Policy-Driven Forest Recovery in a Crisis-Affected Landscape: A Remote Sensing Study in the Rohingya Refugee Region of Bangladesh

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Abstract

Human displacement crises often place sudden pressure on forested environments where shelter materials and cooking fuel are sourced directly from nearby natural resources. Since 2017, the Rohingya refugee influx into Ukhiya and Teknaf sub-districts (Cox's Bazar, Bangladesh) has exerted intense pressure on surrounding forests through rapid settlement expansion and fuelwood extraction. In response, coordinated recovery initiatives, including reforestation and Liquefied Petroleum Gas (LPG) distribution, were introduced in later years. This study examines vegetation change and the effects of reforestation and LPG-distribution programs in vegetation recovery from 2016 to 2024 using multi-temporal Landsat 8 surface reflectance imagery processed in Google Earth Engine. Annual median composites were used to calculate the Normalized Difference Vegetation Index (NDVI) and classify land cover into dense vegetation (NDVI > 0.50), light vegetation (0.20–0.50), and non-vegetated areas (≤ 0.20). Vegetation change was assessed using area estimation and spatial change detection, while temporal trends were analyzed using the Mann–Kendall test and Sen's slope nonparametric trend estimator.

Results reveal a clear shift in vegetation dynamics. Between 2016 and 2018, dense vegetation declined sharply, while light vegetation and non-vegetated areas expanded, indicating widespread canopy disturbance linked to settlement growth and fuelwood use. Spatial analysis identified Kutupalong–Balukhali (Ukhiya) and Jadipara (Teknaf) as major degradation hotspots. Following policy interventions introduced in 2019, particularly large-scale LPG distribution and collaborative reforestation, vegetation trends reversed. Recovery was strongest in areas that had experienced the most severe degradation, although localized pressure persisted in parts of Unchiprang and Whykong of Ukhiya. Overall, the findings provide clear evidence that targeted policies, especially LPG distribution and coordinated reforestation, played a critical role in reversing crisis-driven forest loss and supporting landscape recovery.

Keywords: Vegetation Change, Policy-driven Recovery, Remote Sensing, Rohingya Refugee, Landsat-8

Highlights

- Quantified vegetation changes in Ukhiya-Teknaf using Landsat-8 NDVI for 2016-2024
- Observed sharp influx-period degradation (2016-2018): dense vegetation declined while light and non-vegetated classes expanded
- Post-2019 period showed strong recovery: dense vegetation increased, and light vegetation decreased markedly by 2024
- Hotspot mapping identified severe pre-policy degradation in Kutupalong-Balukhali and Jadipara**,** with widespread recovery by 2024
- Vegetation recovery after 2019 coincided with large-scale LPG distribution and reforestation programs, suggesting a strong policy influence on post-crisis forest regeneration

1. Introduction

Human displacement crises often precipitate significant environmental changes, especially in ecologically sensitive regions with forested landscapes (Sánchez-Cuervo & Aide, 2013). A prime example of this phenomenon is the influx of Rohingya refugees into the southeastern region of Bangladesh, specifically in the Ukhiya and Teknaf sub-districts of Cox's Bazar district. This crisis has led to both the rapid degradation of the forest and the subsequent efforts to recover it (Hasan et al., 2020; Mukul et al., 2019; Hassan et al., 2018). However, studies reveal that since 2017, the expansion of refugee settlements has accelerated deforestation and forest fragmentation, reducing core forest areas while creating more edge and patch habitat. (Hassan et al., 2023; Hassan et al., 2018). The Rohingya refugee influx into Bangladesh represents one of the largest and most protracted humanitarian crises of the 21st century (Chowdhury et al., 2022; Faye, 2021; Taufiq, 2021). Since August 2017, over 1.3 million (Uddin, 2020; Khan, 2024) Rohingya refugees have sought shelter and as of 2024 they live in 34 congested camps (Islam & Siddika, 2021; Kudrat-E-Khuda, 2020) across the Ukhiya and Teknaf sub-districts (Hassan et al., 2018). This mass displacement has generated immense environmental challenges (Hossain, 2022; Ahmed et al., 2021). Forests were cleared to accommodate camps, and fuelwood demand accelerated deforestation, leading to the loss of biodiversity and a change in the ecological landscape (Hasan et al., 2021; Rahman et al., 2019; Hassan et al., 2018). Studies have documented rapid forest decline during the initial crisis period (2016-2018), with thousands of hectares of tree cover lost to settlement expansion and resource extraction (Braun et al., 2019; Hassan et al., 2018). For example, Hassan et al. (2018) reported that between 2016 and 2017, forest cover surrounding the three major camps, particularly Kutupalong and Balukhali, Unchiprang and Nayapara–Leda, reduced by approximately 2,283 hectares, coinciding with a camp expansion of approximately 1,219 hectares. Similarly, Hossain and Moniruzzaman (2021) documented a 17% decline in vegetation cover between 2010 and 2020, with a 582% increase in refugee camp areas. Mitra et al. (2025) also found persistent forest degradation from 2016 to 2024, correlating with the expansion of settlement areas. Mishu et al. (2023) highlighted that shelter construction materials and dense packing increase fire risks, further threatening forested areas. Additionally, a study by Karmakar et al. (2025) shows that the rapid expansion of refugee settlements has led to increased land surface temperatures, exacerbating local climate conditions and impacting forest ecosystems.

Addressing the underlying drivers of deforestation, such as camp expansion and heavy reliance on firewood, has been central to environmental recovery (Ahmed & Sabastini, 2024; Parveen, 2024; Sajib et al., 2022). Though the mass expansion of settlements like 2017 slowed down (Hassan et al., 2018), the growing populations continue to drive up fuelwood demand (Islam et al., 2022; Rafa et al., 2021). The growing number of refugees has led to an escalation in fuelwood consumption, as they need around 750,000 kg of fuelwood for cooking and heating every day. (Rafa et al., 2021; Hassan et al., 2018). This increased fuelwood consumption places immense pressure on the surrounding forests, substantially contributing to the depletion of vegetation in the region of Ukhiya and Teknaf sub-districts of Cox's Bazar (Rahman & Mitani, 2025; Parveen, 2024). In response, several environmental initiatives were launched to address both the immediate needs of the refugee population and the long-term sustainability of the local ecosystem (Bashar & Bernell, 2025; Ali & Shahreen, 2024). Food and Agriculture Organization (FAO), the International Organization for Migration (IOM), and the World Food Programme (WFP) collaboratively launched the Safe Access to Fuel and Energy (SAFE plus) initiative to promote sustainable energy sources and resilient livelihoods (Reliefweb, 2020). One key component of the initiative was the distribution of Liquefied Petroleum Gas (LPG), a cleaner and more efficient fuel alternative to firewood, significantly reducing the pressure on forests while improving the energy access for households within the refugee camps (Rafa et al., 2024; Chowdhury et al., 2022). In addition to the collaboration with the Forest Department, the FAO established a plantation program to restore vegetation cover by planting various fast-growing native species within and around refugee camps (Rahman & Mitani, 2025; Jalal et al., 2023). This fast-growing native species stabilized soil, reduced landslide risk, and improved the microclimatic conditions of the camps with increased vegetation cover (Mahmood et al., 2021). FAO, along with the Forest Department, has restored approximately 258 hectares of land within the camps and an additional 2,000 hectares of adjacent camp area (FAO, 2020).

Since 2018, this multi-sectoral response, including government and humanitarian interventions, has gradually reversed environmental degradation (Rahman & Mitani, 2025; Kumar, 2022). Key initiatives such as tree planting campaigns and clean energy adoption (including distribution of LPG to reduce reliance on fuelwood) have sparked a notable rebound in vegetation (Bashar & Bernell, 2025). By 2019, the trajectory began to shift from degradation to recovery. Reforestation campaigns, legislative measures, and widespread LPG distribution encouraged the gradual regrowth of vegetation (Bashar & Bernell, 2025; Rahman & Mitani, 2025). The reforestation campaigns involved not only planting trees but also choosing site-specific species and care & maintenance of planted trees for ecosystem sustainability, ensuring long-term resilience of restored vegetation (Mahmood et al., 2021). Additionally, the adoption of clean and renewable energy sources reduced pressure on forests by cutting fuelwood demand, contributing to soil conservation and improved vegetation cover (Rahman & Mitani, 2025; Parveen, 2024). By 2024, the region's vegetative cover had not only recovered to pre-crisis levels but had in many areas flourished beyond them (Mitra et al., 2025).

