

Quantifying Post-Eruption Vegetation Recovery on Mount Semeru Using UAV Time-Series Imagery

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Abstract

The December 2021 eruption of Mount Semeru caused massive ecological damage, initiating primary succession across landscapes buried by volcanic material. While satellite monitoring provides macro-scale trends, the micro-scale spatiotemporal dynamics and specific topographic drivers of early recovery remain poorly understood. This study quantifies the rate of vegetation recovery and statistically evaluates its micro-topographic constraints. We conducted a time-series analysis using ultra-high-resolution (2.7 cm/pixel) Unmanned Aerial Vehicle (UAV) RGB imagery acquired in 2022, 2023, and 2025 across a 127.08-hectare Area of Interest within Volcanic Hazard Zone III. Vegetation cover was extracted using the Excess Green (ExG) index with dynamic Otsu thresholding, validated by rigorous accuracy assessments (Overall Accuracy: 89%–95%). A 3-bit spatial coding logic tracked pixel-level successional trajectories, while topographic controls were evaluated using a non-parametric Mann-Whitney U test based on spatial random sampling. The results revealed a net vegetation recovery rate of +1.88 hectares/year, forming concentrated succession islands. Crucially, statistical analysis confirmed that micro-topographic slope acts as the primary abiotic control ($p < 0.001$); pioneer vegetation preferentially colonized steeper slopes (mean 43.20°) that offer structural refuge from active lahar flows, whereas flatter depositional beds (mean 23.64°) remained largely barren. Conversely, elevation (~798 masl) showed no significant correlation ($p = 0.68$), indicating that secondary fluvial disturbances override broad altitudinal gradients within this active corridor. This study demonstrates a validated, reproducible UAV framework for high-precision ecological monitoring, providing fundamental insights for targeted post-eruption restoration strategies.

Keywords: Mount Semeru; Primary Succession; UAV Photogrammetry; Vegetation Recovery; Time-series Analysis

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INTRODUCTION

The eruption of Mount Semeru on December 4, 2021, was a significant natural disaster that triggered an ecological and humanitarian crisis in Lumajang Regency, East Java. The collapse of the lava dome at the Jonggring Saloko crater generated pyroclastic and lahar flows that descended towards the Curah Robokan plains in Supiturang Village, Pronojiwo District. Volcanic materials such as hot ash, pumice, and cold lahar blanketed the area, posing a substantial threat to the surrounding ecosystem and vegetation. Three villages Oro-Oro Ombo, Supiturang, and

Sumberwuluh suffered severe damage, with recorded losses including 51 fatalities, hundreds of injuries, and thousands of affected residents. This disaster not only claimed lives but also crippled the socio-economic foundations of the community, which is heavily dependent on natural resources (Hidayat et al., 2024; Purba et al., 2022; Setiawati et al., 2024).

Ecologically, the scale of the damage was massive. An initial post eruption analysis identified a total affected area of 2,331.34 hectares, of which 95.02% was classified as having sustained a moderate level of damage. This damage encompassed various land cover types vital for ecosystem function and local livelihoods. The agricultural sector, the backbone of the local economy, was severely impacted, with 375 hectares of paddy fields and 46 hectares of cornfields destroyed. Furthermore, coffee and albizia plantations belonging to local residents were also devastated. Subsequent analysis using Sentinel-2 satellite imagery confirmed severe impacts on the forest ecosystem; in Candipuro District, a reduction in forest area of 1,278.34 hectares occurred due to burial by volcanic material. This vegetation loss directly led to a decline in biodiversity, damaged agricultural infrastructure, and threatened wildlife survival (Purba et al., 2022; Syuaibah et al., 2024).

Research on ecosystem resilience and post eruption recovery in Indonesia has predominantly utilized satellite based remote sensing. A study by (Soraya et al., 2016)] at Mount successfully modeled spatial resilience and analyzed land cover transitions from open areas back to vegetated land using multitemporal Landsat imagery. A similar landscape scale approach was employed by (Lai et al., 2022) at Mount Unzen, Japan, who used a Landsat time series to model recovery rates with a linear log function, which more accurately captures the dynamics of primary succession.

Nevertheless, these satellite-based studies possess inherent limitations related to their relatively coarse spatial resolution of 30 meters for Landsat 8. This limitation has been explicitly acknowledged by researchers, who have highlighted that the resulting land cover classifications are often too general to detect changes at the species composition level or to identify the presence of invasive species. Underscored that a 30 meter resolution likely obscures small scale relationships, such as the influence of microtopography on seed survivability (Fang et al., 2024; Hu & Shean, 2022; Park, 2013; Rahimi & Jung, 2024). The urgency for more precise monitoring methods is thus evident, as directly recommended by (Bakó et al., 2021; Keränen et al., 2024; Kerry et al., 2022; Pleniou & Koutsias, 2025), who called for more detailed research using remote sensing imagery with a higher spatial resolution.

Studies on post-eruption vegetation recovery in Indonesia have been widely conducted using medium resolution satellite imagery, such as Landsat. A key study by (Soraya et al., 2016) successfully modeled the spatial resilience of the Mount Merapi ecosystem by analyzing land cover transitions from open areas to vegetated land following the 2010 eruption. A similar approach, albeit with a more complex analytical methodology, was applied by (Lai et al., 2022) at Mount Unzen, Japan, who used a Landsat time series to model recovery rates with a linear log function and analyzed topographic factors as control variables. Although highly useful for landscape scale assessments, these studies explicitly acknowledge the inherent limitation of medium resolution satellite data (30 meters). Previous researchers stated that the resulting classifications were still too general and could not detect changes at the species composition level (Bolyn et al., 2022; Coldea et al., 2025; Polyakova et al., 2023; Rocchini et al., 2016). Similarly experts (Chytrý et al., 2024; Karami et al., 2025; Ramsay

et al., 2025; Taghavi-Bayat et al., 2024) highlighted that a 30 meter resolution likely obscures small scale relationships, such as the influence of microtopography on seed survivability. These limitations underscore the urgent need for research with higher spatial resolution, as directly recommended by researchers (Chen et al., 2021; Hamel & Andréfouët, 2010; Pierrat et al., 2025).

The advancement of Unmanned Aerial Vehicle (UAV) technology in the last decade offers a solution to this resolution gap. UAVs can acquire imagery with very high spatial resolution centimeter level flexibly and at a relatively lower cost than manned aerial photography. The reliability of UAV technology for environmental monitoring has been proven in Indonesia. Specifically at the research location, (Bachri et al., 2024; Kurnianto et al., 2024; Z. Wang et al., 2024) have demonstrated that UAV based mapping is highly effective for detecting and mapping areas affected by the Semeru eruption in detail post 2022. This study validates the use of UAVs for geospatial data collection in difficult to access terrain. Furthermore, the workflow for quantifying vegetation growth parameters from UAV time series data has been well established in other disciplines. For instance, (Bongomin et al., 2024; Rasti et al., 2022) showed how periodic UAV image acquisition can be used to construct high precision growth curves by accurately extracting metrics such as canopy area and height.

