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MORALITY BEFORE KNOWLEDGE

# Spatiotemporal dynamics of vegetation density in moramo district protected forest: A remote sensing approach

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## ABSTRACT

**Background**: Protected forests in the Moramo District play a critical role in maintaining ecosystem balance, but they are increasingly threatened by human activities such as illegal logging and land use change. Vegetation density shifts can disrupt ecosystem functions, particularly the hydrological cycle. This study aims to analyze spatial and temporal changes in vegetation density in the Moramo District Protected Forest using remote sensing. **Methods:** To detect vegetation density changes, the NDVI (Normalized Difference Vegetation Index) algorithm was employed using satellite imagery from Landsat OLI 8 (2013 and 2018) and Landsat OLI 9 (2023), processed with GIS software. NDVI values range from -1 to 1, allowing for vegetation condition assessment based on spectral reflectance. **Findings:** Results show a degradation trend in dense vegetation, with a decrease of 67.25 ha (2.86%) during 2013–2018 and 289.11 ha (12.31%) during 2018–2023. Conversely, moderately dense vegetation increased by 68.45 ha (2.91%) and 300.21 ha (12.78%) over the same periods, indicating signs of vegetation regeneration. **Conclusion**: Despite some vegetation recovery, forest ecosystems continue to face high pressure. More adaptive conservation strategies supported by spatial monitoring are needed to reduce degradation and support long-term sustainability. **Novelty/Originality of this article:** This study uniquely integrates a multi-temporal NDVI-based approach with socio-ecological analysis and GIS tools to monitor vegetation dynamics. It offers valuable insights for adaptive forest management in the Moramo District Protected Forest, an area previously lacking detailed environmental change analysis.

**KEYWORDS**: Moramo District; protected forest; remote sensing; vegetation density.

## 1. Introduction

Southeast Sulawesi has a land area of 3.81 million hectares with a forest area of 2.34 million hectares, equivalent to 61% of its total land area. Of this amount, protected forest areas cover around 1.08 million hectares (Ministry of Environment and Forestry, 2021). However, forest cover in Southeast Sulawesi continues to decline each year. Based on data from the Central Statistics Agency (BPS), during the 2014–2022 period, the forest area in this region decreased by 7,387.03 hectares. The main driver of this decline is increased logging activities, both legal and illegal, as well as land conversion for plantations (Akhmaddhian, 2016).

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Protected forests play a crucial role in maintaining ecosystem balance, including regulating water management, preventing flooding, controlling erosion, preventing seawater intrusion, and maintaining soil fertility (Arba et al., 2023). However, pressure on these forests continues to rise due to expanding economic activities, such as land clearing for plantations, mining resource exploitation, and illegal logging. The decline in vegetation caused by these pressures contributes to environmental disasters like floods, erosion, and landslides, and exacerbates greenhouse gas emissions (Bolan et al., 2024; Wahyunto & Dariah, 2014). Deforestation in protected forest areas is a major cause of hydrometeorological disasters in tropical regions, particularly flash floods and extreme droughts.

Globally, tropical forests have experienced significant loss, an estimated 420 million hectares since 1990, though the rate of deforestation has decreased from 12 million ha per year (2010–2015) to approximately 10 million ha (2015–2020) (FAO, 2020). In Southeast Asia, deforestation pressure remains high, making it one of the global hotspots for biodiversity loss driven by land conversion and monoculture expansion (ASEAN Centre for Biodiversity, 2023).

One of the protected forests experiencing environmental pressure is the Moramo District Protected Forest in South Konawe District. This region features diverse topography, including lowlands, hills, and expansive forest areas. The Moramo Protected Forest acts as an ecological buffer zone with high biodiversity, serving as a habitat for various endemic flora and fauna. However, in recent years, this forest has experienced significant degradation due to land conversion for agriculture and oil palm plantations, along with increased illegal logging. Initial surveys revealed that these human activities have heavily impacted vegetation density, with illegal logging identified as a major contributing factor. Additionally, forest conversion for farming and plantations has altered the vegetation structure, affecting the overall ecosystem function and increasing ecological disaster risks such as landslides and floods.