Despite these positive trends, most studies have focused narrowly on documenting forest loss and land degradation, while insufficiently addressing the efficacy of recovery initiatives. In particular, the policies that promoted the use of LPG over fuelwood for cooking and the reforestation activities, including their care and maintenance. To bridge this gap, the present study examines vegetation recovery in Ukhiya and Teknaf from 2016 to 2024 using multi-temporal remote sensing data and how the policy implementation helped improve the restoration of the degraded vegetation cover in the Rohingya refugee camps.

2. Methods

2.1 Study area

The research area encompasses the Ukhiya and Teknaf upazilas within the Cox's Bazar district, located in the Chittagong division of Bangladesh (Figure 1). Ukhiya and Teknaf upazilas were covered with tropical evergreen and various other vegetation types, with the Teknaf Wildlife Sanctuary serves as a vital forest area in Cox's Bazar (Rashid, 2013). At present, approximately 33 Rohingya refugee camps have emerged, comprising 26 camps in Ukhiya Upazila and 7 camps in Teknaf Upazila, collectively hosting 1,168,398 refugees across 243,497 households, with a demographic composition of 51.5% females and 48.5% males (UNHCR, 2025; Rahman & Mitani, 2025; Mowla, 2021; Uddin, 2020). While the Rohingya camps are primarily located in the PalongKhali union of Ukhiya and the Whykong, Nhila, and Baharchhara unions of Teknaf upazila (Rahman, 2017), this study encompasses the other unions within these two upazilas, excluding Saint Martin Island, to examine the overall changes in vegetation cover from 2016 to 2024.

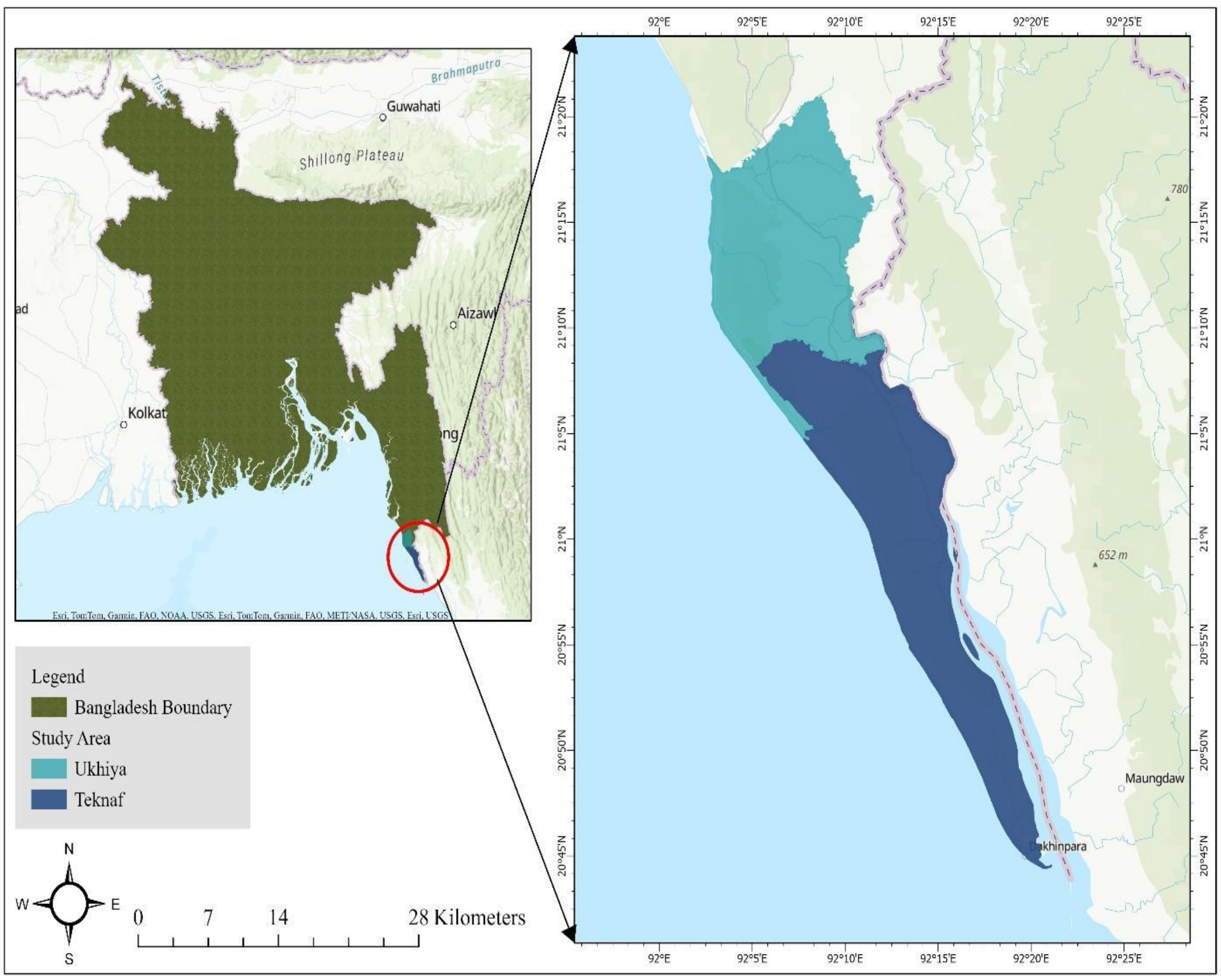

Figure 1: *Study area map encompassing the Ukhiya and Teknaf Upazilas of Cox's Bazar, excluding Saint Martin Island under the Teknaf Upazila*

2.2 Data

This study utilized multispectral remote sensing data acquired from the Landsat-8 Operational Land Imager (OLI) Collection 2, Level-2 surface reflectance products, which provide a spatial resolution of 30 m. Satellite imagery from five reference years (2016, 2018, 2020, 2022, and 2024) was used to evaluate temporal fluctuations in vegetation cover within the Ukhiya and Teknaf upazilas. For all study years, Landsat-8 OLI Band 4 (red) and Band 5 (near-infrared) were employed to characterize vegetation conditions.

All imagery was obtained from the U.S. Geological Survey (USGS) EarthExplorer archive and processed using the Google Earth Engine (GEE) cloud-computing platform. Full-year (January–December) image collections were used to reduce seasonal bias in vegetation phenology, and annual median composites were generated for each study year.

2.3 Image Processing

Image processing and analysis were conducted utilizing Google Earth Engine (GEE). The Landsat 8 image collection was clipped to the specified shapefile of the study area and filtered according to date. To remove cloud and atmospheric distortions, the Quality Assurance pixel band was utilized to mask pixels impacted by clouds (bit 3), cloud shadows (bit 4), snow (bit 5), and cirrus (bit 6). Following the masking process, median composites were created for each year to produce a strong representation of annual vegetation conditions.

2.4 NDVI Calculation

The Normalized Difference Vegetation Index (NDVI) was calculated to quantify vegetation conditions using the red and near-infrared spectral bands derived from Landsat-8 OLI imagery. NDVI was computed using the standard formulation, $NDVI = (NIR - Red) / (NIR + Red)$, where NIR represents the near-infrared reflectance from Band 5, and Red corresponds to the red reflectance from Band 4. The resulting NDVI values range from −1.0 to +1.0, with higher values indicating denser and healthier vegetation cover, while lower or negative values represent sparse vegetation or non-vegetated surfaces. NDVI maps were generated for each study year to assess the spatial and temporal variability of vegetation cover across the study area.

2.5 NDVI-based Classification

NDVI values were categorized into three groups to assess the vegetation cover: Dense vegetation: NDVI > 0.50, Light Vegetation: > 0.20 to ≤ 0.50, and No Vegetation: ≤ 0.20 (U.S. Geological Survey, n.d., Bora et al., 2025; El-Shirbeny et al., 2022; Hashim et al., 2019; Khalil et al., 2024; Thokchom, 2008; Era & Ferdous, 2022). A land cover map was generated for each target year by reclassifying each NDVI map according to these thresholds. NDVI values typically range from -1 to 1, with negative values up to 0.2 indicating non-vegetative surfaces such as water, rocks, or bare soil. Values between 0.2 and 0.5 represent areas with sparse or light vegetation, often including grasslands, shrubs, or young plants. Values above 0.5 reflect dense, healthy vegetation, typically forests or well-established vegetative areas (USGS, 2018; Qui et al., 2018; Zaitunah and Sahara, 2021; Tucker, 1979).