Based on the foregoing review, this research is positioned to bridge the gap between existing landscape scale monitoring and the need for very high-resolution data at the plot level. While satellite-based studies have successfully mapped whether recovery is occurring on a broad scale, this study will answer how precisely and why this recovery occurs at the micro scale. This research directly responds to the recommendation by (Y. Zhong et al., 2020) by implementing UAV technology that offers centimeter level spatial resolution. By adopting a wall-to-wall mapping approach and a time series-based land cover change methodology, this study presents a novel approach to quantifying the rate of post eruption vegetation recovery in Indonesia with an unprecedented level of detail. Consequently, this research will provide a significant contribution to understanding the mechanisms of primary succession and offer a more robust scientific basis for future ecological restoration efforts.

This study is proposed to directly address this need by applying UAV technology, which offers ultra-high spatial resolution at the centimeter level (<5 cm/pixel). The use of UAVs for vegetation monitoring has proven reliable and effective in various Indonesian contexts. The workflow, involving periodic UAV image acquisition and photogrammetric processing, has been validated for its ability to construct high precision growth curves by extracting parameters such as canopy area, height, and volume (Gano et al., 2024; Greco et al., 2023; Guimarães et al., 2020; Sefercik et al., 2025; Zarychta & Zarychta, 2025; Zhang et al., 2021; Y. Zhong et al., 2020). By adapting this high precision phenotyping methodology to an ecological succession context, this research introduces novelty in monitoring post eruption vegetation recovery, shifting the scale from landscape level to high precision plot level analysis, a task that has historically been difficult to achieve.

Despite the wealth of macro-scale satellite studies, there remains a critical knowledge gap regarding the micro-scale spatiotemporal dynamics of primary succession and its specific topographic drivers in highly disturbed active volcanic corridors. Therefore, the novelty of this research lies in the application of a 3-bit pixel trajectory coding logic to quantify ultra-high-resolution (2.7 cm/pixel) recovery

clusters, combined with rigorous non-parametric inferential statistics to evaluate micro-topographic controls.

To address this gap, this study tests two primary hypotheses: (H1) Within the localized active volcanic corridors, micro-topographic slope acts as the primary abiotic control for succession, where recovery probability increases on steeper, stable river banks compared to flat depositional beds; and (H2) Elevation does not significantly limit recovery within this specific highly-disturbed altitudinal zone, as secondary fluvial disturbances override broad climatic gradients. Ultimately, this research aims to provide a precise, reproducible framework for monitoring post-eruption ecological recovery, supporting evidence-based restoration strategies and adaptive management plans for the Semeru disaster area.

METHOD

Research Design

The overall methodological framework of this study is systematically illustrated in Figure 1. The research workflow was structured into four primary phases to ensure high reproducibility and analytical rigor. Phase 1 involved multi-temporal UAV data acquisition and photogrammetric pre-processing to generate high-resolution orthomosaics and Digital Elevation Models (DEMs). Phase 2 focused on feature extraction, utilizing the Excess Green (ExG) index with dynamic Otsu thresholding to isolate vegetation, alongside the derivation of topographic slope from the DEM. Phase 3 encompassed the spatiotemporal change detection using a 3-bit map algebra coding logic and spatial aggregation to map recovery dynamics. Finally, Phase 4 comprised rigorous validation through confusion matrix accuracy assessments and non-parametric statistical topometry (Mann-Whitney U test) to evaluate the ecological drivers of succession.

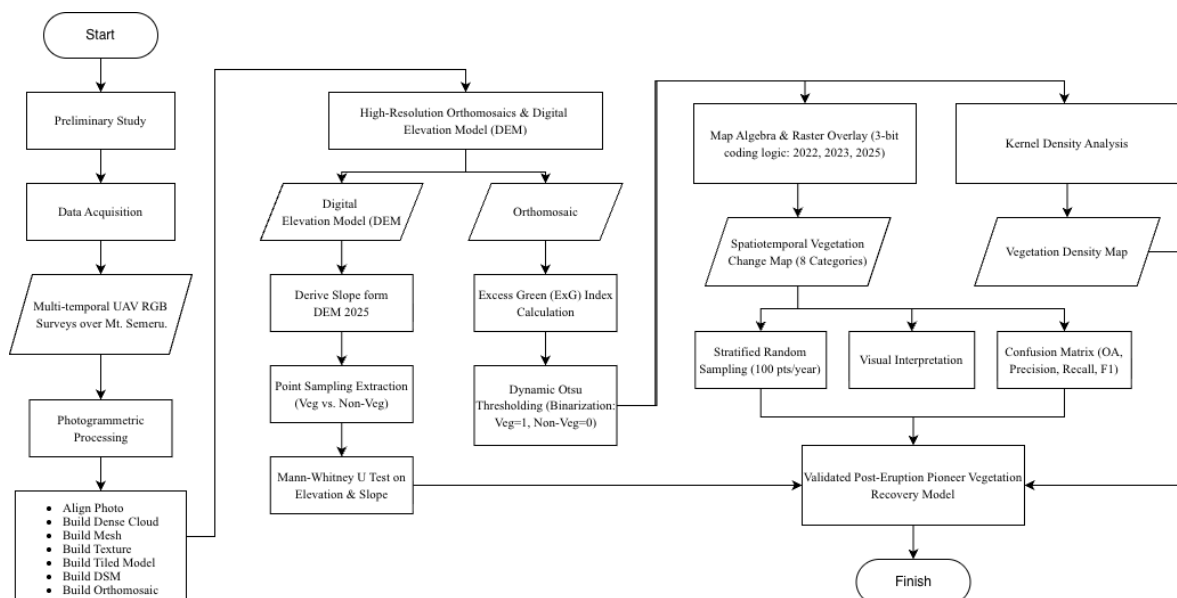


Figure 1. Research Flow Chart

Study Area

This study employed a quantitative approach with a longitudinal (time series) survey design to monitor and measure the dynamics of vegetation recovery in the area affected by the Mount Semeru eruption. The research was administratively located in

the Candipuro and Pronojiwo Districts, Lumajang Regency, East Java, focusing on the southeastern slopes of the volcano, which were most severely impacted by pyroclastic and lahar flows during the December 2021 eruption. Data were collected periodically over a three-year span, from June 2022 to June 2025, to capture the initial stages of the vegetation succession process.

