests	Kamalban	73.55500905	34.71876556	1119.939851
2.	Kaghan	Reserve Forests	Manshi	73.43943117	34.71242372	2114.363594
3.	Kaghan	Reserve Forests	Nagan	73.35132349	34.6545554	822.2979273

Table 2. NDVI-Based vegetation classification for Kamalban Forest (1995–2025).

Years	Sparse vegetation		Moderate vegetation		Dense vegetation		Very dense vegetation	
	No of pixels	Area (Km ²)	No of pixels	Area (Km ²)	No of pixels	Area (Km ²)	No of pixels	Area (Km ²)
2025	1132	1.0188	4551	4.0959	4426	3.9834	2347	2.1123
2020	1184	1.0656	3550	3.195	5080	4.572	2642	2.3778
2015	1352	1.2168	4310	3.879	4523	4.0707	2271	2.0439
2010	550	0.495	3134	2.8206	5120	4.5918	1862	1.6758
2005	53	0.0477	2442	2.1978	5680	5.112	2565	2.3085
2000	61	0.0549	3516	3.1644	6230	5.607	2649	2.3841
1995	2710	2.439	3694	3.3246	3795	3.4155	2257	2.0313

Table 3. NDVI-Based vegetation classification for Manshi Forest (1995–2025).

Years	Sparse vegetation		Moderate vegetation		Dense vegetation		Very dense vegetation	
	No of pixels	Area (Km ²)	No of pixels	Area (Km ²)	No of pixels	Area (Km ²)	No of pixels	Area (Km ²)
2025	1911	1.7199	6628	5.9652	8837	7.9533	6135	5.5215
2020	12314	11.0826	5168	4.6512	5553	4.9977	476	0.4284
2015	2345	2.1105	5981	5.3829	8530	7.677	6655	5.9895
2010	1173	1.0557	2862	2.5758	8034	7.2306	8840	7.956
2005	1316	1.1844	6696	6.0264	8843	7.9587	4286	3.8574
2000	655	0.5895	7279	6.5511	9550	8.595	6072	5.4648
1995	1089	0.9801	8756	7.8804	8338	7.5042	5328	4.7952

Table 4. NDVI-Based vegetation classification for Nagan Forest (1995–2025).

Years	Sparse vegetation		Moderate vegetation		Dense vegetation		Very dense vegetation	
	No of pixels	Area (Km ²)	No of pixels	Area (Km ²)	No of pixels	Area (Km ²)	No of pixels	Area (Km ²)
2025	1697	1.5273	3241	2.9169	2499	2.2491	1703	1.5327
2020	1125	1.0125	2754	2.4786	3121	2.8089	2140	1.926
2015	1443	1.2987	3102	2.7918	2794	2.5146	1801	1.6209
2010	149	0.1341	2076	1.8684	4022	3.6198	2211	1.9899
2005	150	1.2987	2584	2.7918	3703	2.5146	2029	1.6209
2000	44	0.0396	3515	3.1635	3461	3.1149	2120	1.908
1995	1024	0.9216	1658	1.4922	3319	2.9871	3139	2.8251

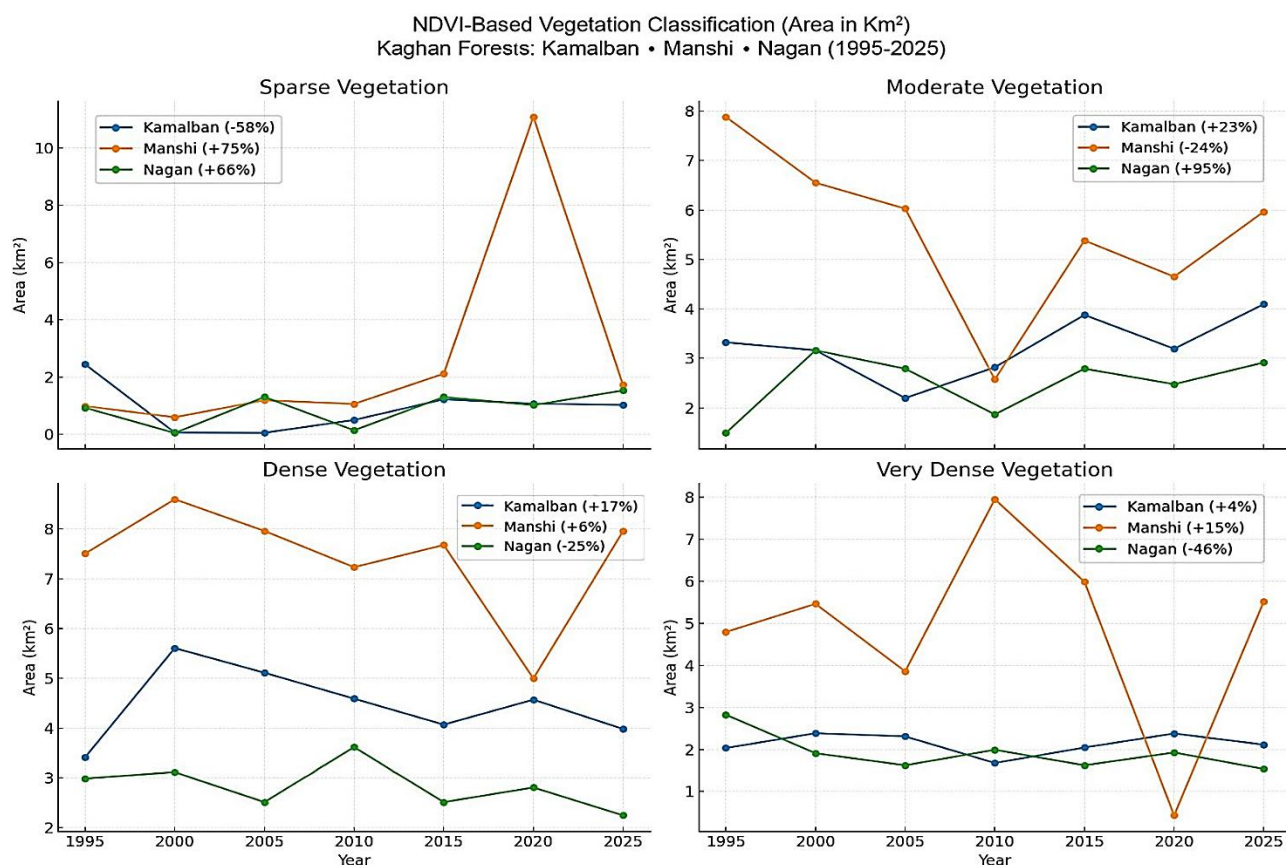


Fig. 8. NDVI-Based Vegetation Trends across Kaghan Forests (1995–2025).

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Authors Contribution: Uroosa Sheikh: Writing - original manuscript. Moazzam Ali Khan: Conception of Idea, Supervision. Muhammad Toheed: Data Analysis, Methodology. Syed Khizar Askari: Editing, Reviewing of GIS maps. Aamir Alamgir: Writing, Reviewing.

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