2.6 Area Estimation

The extent of each vegetation type was ascertained by calculating the total area occupied by pixels and classified as dense vegetation, light vegetation, or non-vegetation. Each pixel, with a spatial resolution of 30 × 30 meters (900 square meters), was converted into an area expressed in hectares (ha). The total area for each class (dense, light, and no vegetation) was determined by aggregating the corresponding pixels over the study area.

2.7 Trend Analysis and Visualization

The estimated area of each vegetation class was compared across the designated years (2016, 2018, 2020, 2022, 2024) to analyze temporal trends in vegetation change. A time-series visualization was developed to demonstrate the interannual fluctuations in dense vegetation, light vegetation, and no vegetation. Distinct color schemes were applied to each image in ArcGIS Pro 3.5 to improve interpretability. Moreover, the total areas of vegetation for each year were calculated and tabulated, and the yearly changes were evaluated. To assess the monotonic trend of vegetation from 2016 to 2024, a non-parametric Mann-Kendall test was performed, and the statistical significance was evaluated using a 95% confidence interval ($\alpha = 0.05$). For each vegetation class, the τ statistic, associated p-value, and Sen's slope estimate were derived.

3. Results

3.1 Changes in vegetation and the estimates from 2016 to 2024

Dense vegetation cover in 2016 was 44272 hectares (ha), and it declined by 13% in 2018 due to the Rohingya influx in 2017, and the vegetation cover was reached at 38476 ha (Table 1). After this massive destruction, by 2020, dense vegetation experienced a partial recovery (+8% relative to 2018), covering 41673 ha, which remained relatively stable, 40742 ha in 2022, though slight damage was noticed (-2% relative to 2020). By 2024, dense vegetation covered 45906 ha, showing a 13% increase compared to 2022, which mostly covered the degraded areas since 2017, and signifies the effort of vegetation recovery.

In 2016, light vegetation covered 10830 ha and exhibited a substantial increase of 49% by 2018. This suggests that dense vegetation has been transformed into light vegetation in certain regions, primarily because of deforestation and extensive harm to forested areas caused by the influx of Rohingya refugees. The peak light vegetation cover decreased by 16% in 2020, amounting to 13546 ha of vegetation cover, which also indicated an increase in dense vegetation resulting from reforestation efforts. A moderate increase of 5.5% was observed in 2022, covering an area of 14290 ha, likely attributable to plantation initiatives undertaken by various agencies in the Ukhiya and Teknaf regions. In 2024, light vegetation experienced a significant decline of 34%, encompassing an area of 9,426.3 ha. This indicates that the light vegetation was transformed into dense vegetation, reflecting the effectiveness of the recovery efforts.

Table 1: Vegetation area (ha) and annual change (%) by vegetation type in the Ukhiya and Teknaf sub-districts (2016–2024)

Year	Dense Vegetation (ha)	Dense Change (%)	Light Vegetation (ha)	Light Change (%)	Non-Vegetation (ha)	Non-Vegetation Change (%)
2016	44272	N/A	10830	N/A	6644	N/A
2018	38476	−13	16136	+49	6862	+3
2020	41673	+8	13546	−16	6383	−7
2022	40742	−2	14290	+5.5	6283	−1.6
2024	45906	+13	9426	−34	6256	−0.4

The coverage of non-vegetated areas in 2016 was 6644 hectares, which rose by approximately 3% to 6862 hectares in 2018. This signifies the expansion of settlement zones in the Ukhiya and Teknaf regions that were cleared to establish essential infrastructure for the Rohingya refugees. After 2018, the non-vegetated areas shrank by 7%, 1.6%, and 0.4% in 2020, 2022, and 2024, respectively. In 2020, the non-vegetated areas comprised 6383 hectares, decreasing to 6256 hectares by 2024. The findings demonstrate the conversion of non-vegetated areas into vegetated areas as dense vegetation became more prevalent in 2024.

3.2 Pre-policy decline of the forest resources (Pre and post influx 2017)

Spatial comparison of vegetation maps for 2016 and 2018 reveals extensive degradation across the Ukhiya and Teknaf sub-districts following the 2017 influx (Figure 2). Dense vegetation was extensively transformed into light vegetation, with localized transitions to non-vegetated surfaces. This pattern reflects widespread canopy disturbance rather than uniform forest clearing. The 3% increase in non-vegetated areas observed in 2018 further corroborates the degradation of vegetated surfaces and their partial conversion to non-vegetated land.

The most severe vegetation degradation was concentrated in Ukhiya sub-district, particularly within the Kutupalong and Balukhali areas, where large, contiguous zones of dense vegetation loss were observed. This pronounced degradation corresponds spatially with the concentration of 26 Rohingya refugee camps established within Ukhiya, indicating intense localized pressure on surrounding forest resources. These findings are consistent with those of Hassan et al. (2018), who reported that settlement area in the Kutupalong–Balukhali complex expanded from approximately 146 ha in December 2016 to 1365 ha in December 2017, while forest cover within a 10-km buffer declined from approximately 11800 ha to 9740 ha, representing a net forest loss of ~2060 ha

(~18%) over the same period. Together, these results reflect the rapid conversion of forested land to settlements and associated disturbed surfaces following the influx.

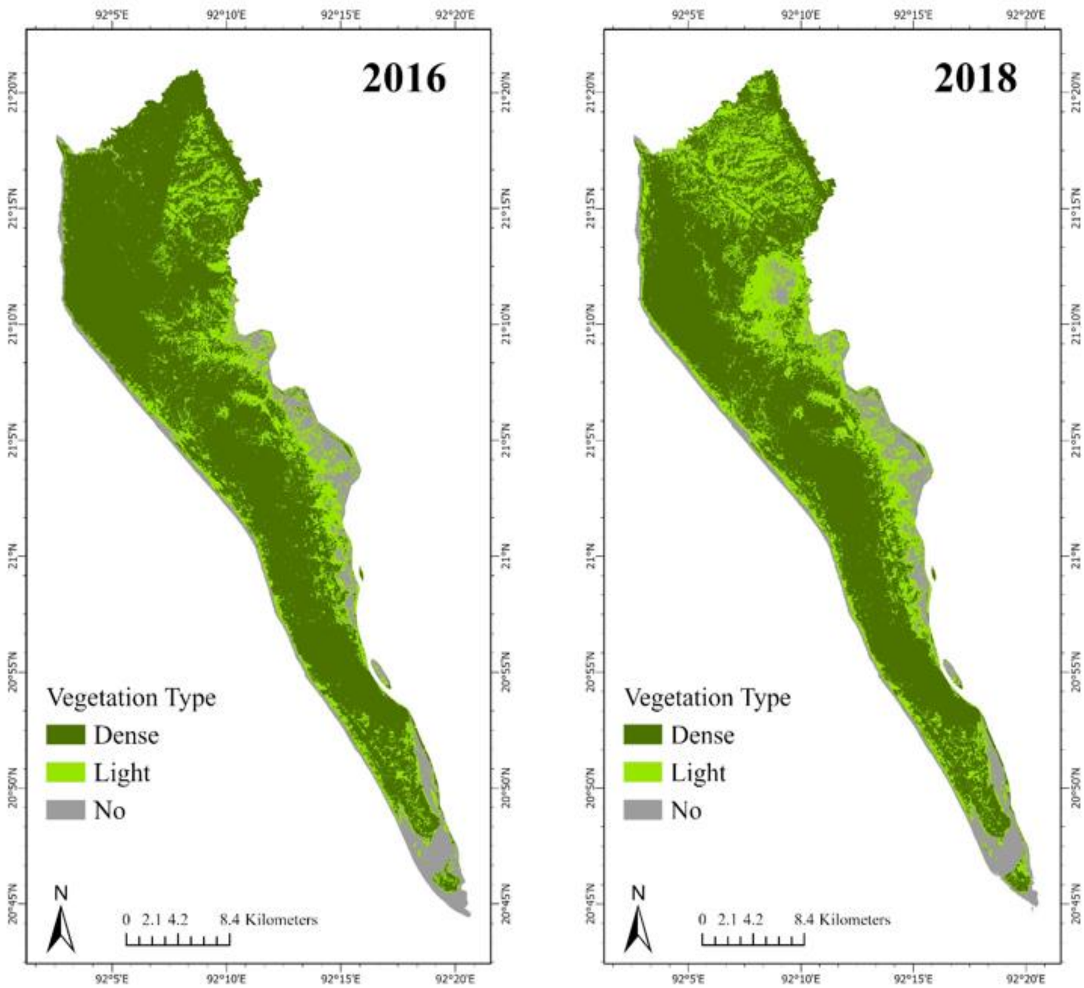

Figure 2: *Pre-policy vegetation cover in the Ukhiya and Teknaf sub-districts of Cox's Bazar*

Additional degradation occurred in Haldia Palong, Court Bazar, Morichya, and Rumkhapalong, indicating broader but less intense canopy disturbance beyond the main settlement corridor. Though there were no Rohingya camps, the vegetation loss happened due to the demand for fuelwood and the management of it from the surrounding areas. In the Teknaf sub-district, degradation was more spatially fragmented but pronounced in Jadipara, with additional impacts in Nhila and Rangikhali unions.