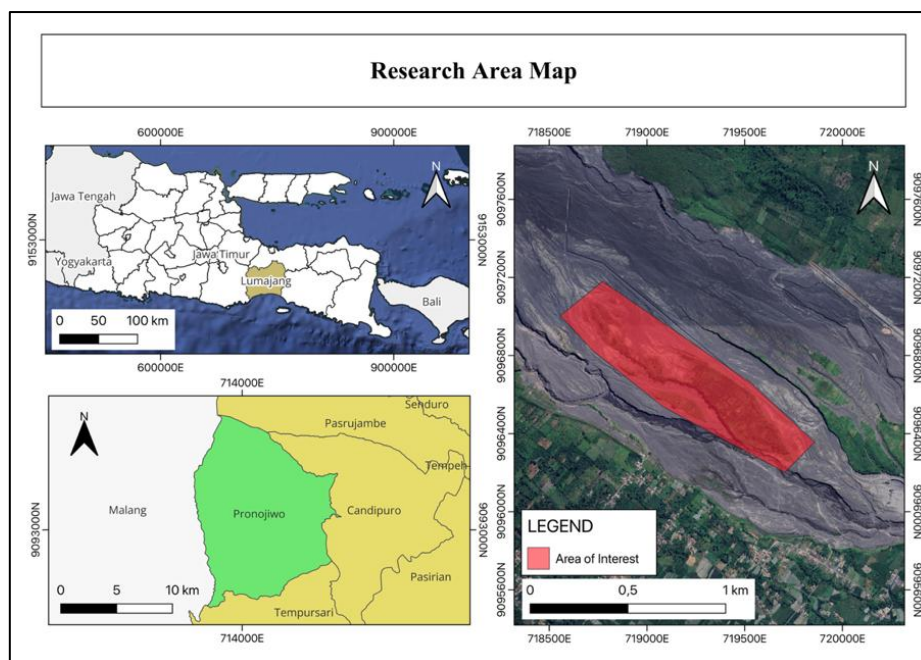


Figure 2. Research Area Map

The object of this research is the dynamic process of vegetation recovery, which was measured through a land cover change analysis of high-resolution UAV imagery. This study utilized a wall-to-wall mapping approach, a method that allows for a comprehensive analysis of land change across the entire study area (Choi et al., 2023; Guerra-Hernández et al., 2021; Horning et al., 2020; Nevalainen et al., 2025; Oddi et al., 2021). This approach was applied to a single primary Area of Interest (AOI) that was delineated to cover 127.08 hectares, which representatively captures key areas where various ecological processes occur. The research design focused on the identification and quantification of various categories of vegetation change dynamics that occurred between 2022 and 2025. The categories of focus for the analysis included stable conditions (Stable Non-Vegetation and Stable Vegetation), growth processes (New Growth), loss processes (Vegetation Loss), and complex dynamics such as Temporary Vegetation (growth followed by loss) and Recovered Vegetation (loss followed by regrowth).

UAV Data Acquisition

Primary Data Acquisition

The primary data for this study consisted of very high-resolution optical imagery acquired using a DJI Mavic 2 Pro Unmanned Aerial Vehicle (UAV). Data collection was conducted comprehensively (wall to wall) over the 127.08-hectare Area of Interest (AOI). To ensure a consistent temporal change analysis, data acquisition was performed at three distinct time points: June 2022, May 2023, and April 2025. The timing of acquisition during the dry season was intended to minimize potential cloud cover and other atmospheric disturbances, thereby ensuring optimal image quality.

Table 1. Unmanned Aerial Vehicle (UAV) flight parameters and environmental conditions (2022–2025)

Parameter	2022 Dataset	2023 Dataset	2025 Dataset
UAV Platform	DJI Mavic 2 Pro	DJI Mavic 2 Pro	DJI Mavic 2 Pro
Camera Sensor	1" CMOS, 20 MP (RGB)	1" CMOS, 20 MP (RGB)	1" CMOS, 20 MP (RGB)
Flight Altitude	100m AGL	100m AGL	100m AGL
Image Overlap	70% Front, 60% Side	70% Front, 60% Side	70% Front, 60% Side
Weather/Illumination	Clear sky, morning	Partly cloudy, morning	Clear sky, morning
Resulting GSD	2.7 cm/pixel	2.7 cm/pixel	2.7 cm/pixel

All flight missions were configured with consistent parameters to guarantee data comparability. Flights were conducted at an altitude of 100 meters Above Ground Level (AGL) with a cruising speed of 10 m/s. This configuration yielded imagery with a very high spatial resolution (< 5 cm/pixel), enabling the identification of individual vegetation objects. To ensure the quality of the photogrammetric results, the image overlap was set to 70% forward overlap and 60% side overlap. To guarantee georeferencing accuracy and minimize spatial shifts between images from different years, a series of Ground Control Points (GCPs) were established and measured using a Geodetic GPS prior to each acquisition mission.

Secondary Data Acquisition

Secondary data were utilized in this study to provide context and justification for the research design, as well as for the analysis of external factors influencing vegetation recovery. The primary secondary data used were: (1) Volcanic Hazard Zone Map (KRB Map) for Mount Semeru, published by the Center for Volcanology and Geological Hazard Mitigation (PVMBG), was used as the fundamental basis for defining the hazard level at the research location. According to this map, the entire Area of Interest (AOI) under investigation was identified as being within the KRB III zone, which is the area with the highest potential hazard. (2) Monthly Climate Data for the 2022 to 2025 research period was obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) of the Class II Climatology Station of East Java. This dataset includes monthly rainfall (mm), average air temperature ($^{\circ}\text{C}$), and average air humidity (%) from the representative Tamanayu/Pronojiwo Station. This climate data will be used in the discussion phase to analyze the influence of seasonal and climatic factors, particularly rainfall, on the observed vegetation change dynamics.

Additionally, high resolution satellite imagery from public geospatial platforms such as Google Earth was used in the initial phase for field orientation and AOI delineation. It must be emphasized that while secondary data were crucial for the design and discussion, all quantitative analyses of vegetation change in this study were based exclusively on the primary UAV data acquired in the field.