3.3 Post policy improvement/recovery of the forest resources (2019-2024)

Vegetation maps for 2020, 2022, and 2024 indicate a clear improvement in vegetation conditions following the implementation of policy interventions in 2019 (Figure 3). Before these interventions, forest degradation had reached a critical level, with Hasan et al. (2021) projecting losses of 1506 ha of shrubland and 1,264 ha of mixed forest by 2023 under a continuation of pre-policy trends. In contrast, the post-policy period is characterized by an expansion of dense vegetation, a contraction of light vegetation, and a gradual reduction of non-vegetated areas. This shift coincides with the implementation of two major policy measures, including Liquefied Petroleum Gas (LPG) distribution to reduce fuelwood dependence and collaborative reforestation initiatives supported by community-based care and maintenance, which together contributed to sustained vegetation recovery over time.

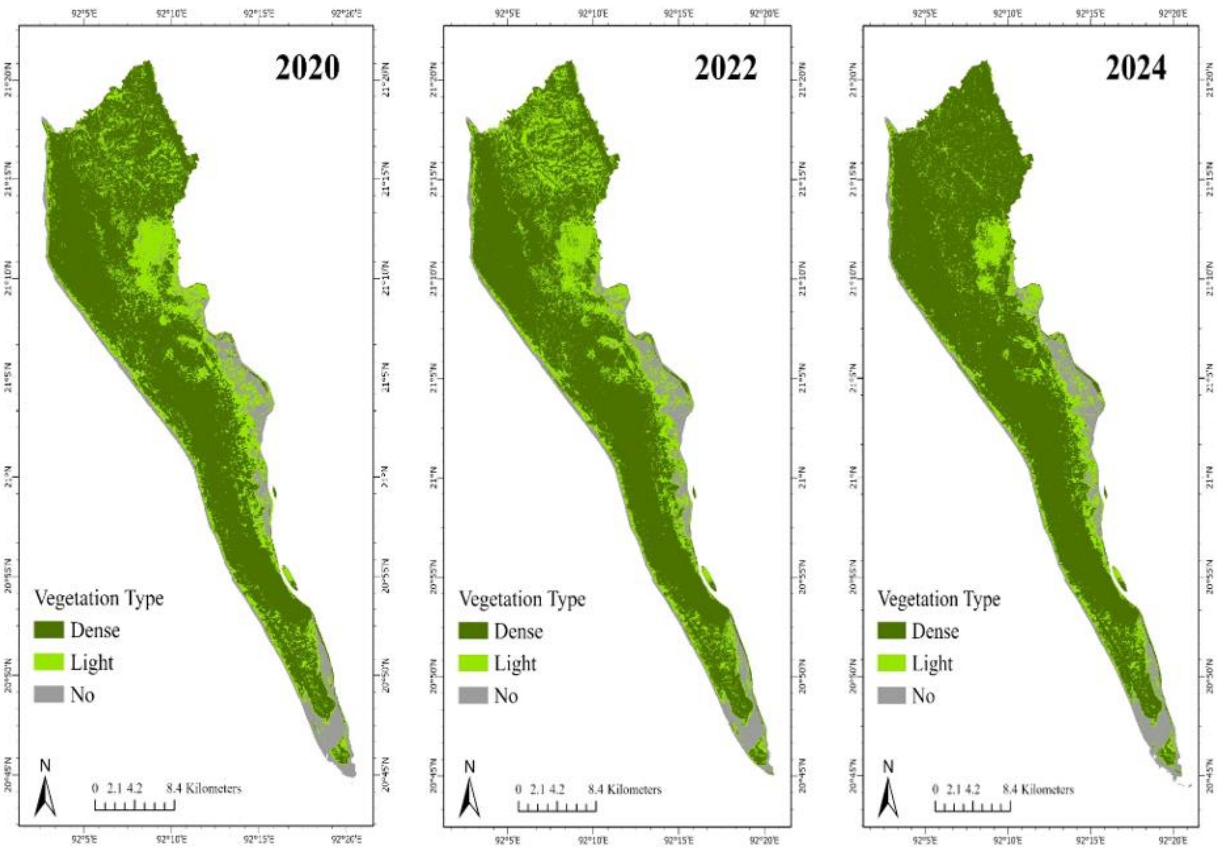

Figure 3: *Post-policy vegetation cover in the Ukhiya and Teknaf sub-districts of Cox's Bazar*

Across the post-policy period, vegetation dynamics show progressive strengthening of canopy structure rather than short-term regrowth. Dense vegetation expanded steadily through 2024, while light vegetation declined sharply by the end of the study period, indicating transitions from degraded or intermediate vegetation states toward more structurally intact forest cover. Concurrently, non-vegetated areas exhibited a gradual contraction, suggesting limited new land clearing after 2019. Together, these temporal patterns demonstrate that the post-policy phase was dominated by recovery-oriented vegetation change, especially in the degradation hotspots of Ukhiya and Teknaf sub-districts.

3.4 Spatial distribution of vegetation loss (2016 and 2018) and recovery (2018 and 2024) hotspots

Change-detection analysis provides a spatially explicit synthesis of vegetation dynamics by classifying transitions into High degradation, Low degradation, No change, Low recovery, and

High recovery categories (Figure 4). Unlike the class-based maps in Sections 3.2 and 3.3, this analysis isolates where vegetation loss and recovery were concentrated, allowing direct identification of degradation and recovery hotspots.

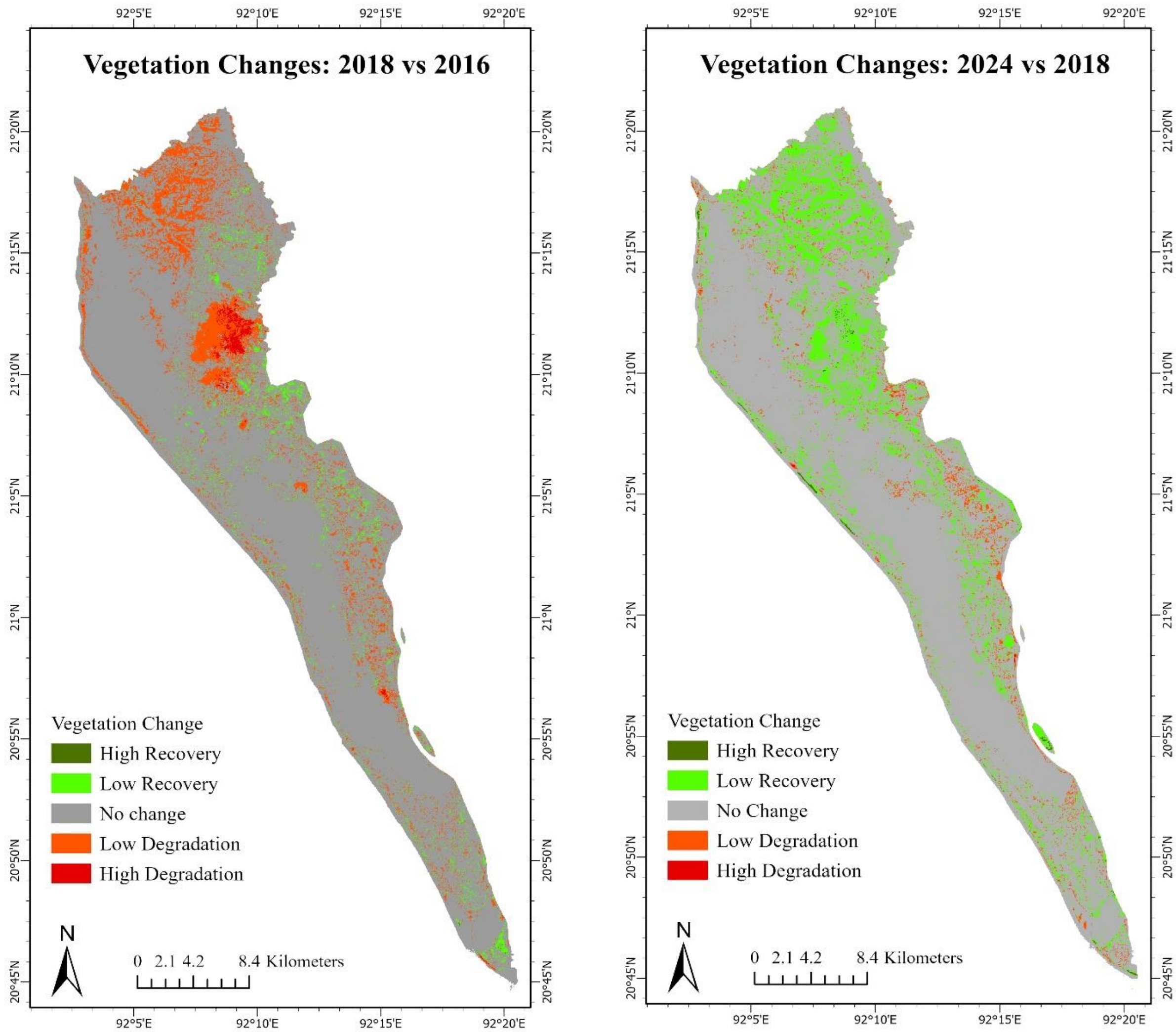

Figure 4: *Spatial distribution of vegetation loss and recovery in the Rohingya refugee region, comparing post-crisis (2018) and recovery (2024) periods*

The vegetation change map from 2016 to 2018 shows that vegetation loss was highly clustered in discrete locations, while recovery signals were minimal. High degradation was confined primarily to Kutupalong and Balukhali in Ukhiya sub-district and Jadipara in Teknaf, indicating zones of intense and localized disturbance. Surrounding these hotspots, Low degradation formed a broader belt of partial canopy disturbance across Haldia Palong, Court Bazar, Morichya, and Rumkhapalong in Ukhiya, and Nhila and Rangikhali in Teknaf. The near absence of High recovery and the limited extent of Low recovery during this period confirm that vegetation change between 2016 and 2018 was overwhelmingly degradational.

In contrast, the vegetation change map from 2018 to 2024 reveals a marked spatial reorganization toward recovery. Large portions of Ukhiya and Teknaf transitioned into Low recovery and localized High recovery classes, indicating widespread improvement in vegetation condition. Importantly, the earlier degradation epicenter in the Kutupalong–Balukhali corridor shifted prominently into recovery classes, demonstrating that areas most severely affected during the influx experienced the strongest recovery. Residual degradation was spatially restricted and largely confined to Unchiprang and Whykong in Teknaf, where Low degradation persisted. These patterns indicate that recovery was spatially heterogeneous, with earlier disturbance hotspots responding more strongly than areas subject to continued or emerging pressure.

3.5 Vegetation trajectory and trend characteristics following policy intervention

Vegetation cover dynamics across Ukhiya and Teknaf exhibit a distinct two-phase trajectory, characterized by a rapid decline following the 2017 Rohingya refugee influx and a subsequent recovery phase beginning after policy intervention in 2019 (Table 1; Figure 5). Before intervention, the total vegetated area declined sharply between 2016 and 2018, reflecting widespread forest degradation during the influx period. Following the implementation of policy measures in 2019, this declining trajectory reversed, with vegetation cover showing consistent gains through 2020, 2022, and 2024. By the end of the study period, total vegetation area had recovered to levels comparable to the pre-influx baseline, indicating substantial restoration of degraded landscapes (Table 1, Figure 5).

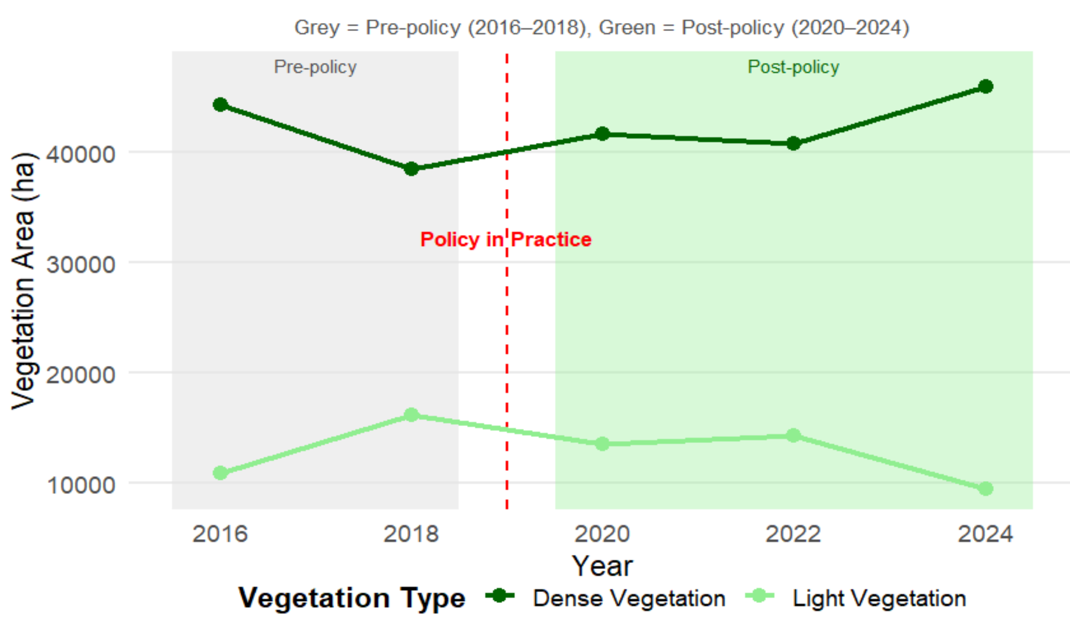

Figure 5: *Policy implication effects on dense and light vegetation, showing the pre- and post-policy changes*

This trajectory reflects a marked shift in vegetation dynamics rather than a gradual fluctuation. The post-policy period is characterized by successive increases in vegetated areas relative to the minimum of 2018, representing a sustained recovery trend over multiple observation intervals (Table 1). The trajectory analysis, therefore, indicates a policy-associated inflection point in vegetation dynamics, separating a degradation-dominated phase from a recovery-oriented phase.

To assess whether these observed changes constitute statistically significant monotonic trends over the full study period, a Mann–Kendall (MK) trend test was applied to even-year observations from 2016 to 2024 (Figure 6). The MK results indicate no statistically significant monotonic trend for dense vegetation ($\tau = 0.20$, $p = 0.806$) or light vegetation ($\tau = -0.20$, $p = 0.806$). Although Sen's slope estimates suggest a modest positive tendency for dense vegetation (+771 ha yr^{-1}) and a negative tendency for light vegetation (-637 ha yr^{-1}), the associated p-values indicate that these tendencies are not distinguishable from interannual variability.