Photogrammetric Processing

The processing of raw UAV imagery into the final vegetation change map were performed through a systematic workflow. This process integrated photogrammetric software with a Geographic Information System (GIS). The stages of this workflow are detailed as follows: (1) Photogrammetric Processing began by processing the

collection of RGB aerial photographs from each acquisition period (2022, 2023, and 2025). A standard photogrammetric workflow was applied to generate the primary geospatial data products. This process started with image alignment, where the software automatically identifies and matches features in overlapping photos to generate a sparse point cloud (*tie points*). Based on the tie points and GCP information, a dense point cloud was subsequently built using a high quality setting. From this dense point cloud, two primary geospatial products that form the basis for further analysis were exported a Digital Elevation Model (DEM) with a spatial resolution of 5.39 cm/pixel and an RGB Orthomosaic with a spatial resolution of 2.70 cm/pixel; (2) Vegetation Index Calculation from the RGB orthomosaic product for each time period, the Excess Green (ExG) vegetation index was calculated using GIS software. This index was selected for its effectiveness in discriminating green vegetation pixels from non vegetation pixels, such as soil or dry volcanic material, using only the available RGB spectral bands. This process, conducted via a Raster Calculator function, converted the RGB orthomosaic into a single band grayscale image where vegetation pixels have higher intensity values; (3) Land Cover Classification the ExG image from each year (2022, 2023, and 2025) was then classified to produce a binary land cover map consisting of two primary classes: vegetation and non vegetation. This process was performed using a thresholding method. To ensure objectivity, the automated Otsu method was used to calculate the optimal threshold value from the image histogram. Pixels with an ExG value above the determined threshold were classified as vegetation and assigned a pixel value of 1, while pixels below the threshold were classified as non vegetation and assigned a pixel value of 0. The result was three binary land cover maps, one for each year; and (4) Change Detection Analysis, final stage was a post classification comparison analysis. Using a Raster Calculator, the three binary land cover maps were mathematically combined to create a new thematic map. Each pixel in this new map has a unique value representing its change history from 2022 to 2025. These unique values were then reclassified into informative vegetation change categories, such as *Stable Non Vegetation*, *Stable Vegetation*, *New Growth*, *Vegetation Loss*, *Temporary Vegetation*, and *Recovered Vegetation*. The final output of this stage is a single thematic map that visualizes the spatial distribution of each vegetation change dynamic category across the entire AOI.

To ensure precise spatial alignment for the multi-temporal overlay analysis, all datasets were georeferenced to the WGS 84 / UTM zone 49S projected coordinate reference system (EPSG: 32749). The final generated orthomosaics and DEMs achieved an average Ground Sample Distance (GSD) of <2.5 cm/pixel, providing the ultra-high spatial resolution strictly required for detecting micro-scale pioneer vegetation dynamics.

Data Analysis Techniques

Vegetation Classification with ExG

To extract the spatial distribution of pioneer vegetation from the high-resolution RGB orthomosaics, the Excess Green (ExG) index was utilized. The ExG index is highly effective in discriminating green plant canopies from bare soil, rocks, and fresh volcanic ash backgrounds. It operates by emphasizing the green spectral band reflectance while penalizing the red and blue bands. The index was computed using the normalized RGB chromatic coordinates according to Equation 1.

$$ExG = 2G - R - G \dots\dots\dots Eq1$$

Following the index calculation, a binarization process was required to separate the pixels into two distinct classes: Vegetation (Value = 1) and Non-Vegetation (Value = 0). Instead of relying on a global, static threshold which often introduces severe bias across multi-temporal datasets due to varying illumination and seasonal phenology this study employed a dynamic Otsu thresholding approach. The Otsu algorithm determines the optimal threshold automatically by minimizing the intra-class variance and maximizing the inter-class variance between the vegetation and background pixels.

The specific threshold values derived and applied for each acquisition year are detailed in Table 2. The threshold was consistently set at 35 for the 2022 and 2023 datasets, ensuring the accurate extraction of establishing primary succession on the weathering substrate. However, a critical adjustment was made for the 2025 dataset. Because the 2025 flight was conducted in April (transitioning into the dry season), the threshold was lowered to 30. This dynamic calibration was ecologically necessary to account for the seasonal senescence and water stress of shallow-rooted pioneer grasses, ensuring that browning vegetation was accurately detected rather than misclassified as bare volcanic substrate.

Table 2. Dynamic threshold values derived from the Otsu method for Excess Green (ExG) index binarization.

Year	ExG Data Range (Min to Max)	Applied Otsu Threshold	Justification for Threshold Selection
2022	-44 to 207	35	Optimal separation of early pioneer vegetation from highly reflective fresh volcanic ash and lahar deposits.
2023	-35 to 216	35	Maintained consistency with 2022 parameters to accurately capture establishing primary succession on the weathering substrate.
2025	-40 to 243	30	Lowered threshold to account for dry-season senescence, ensuring the detection of browning pioneer grasses while accommodating patches of mature, highly green vegetation (Max 243).

Times Series Change Detection

To quantify the precise spatiotemporal dynamics of pioneer succession, a pixel-based time-series change detection was performed using GIS map algebra. The binary classification maps (where 1 represents vegetation and 0 represents non-vegetation) from 2022, 2023, and 2025 were chronologically stacked and overlaid. This spatial operation generated a unique 3-bit spatiotemporal sequence code for every single pixel within the study area, documenting its specific ecological trajectory over the three-year observation period.

As detailed in Table 3, this coding logic successfully categorized the landscape into eight distinct successional classes. For instance, a pixel sequence of "0-0-0" denotes a stable non-vegetated area representing persistent bare volcanic substrate or active lahar channels. Conversely, a sequence of "0-1-1" signifies successful primary succession that established in 2023 and survived through the 2025 observation. This granular classification system allows for a highly nuanced understanding of post-

eruption recovery, strictly differentiating between permanent colonization, temporary ephemeral growth, and vegetation loss caused by secondary disturbances or seasonal extreme dry periods. Furthermore, to visualize the spatial clustering of the recovery process, a vegetation density map was generated. This was achieved by aggregating the binary classification results using spatial density analysis, which effectively delineates the core areas of intensive pioneer colonization from dispersed, isolated growth across the volcanic corridors.

Table 3. Spatiotemporal pixel coding logic for vegetation change detection. The 3-bit code represents the chronological binary sequence (Vegetation = 1, Non-Vegetation = 0) across the three observation years.

Time-Series Code (2022 - 2023 - 2025)	Ecological Interpretation	Description of Succession Dynamics
0 - 0 - 0	Stable Non-Vegetation	Bare volcanic substrate or active lahar channels with no recovery.
1 - 1 - 1	Stable Vegetation	Surviving vegetation or early pioneers that persisted throughout.
0 - 1 - 1	New Growth (2023+)	Primary succession established in 2023 and survived until 2025.
0 - 0 - 1	New Growth (2025)	Delayed primary succession that only emerged in the 2025 dataset.
0 - 1 - 0	Temporary Vegetation	Ephemeral growth in 2023 that was subsequently lost or buried by 2025.
1 - 0 - 1	Recovered Vegetation	Initial vegetation lost in 2023, but recolonized by 2025.
1 - 1 - 0	Vegetation Loss (2025)	Vegetation present until 2023 but lost in 2025.
1 - 0 - 0	Vegetation Loss (2023)	Initial vegetation destroyed in 2023 with no subsequent recovery.

Accuracy Assessment & Statistical Validation

To ensure the reliability of the ExG-based binary classification, a rigorous accuracy assessment was conducted for each observation year (2022, 2023, and 2025). A stratified random sampling approach was employed to generate 100 validation points per year, evenly distributed between the vegetation (n=50) and non-vegetation (n=50) classes to prevent sample bias. Visual interpretation of the ultra-high-resolution RGB orthomosaics served as the reference ground truth. A confusion matrix was then constructed to calculate the True Positives (TP), True Negatives (TN), False Positives (FP), and False Negatives (FN). Based on these matrices, the Overall Accuracy (OA) and F1-Score were computed to evaluate the classification performance.

Furthermore, to investigate the micro-topographic constraints governing pioneer succession, a spatial statistical analysis was performed. A set of 200 random points was generated within the study bounds to extract values from the 2025 Digital Elevation Model (DEM) and the derived Slope map, concurrently with the 2025 binary vegetation status (Recovered vs. Non-Recovered). Because micro-topographic variables in highly rugged volcanic terrains often deviate from a normal distribution, a non-parametric two-sided Mann-Whitney U test was applied. This test was utilized to determine whether the differences in median elevation and slope between the

vegetated and non-vegetated areas were statistically significant ($\alpha = 0.05$). All statistical computations were executed using Python's SciPy library.

RESULTS AND DISCUSSION

Vegetation Recovery Rate

The analysis of land cover change within the 127.08 hectare Area of Interest (AOI) between 2022 and 2025 revealed significant dynamics in vegetation recovery. Of the total study area, 8.93 hectares consisted of stable vegetation that was consistently present throughout the observation period. The primary recovery process was identified through the emergence of 7.50 hectares of new vegetation growth and 0.94 hectares of recovered area. Conversely, a loss of 1.33 hectares of vegetation and the appearance of 1.46 hectares of temporary vegetation were also observed. A detailed breakdown of the area for each change category is presented in Table 1.

Based on the aggregation of this data, the total increase in vegetation cover (new growth and recovered vegetation) reached 8.44 hectares, while the total loss of vegetation cover (encompassing loss and temporary vegetation) amounted to 2.79 hectares. From these calculations, a positive Net Change Rate of +1.88 hectares per year was determined. This value indicates that, overall, the processes of succession and vegetation recovery were more dominant than degradation processes within the study area during the three year observation period.

Table 4. Detailed Area of Vegetation Change Categories

Change Category	Measure	
	Pixsel Code	Area (hectares)
Stable Non-Vegetation	0	106.89
Stable Vegetation	111	8.93
New Growth (in 2023 & persisting)	110	4.38
New Growth (only in 2025)	100	3.12
Temporary Vegetation (grew then lost)	10	1.46
Recovered Vegetation (lost then regrew)	101	0.94
Vegetation Loss (in 2025)	11	0.9
Vegetation Loss (in 2023 & not recovered)	1	0.43
Total AOI		127.08

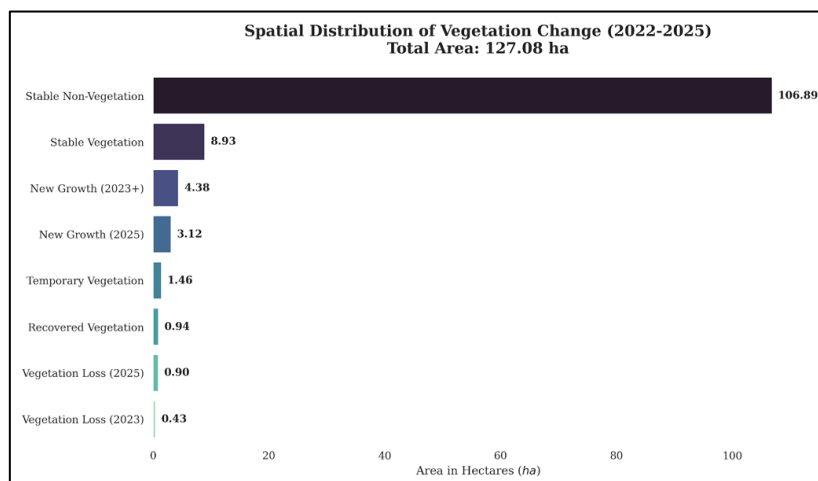


Figure 3. Spatial Distribution of Vegetation change

The accuracy assessment demonstrates robust classification performance across all years, with Overall Accuracy consistently exceeding 89%. With F1-scores remaining ≥ 0.90 . The slight decrease in accuracy and increase in False Negatives (FN = 9) observed in the 2025 dataset can be attributed to the specific acquisition month (April). During this transition into the dry season, early successional grasses began to experience water stress and senescence, lowering their green reflectance and causing the ExG index to conservatively exclude some browning vegetation. Nevertheless, the high precision and recall rates confirm that the dynamic Otsu thresholding effectively isolated the vegetation from the highly reflective volcanic ash.

Table 5. Confusion Matrix Components and Accuracy Assessment Metrics

Year	True Positive (TP)	True Negative (TN)	False Positive (FP)	False Negative (FN)	Overall Accuracy (OA)	F1-Score
2022	49	46	1	4	95.00%	0.95
2023	47	48	3	2	95.00%	0.95
2025	48	41	2	9	89.00%	0.90

Spatial Patterns of Vegetation Recovery

Spatial analysis of the land cover change classification results identified clear agglomeration patterns for each category of vegetation dynamics, as presented in Figure 4. Areas undergoing recovery, primarily classified as *Stable Vegetation* and *New Growth*, formed a dominant spatial aggregation in the central part of the Area of Interest (AOI). Conversely, the *Stable Non-Vegetation* category was concentrated along channels that serve as active sediment transport pathways post eruption. The *Vegetation Loss* category, representing degradation, was detected in much smaller areas and was sporadically distributed, mainly at the edges of the primary vegetation clusters.