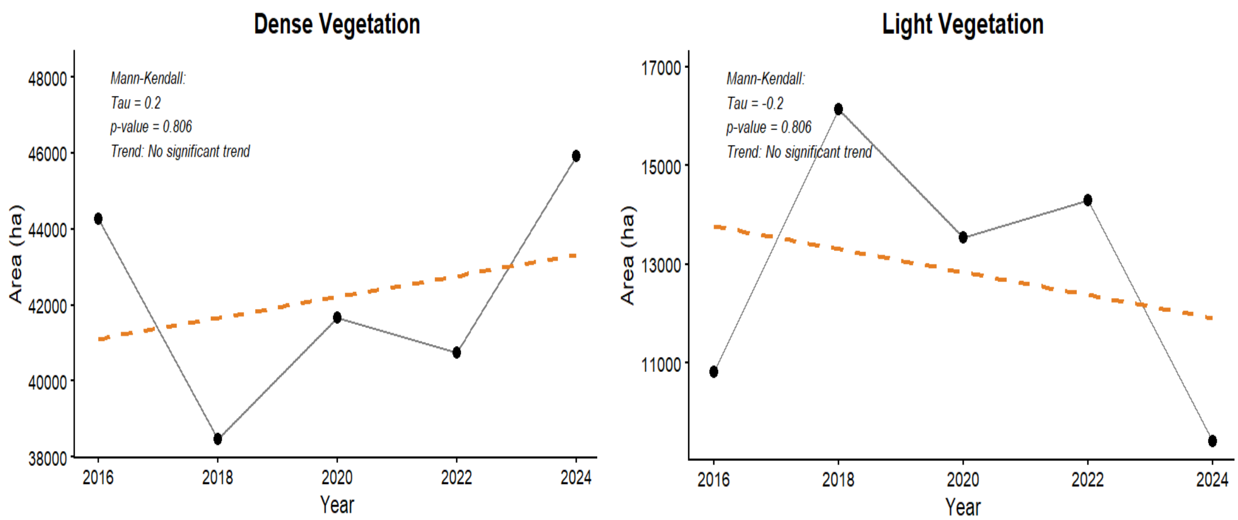

Figure 6: *Mann-Kendall test of dense and light vegetation showing the trend of vegetation changes over the years*

In contrast, non-vegetated land exhibited a stronger negative monotonic association with time ($\tau = -0.80$, $p = 0.086$), accompanied by a Sen's slope of -110 ha yr^{-1}. While this trend did not reach the conventional 0.05 significance threshold, the magnitude and direction of τ suggest a consistent decline in non-vegetated surfaces over the study period (Figure 6).

Taken together, the trajectory and trend analyses indicate that vegetation change in the study area is best described as non-linear and phase-dependent, rather than as a single monotonic process. The sharp decline during the influx period, followed by post-policy recovery, produces an overall trajectory that masks monotonic significance when evaluated across the full 2016-2024 interval. These results highlight the importance of trajectory-based analysis for detecting policy-driven landscape responses in humanitarian crisis settings.

4. Discussion

This study demonstrates that subsequent policy interventions have reshaped the trajectory of forest cover in Ukhiya and Teknaf following destruction during and immediately after the influx. Remote sensing analysis revealed two distinct phases: a period of severe vegetation loss between 2016 and 2018, followed by substantial recovery from 2019 to 2024.

4.1 Crisis-Driven Vegetation Collapse: Energy Crisis, Shelter Demand, and Ecological Thresholds

The magnitude and rate (13% dense vegetation loss and 3% non-vegetated area increase) of deforestation after the 2017 Rohingya influx suggest that the forest loss in the Ukhiya-Teknaf area was driven by immediate structural pressures associated with humanitarian survival rather than gradual land-use changes. Two interconnected variables, the construction of emergency shelters and household energy scarcity, were responsible for most of the forest clearing during the initial crisis phase, with almost 60% of forest loss linked to the establishment of makeshift shelters and the collecting of fuelwood (Hasan et al., 2021; Brac, 2017). Energy demand assumed a notably pivotal role. With an average household size of approximately seven members, each refugee family necessitated around 151 kg of firewood per month, leading to an estimated extraction of 6800 tons of biomass from nearby forests within a short period (Mohiuddin and Molderez 2023; Barua, 2018). This degree of extraction is considerably beyond the regenerative potential of local forest ecosystems, thereby converting adjacent forests into an open-access resource under crisis conditions. In this scenario, deforestation resulted not just from unregulated exploitation but also from an unavoidable consequence of energy instability coupled with institutional deficiencies throughout the emergency response phase.

The recorded 13% reduction in dense vegetation cover from 2016 to 2018 signifies a threshold disruption rather than gradual degradation. Upon the simultaneous destruction of the canopy structure and undergrowth plants, the regulatory functions of the ecosystem swiftly declined. The associated 3% rise in non-vegetated areas in 2018 suggests that some previously vegetated land was transformed into settlements, infrastructure, and bare surfaces during the crisis, underscoring the impact of emergency land conversion on ecological instability. This elucidates why deforestation was accompanied by a series of subsequent environmental repercussions, including intensified soil erosion, habitat degradation, modified hydrological dynamics, and increased vulnerability to landslides (Ahmed et al., 2020; Kamal et al., 2022). The pre-policy phase underscores a crucial fact for crisis ecology that when humanitarian solutions inadequately meet energy and material requirements early on, forest ecosystems may cross ecological thresholds, rendering recovery progressively expensive and risky.

4.2 Policy-Enabled Recovery: Coupling Reforestation with Fuelwood Pressure Reduction

The recovery trajectory in the Ukhiya–Teknaf region post-2019 suggests that forest regeneration in crisis-affected areas is facilitated by policies rather than occurring spontaneously. The simultaneous increase of dense vegetation and reduction of light and non-vegetated classes following policy implementation indicates that recovery comprised structural and functional enhancements rather than just short-term regrowth.

Reforestation initiatives were central to initiating this transition by stabilizing degraded slopes, restoring canopy-forming species, and overcoming biophysical constraints that limited natural regeneration. In camp areas, reforestation activities such as site preparation, plantation management, and maintenance were carried out by the refugees, and host communities were involved in restoration outside the camps. The increasing dominance of dense vegetation over light vegetation implies successional advancement, consistent with restoration pathways observed in highly disturbed tropical systems where active intervention is required (Rahman & Mitani, 2025; Bashar & Bernell, 2025).

However, the persistence recovery cannot be solely credited to reforestation efforts. The concurrent decrease in non-vegetated regions indicates a drop in new land clearing, underscoring the significance of alleviating fuelwood demand via clean energy alternatives. Before the implementation of policy measures, households' dependence on forest biomass led to a self-sustaining cycle of degradation. The widespread adoption of Liquefied Petroleum Gas (LPG) interrupted this cycle by separating daily energy requirements from the use of forest resources. In this context, LPG distribution served as an indirect land-use policy tool rather than merely an energy intervention. The SAFE+2 programme, which provided nearly 1.2 million LPG cylinders to around 200,000 households, substantially reduced fuelwood extraction, allowing restored areas to endure instead of facing continuous degradation (Dampha et al., 2022). The decline in light vegetation observed after 2022 reinforces this interpretation, indicating a shift from degraded or early-regrowth states to denser, more stable canopy conditions. The patterns suggest that the alignment of policies in the energy and restoration sectors, rather than merely favorable climatic conditions, played a crucial role in the observed recovery.

4.3 Collaborative and Community-Based Governance: Why Recovery Was Sustained but Remains Incomplete

One of the key insights of the findings is that sustained recovery would not have been achieved through reforestation or LPG distribution alone, but rather through collaborative, multi-level governance and active community engagement. Environmental and energy interventions were integrated into coordinated institutional frameworks that included the Bangladesh Forest Department, humanitarian organizations, NGOs, and both refugee and host communities.
Coordination platforms like the Environmental and Energy Technical Working Group (EETWG), Inter-Sector Coordination Group (ISCG), and Site Management and Site Development (SMSD) mechanisms have enabled alignment in areas such as forestry, energy provision, and settlement

management (Mahamud et al., 2022). This integration minimized institutional fragmentation and allowed for the incorporation of environmental objectives into standard humanitarian response planning. The involvement of the community greatly improved the execution process. Refugees and host communities played an integral part in managing nurseries, establishing plantations, and maintaining sites, which improved scalability and encouraged local stewardship. This type of engagement is broadly acknowledged as essential for lasting restoration in situations where enforcement-based methods are not feasible. Even with these advancements, the recovery is still incomplete. Although the rate of deforestation linked to fuelwood has decreased, reliance on bamboo and various construction materials continues, with around 99% of shelters needing bamboo, muli, and borak for building or maintenance (UNHCR, 2020; Dampha et al., 2022). The ongoing demand for materials clarifies why non-vegetated areas, despite their decline, have not been completely eradicated.

Furthermore, the lack of statistically significant monotonic trends in the Mann–Kendall analysis needs to be understood within the context of the non-linear, policy-punctuated dynamics of landscape change in humanitarian contexts. A sudden disruption accompanied by focused intervention results in incremental changes instead of gradual trends, highlighting the importance of trajectory-based analysis when assessing policy effects through remote sensing.

Limitations

This study emphasizes vegetation recovery rather than explicit forest loss or gain, which may oversimplify complex landscape dynamics. Although NDVI effectively captures broad changes in vegetation greenness, it is subject to spectral saturation in dense forest canopies, reducing sensitivity to increases in biomass, canopy closure, and structural complexity beyond moderate vegetation densities. Consequently, NDVI-based classifications may underestimate changes within dense vegetation classes and cannot fully represent forest structural quality. Field-based validation was limited due to restricted access in parts of the refugee camps and surrounding forests, and the analysis did not assess species composition or forest age structure. Future studies integrating ground observations, higher-resolution imagery, or structural metrics (e.g., radar or LiDAR) would provide a more comprehensive assessment of ecological recovery and the long-term impacts of reforestation and clean energy interventions.