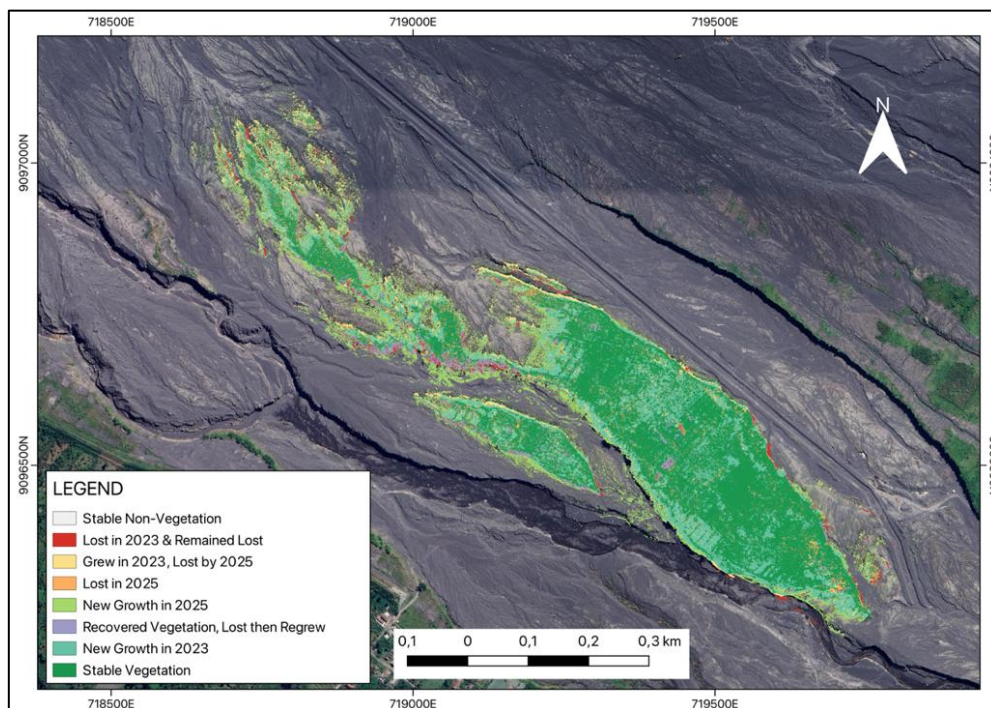


Figure 4. Map of Vegetation Change Category Distribution in the Semeru AOI 2022-2025

To quantitatively validate these visual observations and identify statistically significant recovery clusters, a Vegetation Recovery Density Map was generated based on the density of recovery points, the results of which are presented in Figure 5. This analysis confirmed the presence of a primary high density cluster, a statistically significant cluster of high recovery density, whose location coincides with the vegetation aggregation observed in Figure 5. Areas with the lowest recovery density are clearly associated with the Stable Non Vegetation areas. Collectively, these two spatial analyses demonstrate that the vegetation recovery process is not randomly distributed but is strongly influenced by local spatial conditions, the relationship of which with topographic factors will be analyzed in the following subsection.

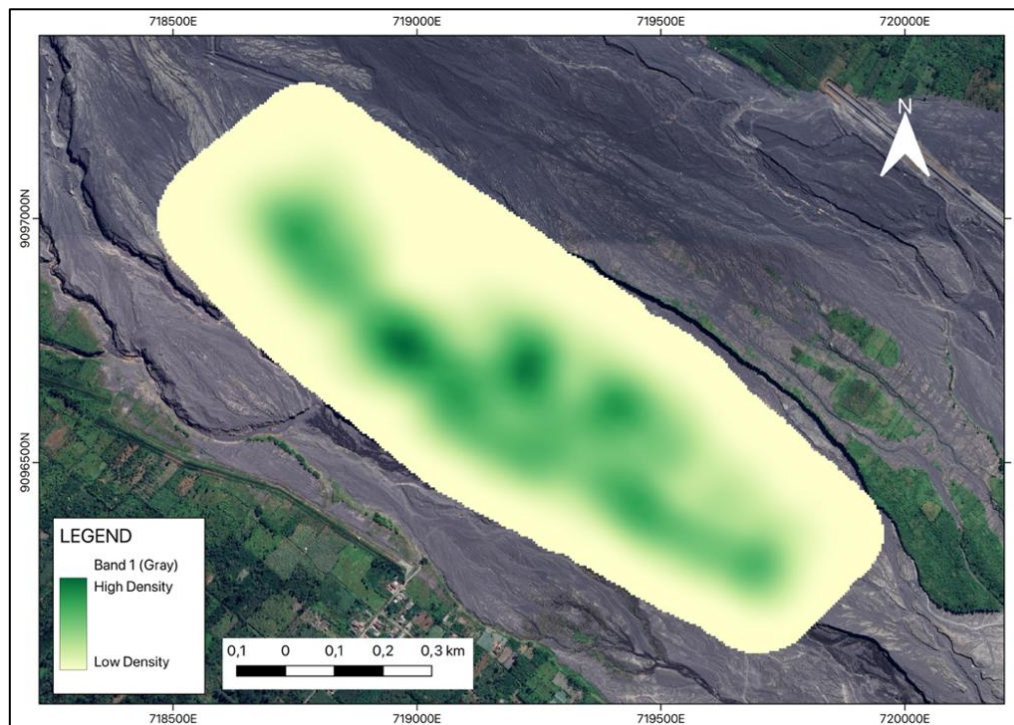


Figure 5. Vegetation Recovery Density Map within the AOI

Topographic Control Factors

This study identified a net vegetation recovery rate of +1.88 hectares per year within the AOI. This positive value quantitatively confirms that the ecological succession process is actively underway, where the colonization and growth of new vegetation are more dominant than mortality or degradation rates. This rate, although seemingly moderate in absolute terms, represents a significant dynamic in the early stages of primary succession in a severely disturbed environment. This finding is consistent with research in other post-eruption landscapes, which also shows rapid vegetation recovery in the initial years following a disturbance, before eventually slowing and reaching a plateau phase. A study at Mount Unzen (Lai et al., 2022), for example, modeled this recovery trend using a logarithmic function, which reflects accelerated growth in the early stages. Thus, the high-resolution data from the UAV in this study provide micro-scale confirmation of the landscape-scale recovery patterns previously observed only through satellite imagery.

The vegetation change map and the Density Map collectively demonstrate that vegetation recovery is not randomly distributed but forms significant spatial clusters. The high concentration of recovery in the central and upper parts of the AOI indicates

the presence of succession islands where local biophysical conditions are more conducive to colonization. Conversely, the low recovery density area, which coincides with the main river channels, suggests that substrate instability due to secondary fluvial processes (transport of lahar material by water) is a major impediment to the permanent establishment of vegetation. This pattern is consistent with the mapping of affected areas by (Bachri et al., 2025), who identified these channels as active lahar pathways post-2022 eruption. Therefore, it can be concluded that the spatial heterogeneity in vegetation recovery within KRB III is strongly influenced by post-eruption surface stability.