Conclusion

This study provides evidence that forest degradation associated with humanitarian crises is not inherently irreversible. In Ukhiya and Teknaf, the 2017 Rohingya influx triggered rapid and spatially concentrated vegetation loss that exceeded the natural resilience of local forest systems. However, the observed post-2019 recovery demonstrates that policy alignment across energy provision, reforestation, and community engagement can fundamentally alter landscape trajectories. Importantly, recovery was strongest in areas that had previously experienced the most severe degradation, indicating that targeted interventions can overcome threshold-level disturbances. The absence of statistically significant monotonic trends highlights the limitation of linear trend metrics in crisis-affected landscapes and underscores the value of phase-dependent vegetation dynamics inferred from multi-temporal change analysis. While recovery remains spatially uneven and vulnerable to continued settlement pressure, the Ukhiya–Teknaf case illustrates that environmental restoration can coexist with humanitarian response when ecological considerations are embedded within policy design. These findings can support policymakers in making more informed and effective decisions for managing natural resources in comparable crisis-affected forest landscapes.

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Conflicts of interest

No authors report conflicts of interest.

Author contributions

M.S.R. & M.J.S.S conceptualized the study, created the methodology; M.S.R conducted the analysis; M.S.R & M.A.I did the visualization; M.S.R., M.J.S.S., M.A.I, T. R., M.R.I and T.D.U. wrote the original draft and contributed to editing and reviewing.

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Data Availability Statement

Data will be made available by the corresponding author upon request.

References

Ahmed, B., M. S. Rahman, P. Sammonds, R. Islam and K. Uddin (2020). "Application of geospatial technologies in developing a dynamic landslide early warning system in a humanitarian context: the Rohingya refugee crisis in Cox's Bazar, Bangladesh." Geomatics, Natural Hazards and Risk 11(1): 446–468.

Ahmed, S., Simmons, W. P., Chowdhury, R., & Huq, S. (2021). The sustainability–peace nexus in crisis contexts: how the Rohingya escaped the ethnic violence in Myanmar, but are trapped into environmental challenges in Bangladesh. Sustainability Science, 16(4), 1201–1213. https://doi.org/10.1007/s11625-021-00955-6

Ahmed, T., & Sabastini, P. (2024). Deforestation as a site of conflict and differentiation: the case of the Rohingya refugee influx in the Teknaf Wildlife Sanctuary. Human Ecology, 52(1), 115–127. https://doi.org/10.1007/s10745-024-00480-x

Ali, N. M., & Shahreen, N. T. (2024). Climate-resilient water resource management for Rohingya refugee camps in Bangladesh. International Journal of Science and Research Archive, 12(1), 2661–2694. https://doi.org/10.30574/ijsra.2024.12.1.1139

Barua, P., M. H. Molla and S. H. Rahmar (2018). "Rohingya influx and environmental catastrophes in south-eastern Bangladesh." Social Change 8(1): 86–100.

Bashar, S., & Bernell, D. (2025). Stranded ecosystems: mitigating environmental impacts of Rohingya refugee camps in Cox's Bazar. Journal of Environmental Planning and Management, 1–19. https://doi.org/10.1080/09640568.2025.2494748

Bora, K., Borah, N., Bose, S., Goswami, J., & Kashyap, P. J. (2025). NDVI-Based Geospatial Analysis of Forest Cover Alterations in Daldali Reserve Forest, Assam, India. *Asian Journal of Geographical Research*, *8*(1), 61-72.

Braun, A., Fakhri, F., & Hochschild, V. (2019). Refugee Camp Monitoring and Environmental Change Assessment of Kutupalong, Bangladesh, based on radar imagery of Sentinel-1 and ALOS-2. Remote Sensing, 11(17), 2047. https://doi.org/10.3390/rs11172047

Brac (2017). Impact of forcibly displaced Myanmar nationals influx on host community. Dhaka, Bangladesh: Brac University, 25–26

Chowdhury, H., Chowdhury, T., Sharifi, A., Corkish, R., & Sait, S. M. (2022). Role of biogas in achieving sustainable development goals in Rohingya refugee camps in Bangladesh. Sustainability, 14(19), Article 11842. https://doi.org/10.3390/su141911842

Chowdhury, M., Williams, N. L., Thompson, K., & Ferdous, G. (2022). The Rohingya refugee crisis in Bangladesh: an analysis of the involvement of local humanitarian actors. Third World Quarterly, 43(9), 2188–2208. https://doi.org/10.1080/01436597.2022.2085087

Dampha, N. K., C. Salemi and S. Polasky (2022). Rohingya refugee camps and forest loss in Cox's Bazar, Bangladesh: an inquiry using remote sensing and econometric approaches, The World Bank.

El-Shirbeny, M. A., Biradar, C., Amer, K., & Paul, S. (2022). Evapotranspiration and vegetation cover classifications maps based on cloud computing at the Arab countries scale. *Earth Systems and Environment*, *6*(4), 837-849.

Era, T. J., Ferdous, Z. (2022). Analysing the Effects of Landuse Change on the Physical Environment of Teknaf and Ukhiya Upazila due to the Influx of Rohingya Refugees in Bangladesh. Journal of Remote Sensing & GIS. ISSN: 2469-4134

FAO (2020). FAO and Rohingya refugees restore forests in and around once barren camps. Website: https://www.fao.org/emergencies/resources-repository/news/detail/Bangladesh-FAO-and-Rohingya-refugees-restore-forests-in-and-around-once-barren-camps-/en

Faye, M. (2021). A forced migration from Myanmar to Bangladesh and beyond: humanitarian response to Rohingya refugee crisis. Journal of International Humanitarian Action, 6(1). https://doi.org/10.1186/s41018-021-00098-4

Hasan, M. E., Zhang, L., Dewan, A., Guo, H., & Mahmood, R. (2020). Spatiotemporal pattern of forest degradation and loss of ecosystem function associated with Rohingya influx: A geospatial approach. Land Degradation and Development, 32(13), 3666–3683. https://doi.org/10.1002/ldr.3821

Hasan, M. E., Zhang, L., Mahmood, R., Guo, H., & Li, G. (2021). Modeling of Forest Ecosystem Degradation Due to Anthropogenic Stress: The Case of Rohingya Influx into the Cox's Bazar–Teknaf Peninsula of Bangladesh. Environments, 8(11), 121. https://doi.org/10.3390/environments8110121

Hassan, M. M., Duveneck, M., & Southworth, J. (2023). The role of the refugee crises in driving forest cover change and fragmentation in Teknaf, Bangladesh. Ecological Informatics, 74, 101966. https://doi.org/10.1016/j.ecoinf.2022.101966

Hassan, M. M., Smith, A. C., Walker, K., Rahman, M. K., & Southworth, J. (2018). Rohingya refugee crisis and forest cover change in Teknaf, Bangladesh. Remote Sensing, 10(5), 689. https://doi.org/10.3390/rs10050689

Hashim, H., Abd Latif, Z., & Adnan, N. A. (2019). Urban vegetation classification with NDVI threshold value method with very high resolution (VHR) Pleiades imagery. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*, 237-240.

Hossain, F., & Moniruzzaman, D. (2021). Environmental change detection through remote sensing technique: A study of Rohingya refugee camp area (Ukhia and Teknaf sub-district), Cox's Bazar, Bangladesh. Environmental Challenges, 2, 100024. https://doi.org/10.1016/j.envc.2021.100024

Hossain, M. P. (2022). The Rohingya refugee crisis: analysing the international law implications of its environmental impacts on Bangladesh. The International Journal of Human Rights, 27(2), 238–257. https://doi.org/10.1080/13642987.2022.2081159

Islam, M. D., & Siddika, A. (2021). Implications of the Rohingya Relocation from Cox's Bazar to Bhasan Char, Bangladesh. International Migration Review, 56(4), 1195–1205. https://doi.org/10.1177/01979183211064829

Islam, T., Hemstock, S. L., Charlesworth, M., & Kabir, K. H. (2022). Assessment of the domestic energy use impacts of unplanned refugee settlements on the forest ecology of Cox's Bazar, Bangladesh. Ecocycles, 8(1), 86–98. https://doi.org/10.19040/ecocycles.v8i1.225

Jalal, R., Mahamud, R., Arif, M. T. A., Ritu, S., Kumar, M. F., Ahmed, B., … Henry, M. (2023). Restoring Degraded Landscapes through an Integrated Approach Using Geospatial Technologies in the Context of the Humanitarian Crisis in Cox's Bazar, Bangladesh. Land, 12(2), 352. https://doi.org/10.3390/land12020352

Kamal, A. M., B. Ahmed, S. Tasnim and P. Sammonds (2022). "Assessing rainfall-induced landslide risk in a humanitarian context: The Kutupalong Rohingya Camp in Cox's Bazar, Bangladesh." Natural Hazards Research 2(3): 230–248.