To quantitatively identify the micro-topographic constraints influencing these vegetation recovery patterns, an analysis was conducted on primary topographic variables. To fulfill the statistical rigor required to prove these differences, a non-parametric Mann-Whitney U test was performed, comparing the topographic characteristics between the recovery zone (DN=1) and the non-recovery zone (DN=0). The results are presented in Table 6.

Table 6. Mann-Whitney U test results comparing average elevation and slope between Recovery and Non-Recovery zones.

Topographic Variable	Recovered (n=84) (Mean $\pm$ SD)	Non-Recovered (n=116) (Mean $\pm$ SD)	U-Statistic	p
Elevation (masl)	798.46 $\pm$ 18.99	798.29 $\pm$ 30.67	4708.0	6.857
Slope (°)	43.20 $\pm$ 23.37	23.64 $\pm$ 20.41	7354.5	< 0.0001

The analysis of these topographic factors provides a clear explanation for the mechanisms behind the observed spatial patterns. The combination of local topographic constraints creates safe sites, which are small areas with the most ideal conditions for seeds to germinate and grow in the extreme post-eruption environment (Li et al., 2023; Liang et al., 2024; Zhou et al., 2025).

The non-parametric statistical analysis confirms that terrain slope acts as a highly significant abiotic control factor ($p < 0.001$). Strikingly, vegetation recovery is statistically more dominant on steeper slopes, with an average of approximately 43.20° for the recovery zone, which is significantly higher than the non-recovery zone's flatter average of 23.64°. This initially counter-intuitive finding is highly consistent with the principles of ecological restoration in active volcanic corridors. The flatter areas (~23°) represent the active depositional beds of the lahar channels that experience continuous secondary disturbances in the form of cold lahar (debris flows) triggered by rain.

These fluvial processes constantly inhibit succession by washing away seeds and burying new seedlings. In contrast, the steeper slopes (~43°) correspond to the consolidated river banks and ravine terraces. These steeper micro-sites are physically more stable from unconsolidated volcanic material erosion. This stability allows for the accumulation of crucial resources such as water due to higher infiltration and nutrients, and also serves as effective seed traps. Many studies have confirmed this dynamic; for example (Crockett & Hurteau, 2024; Zahura et al., 2024) also identified slope as a key variable influencing vegetation recovery in post-eruption landscapes.

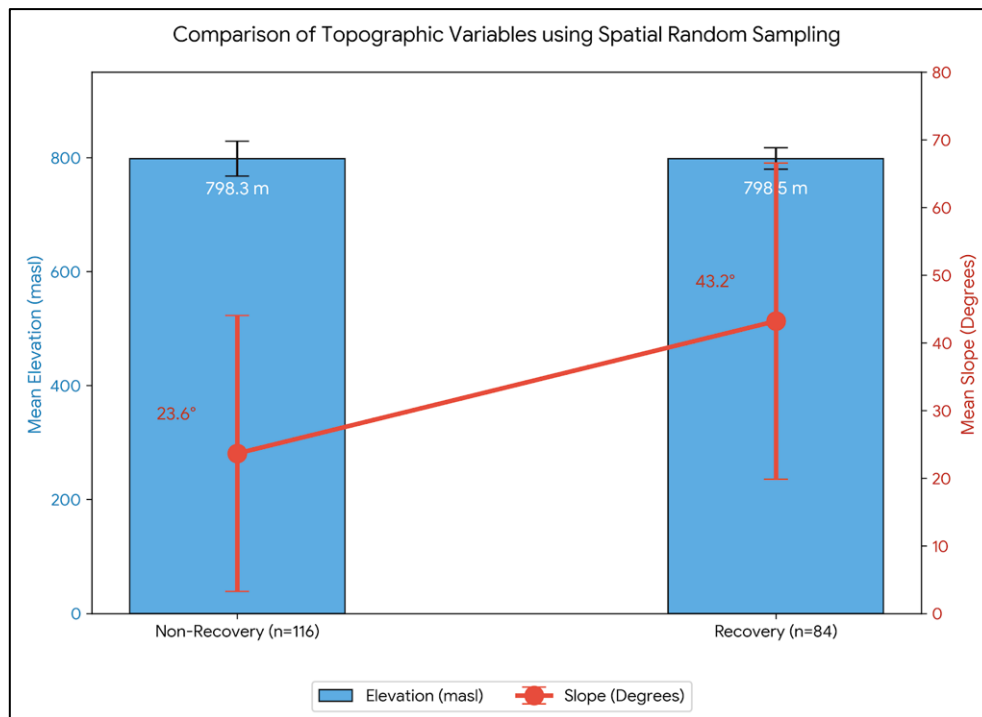


Figure 6. Comparison of mean elevation and slope between recovery and non-recovery zones based on spatial random sampling

Conversely, the statistical test revealed that elevation had no significant correlation with recovery success ($p = 0.6857$), with both vegetated and bare areas sharing a nearly identical average altitude of ~ 798 masl. While a study at Mount Unzen found that elevation was one of the most significant predictors in their vegetation recovery model because different elevations experience different types of eruption impacts (Lai et al., 2022) our findings demonstrate that within a localized, highly disturbed lahar corridor, secondary fluvial disturbances completely override broad altitudinal gradients. Furthermore, while the influence of slope aspect on microclimate (solar radiation, soil temperature, and moisture) is a fundamental concept in landscape ecology known to significantly influence recovery (Wang et al., 2023; Yang et al., 2020; Zhong et al., 2023), the extreme physical instability of the lahar channels in our study area dictates that substrate stability driven by slope is the absolute primary prerequisite for safe site establishment before microclimatic preferences can take effect.

In addition to the static topographic factors, the observed vegetation recovery dynamics also show a strong correlation with dynamic climatic factors. Historical data from the nearest BMKG station confirm a clear monsoonal pattern during the research period. The Figure 7 simultaneously displays the trends of monthly rainfall, average temperature, and average humidity, which collectively describe the environmental conditions experienced by the vegetation during the observation period.

From the climate data (Figure 7), several temporal correlations with vegetation dynamics can be identified. The significant period of new growth detected in the June 2023 image acquisition is very likely a direct response to the high rainfall during the preceding rainy season from October 2022 to April 2023. It is worth noting the unusually high rainfall in October 2022, with a value of 1,240 mm at the Pronojiwo station, which can be interpreted as a triggering event for the mass germination of pioneer seeds.

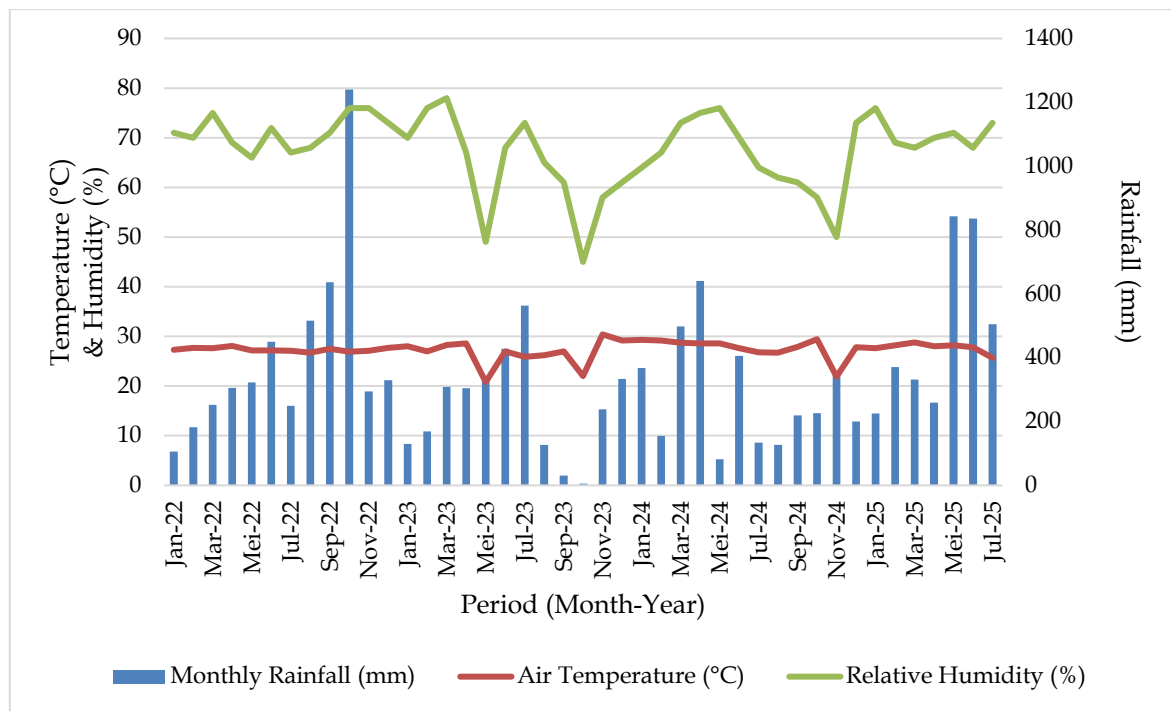


Figure 7. Monthly Climate Trends in the Research Area 2022-2025, Displaying Rainfall, Temperature, and Average Humidity. (BMKG, 2025).

On the other hand, dynamics such as temporary vegetation that grew in 2023 and then disappeared by 2025 are very likely associated with environmental stress during the dry season. The significant dry period from August to October 2023, where rainfall was recorded at 0 mm at the Pasirian station, was exacerbated by an increase in average temperature, reaching a peak of 32.0°C, and a sharp drop in air humidity to 45% in October. This combination of no water, high temperatures, and dry air created extreme evaporative stress conditions, which could lead to mortality in seedlings that had not yet developed a deep root system to access subsurface moisture.

Furthermore, extreme rainfall during the rainy season, such as that recorded in April 2024 with a rainfall value of 640 mm, also has the potential to trigger physical disturbances in the form of surface erosion and small scale debris flows. These secondary fluvial processes can damage or wipe out newly grown vegetation patches, a mechanism also highlighted by (Gurnell & Bertoldi, 2024; McMahon et al., 2020) as a factor that can disrupt and reset the expected recovery trajectory. Thus, it can be concluded that the success of vegetation succession in the post eruption landscape of Semeru depends not only on the availability of water for growth but also on a balance between sufficient rainfall to sustain life and an intensity that does not cause physical disturbance to the still unstable substrate.

CONCLUSION

Based on the time-series analysis of ultra-high-resolution UAV imagery across the 127.08-hectare Area of Interest (AOI) within the Volcanic Hazard Zone III (KRB III) of Mount Semeru from 2022 to 2025, several key conclusions emerge. First, the primary succession exhibits a positive trajectory, yielding a net recovery rate of +1.88 hectares per year, indicating that the colonization of new vegetation outpaces degradation in the early post-eruption stages. Second, this recovery is highly spatially heterogeneous, forming "succession islands" rather than uniform greening. Finally,

non-parametric statistical testing (Mann-Whitney U) confirmed that micro-topographic slope rather than elevation acts as the definitive abiotic control for initial succession in this localized zone. Pioneer vegetation significantly preferred steeper slopes (mean 43.20°) that provide structural refuge from active lahar flows, whereas flatter depositional beds (mean 23.64°) remained largely barren due to severe geomorphological instability. Elevation (~798 masl) showed no significant correlation, indicating that secondary fluvial disturbances override broad altitudinal gradients within this specific active corridor.

RECOMMENDATION

These findings offer targeted, evidence-based recommendations for post-eruption land restoration by stakeholders such as the Regional Disaster Management Agency (BPBD) and Perhutani. Interventions and active rehabilitation should be prioritized along the highly unstable, flat river channels where natural recovery is severely hindered by secondary lahar flows. Conversely, the naturally recovering vegetation on the steeper, consolidated ravine walls and channel terraces can be designated as natural succession monitoring zones or utilized as natural seed sources for surrounding degraded areas.

Despite these insights, several limitations must be acknowledged. The reliance on RGB sensors and the Excess Green (ExG) index may conservatively underestimate browning vegetation during dry-season senescence compared to multispectral sensors. Furthermore, while the UAV-photogrammetry approach successfully captures spatial canopy extent, it currently lacks ground-level taxonomic data. For future research, it is recommended to conduct in-depth field-plot surveys for the species composition of the pioneer vegetation. The future integration of multispectral or LiDAR sensors on UAVs could enable detailed biochemical and structural identification. Finally, expanding the spatial scope to include KRB II and KRB I would provide a more comprehensive comparative overview of ecosystem resilience across varying gradients of eruption impacts.

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A. Rahardjanto	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓		
Tutut Indria Permana					✓		✓			✓		✓		
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C : Conceptualization	I : Investigation	Vi : Visualization
M : Methodology	R : Resources	Su : Supervision
So : Software	D : Data Curation	P : Project administration
Va : Validation	O : Writing - Original Draft	Fu : Funding acquisition
Fo : Formal analysis	E : Writing - Review & Editing	

Conflict of Interest Statement

Authors state no conflict of interest.

Data Availability

The data that support the findings of this study are available from the first author and corresponding author, [initials, LSR and HH], upon reasonable request.

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