Karmakar, S., Rahman, M., & Meng, L. (2025). Land cover changes and land surface temperature dynamics in the Rohingya refugee area, Cox's Bazar, Bangladesh: An analysis from 2013 to 2024. Atmosphere, 16(3), Article 250. https://doi.org/10.3390/atmos16030250

Khalil, R., Khan, M. S., Hasan, Y., Nacer, N., & Khan, S. (2024). Supervised ndvi composite thresholding for arid region vegetation mapping. *Engineering, Technology & Applied Science Research*, *14*(3), 14420-14427.

Khan, A. K. (2024). A critical analysis of the factors influencing peaceful coexistence between Rohingya refugees and host communities in Cox's Bazar, Bangladesh. *Frontiers in Human Dynamics*, *6*, 1457372.

Kudrat-E-Khuda (2020). The impacts and challenges to host country Bangladesh due to sheltering the Rohingya refugees. Cogent Social Sciences, 6(1). https://doi.org/10.1080/23311886.2020.1770943

Kumar, S. (2022). Social and Environmental Imperatives for Risk Management: Lessons from the Rohingya Refugee Crisis. In Springer eBooks (pp. 161–188). https://doi.org/10.1007/978-3-030-85829-2_7

Mahmood, H., Saha, C., Paul, N., Deb, S., Abdullah, S. R., Tanvir, M. S. S. I., Bashar, A., Roy, S., Rabby, F., Ahmed, S. N., & Ali, M. H. (2021). The soil quality of the world's largest refugee campsites located in the hill forest of Bangladesh and the way forward to improve the soil quality. Environmental Challenges, 3, Article 100048. https://doi.org/10.1016/j.envc.2021.100048

Mahamud, R., R. Jalal, S. Ritu, E. Donegan, M. T. A. Arif, M. F. Kumar, M. F. Arafat, M. De Gaetano, M. H. Kabir and M. Henry (2022). "Restoring degraded land in Rohingya refugee camps in Cox's Bazar, Bangladesh."

Mishu, M. F. H., Rahim, R. R., & Rahman, M. A. (2023). A computational approach to evaluate the effect of shelter construction material and fuel load on the fire spread behavior in Rohingya refugee camp. arXiv preprint arXiv:2310.06078. https://doi.org/10.48550/arxiv.2310.06078

Mitra, J. R., Ahmed, T. T., & Czajkowski, K. (2025). Landscape fragmentation and population distribution in refugee camps: evidence from the Rohingya refugee influx in Bangladesh. Population and Environment, 47(2). https://doi.org/10.1007/s11111-025-00489-4

Mohiuddin, M., & Molderez, I. (2023). Rohingya influx and host community: A reflection on culture for leading socioeconomic and environmental changes in Bangladesh. European Journal of Cultural Management and Policy, 13, 11559.

Mowla, Q. A., & Hossain, S. T. (2021). Rohingya settlements in Ukhia and Teknaf and its impact on the ecosystem. Journal of Business, Society and Science, 8(1), 62–82.

Mukul, S. A., Huq, S., Herbohn, J., Nishat, A., Rahman, A. A., Amin, R., & Ahmed, F. U. (2019). Rohingya refugees and the environment. Science, 364(6436), 138. https://doi.org/10.1126/science.aaw9474

Parveen, S. (2024, April 1). The environmental impacts of Rohingya forced migration on host communities in Bangladesh.

Qiu, J., Yang, J., Wang, Y., & Su, H. (2018). A comparison of NDVI and EVI in the DisTrad model for thermal sub-pixel mapping in densely vegetated areas: A case study in Southern China. International Journal of Remote Sensing, 39(8), 2105–2118.

Rafa, N., Khalid, R., & Uddin, S. M. N. (2024). Energy access and sustainable development for displaced populations: Achieving energy justice in the Rohingya refugee camps of Cox's Bazar, Bangladesh. Energy Research & Social Science, 114, Article 103621. https://doi.org/10.1016/j.erss.2024.103621

Rafa, N., Van To, T. T., Gupta, M., & Uddin, S. M. N. (2021). The pursuit of energy in refugee contexts: Discrimination, displacement, and humanitarian energy access for the Rohingya refugees displaced to Bangladesh. Energy Research & Social Science, 83, 102334. https://doi.org/10.1016/j.erss.2021.102334

Rahman, M. H., & Mitani, Y. (2025). Can the Rohingya Refugee Crisis Be Solved Sustainably? Addressing Environmental Concerns in Ukhiya, Cox’s Bazar. In Reshaping Rohingya Futures (pp. 19–42). Palgrave Macmillan, Singapore.

Rahman, M., Islam, & Chowdhury, T. (2019). Change of Vegetation Cover at Rohingya Refugee Occupied Areas in Cox’s Bazar District of Bangladesh: Evidence from Remotely Sensed Data. Journal of Environmental Science and Natural Resources, 11(1–2), 9–16. https://doi.org/10.3329/jesnr.v11i1-2.43360

Rahman, M. Z. (2017). Livelihoods of Rohingyas and their impacts on deforestation. In *Deforestation in the Teknaf Peninsula of Bangladesh: A study of political ecology* (pp. 113-125). Singapore: Springer Singapore.

Rashid, H. E. (2013). Bangladesh: National Conservation Strategy. In Strategies for Sustainability: Asia (pp. 15–26). Routledge.

Reliefweb (2020). UN launch initiative to improve environment and livelihoods and energy supply in Cox's Bazar. Website: https://reliefweb.int/report/bangladesh/un-launch-initiative-improve-environment-and-livelihoods-and-energy-supply-coxs

Sajib, S. M. S. A., Islam, S. A. M. Z., & Sohad, M. K. N. (2022). Rohingya influx and socio-environmental crisis in southeastern Bangladesh. The International Journal of Community and Social Development, 4(1), 89–103. https://doi.org/10.1177/25166026211067604

Sánchez-Cuervo, A. M., & Aide, T. M. (2013). Consequences of the armed conflict, forced human displacement, and land abandonment on forest cover change in Colombia: a multi-scaled analysis. Ecosystems, 16(6), 1052–1070. https://doi.org/10.1007/s10021-013-9667-y

Taufiq, H. A. (2021). Rohingya refugee crisis and the state of insecurity in Bangladesh. arXiv preprint. https://doi.org/10.48550/arxiv.2107.12080

Thokchom, D. S. (2008). Monitoring Of Deforestation and Forest Degradation Using Normalized Difference Vegetation Index (NDVI): A Case Study of Imphal and Its Umland. *J. of Res. in Envi. & Earth Sci*, *8*(6), 54-59.

Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment, 8(2), 127–150.

Uddin, N. (2020). The Rohingya refugee crisis. Migration Research and Intercultural Studies.

UNHCR (2025). Rohingya refugee population dashboard. October 31, 2025. Website: https://reliefweb.int/report/bangladesh/joint-government-bangladesh-unhcr-rohingya-refugee-population-dashboard-31-oct-2025

UNHCR (2020). Bangladesh – Shelter Need Assessment Cox’s Bazar 2019. Website: https://microdata.unhcr.org/index.php/catalog/209

U.S. Geological Survey. (n.d.). Landsat Normalized Difference Vegetation Index (NDVI). Website: https://www.usgs.gov/landsat-missions/landsat-normalized-difference-vegetation-index

U.S. Geological Survey (2018). NDVI, the foundation for Remote Sensing Phenology. Website: https://www.usgs.gov/special-topics/remote-sensing-phenology/science/ndvi-foundation-remote-sensing-phenology

Zaitunah, A., Samsuri, & Sahara, F. (2021). Mapping and assessment of vegetation cover change and species variation in Medan, North Sumatra. Heliyon, 7(7), e07637.