A recent study by the IPCC (2023) found that changes in vegetation density in protected areas can accelerate microclimate shifts, elevate local temperatures, and reduce soil water retention capacity, thereby increasing the frequency of floods and droughts. Decreased vegetation density not only threatens local ecosystems but also has broader implications. According to Forest Digest (2025), deforestation transforms carbon-absorbing forests into major carbon emitters, intensifying global climate change. Furthermore, the loss of dense vegetation can disrupt hydrological patterns and directly affect regional water cycles, potentially causing water shortages, especially during dry seasons.

Monitoring the condition of vegetation and its changes in the Moramo District Protected Forest is essential to assess environmental impacts and ecosystem sustainability. Remote sensing technology using Landsat satellite imagery, along with Geographic Information System (GIS)-based analysis, offers an efficient and accurate method for tracking vegetation dynamics (Irawan & Sirait, 2017). These technologies are cost-effective, time-efficient, and capable of providing spatially explicit data crucial for forestry-related decision-making. This study utilizes a multi-temporal analysis approach using three time periods (2013, 2018, and 2023), allowing for a comprehensive assessment of vegetation density shifts. This includes analyzing transitions between vegetation classes, such as from dense to moderately dense or moderately dense to sparse, which are critical indicators of forest degradation processes.

The high-resolution findings of this study can be used as a scientific basis for designing effective forest conservation and rehabilitation strategies in the Moramo District. Additionally, this research contributes to mitigation and adaptation efforts by providing spatial data-based recommendations for prioritizing forest conservation. Forest Europe (2025) states that sustainable forest management (SFM), guided by measurable criteria and indicators, can enhance ecosystem functions such as carbon storage and biodiversity while ensuring responsible resource use. This integrated approach supports global commitments like the Forest Declaration and provides a scientific basis for local conservation and rehabilitation policies.

Furthermore, NDVI-based monitoring can inform the development of hybrid agroforestry strategies, which have been proven to reduce deforestation while enhancing carbon stock and improving rural livelihoods in Southeast Asia (Garrity, 2012). The integration of socio-economic and ecological factors in spatial analysis bridges national policy and landscape-scale strategies, promoting a balanced approach to forest utilization and preservation.

This research aims to identify spatial and temporal changes in vegetation density in the Moramo District Protected Forest using remote sensing technology. It contributes a novel perspective on NDVI-based vegetation monitoring through a multi-temporal approach, integration of socio-economic factors, improved field validation, and policy recommendations that are adaptive to environmental changes in the Moramo District—an approach not previously applied to this region. The outcomes are also relevant to global forest conservation and climate change mitigation policies. As emphasized by Forest Europe (2024), forest management must strike a balance between sustainable use and environmental preservation. Therefore, this study seeks to provide actionable recommendations and serve as a reference for data-driven forest management policy development in the Moramo District.

## 2. Methods

### *2.1. Study area*

This research was conducted in the Protected Forest Area of Moramo District, South Konawe Regency, Southeast Sulawesi Province (122°41′0″S - 122°46′0″ S and 04°10′51″ E-04°13′26″ E) from June to July 2024. The population in this study is the entire protected forest area in the Moramo district, covering an area of 2,348.41 hectares (ha). Geographically, Moramo District is bordered by the Staring Sea to the North, North Moramo District to the East, Kolono District to the South, and Laonti District to the West. Moramo district is divided into 20 villages (Moramo district in Figures, 2023), while the Moramo district Protected Forest area has an area of 2,348.41 ha, which is administratively included in the administrative area of 5 villages and 1 sub-district with a different distribution of protected forest areas. Ulusena Village has the largest area, reaching 1,128.47 ha or 45.05% of the total area. Bisikori village follows with 591.84 hectares (25.20%), followed by Lapuko village with 341.52 hectares (14.54%). Lamboo village has 240.1 hectares of protected forest (10.22%), while Sumber Sari has 31.31 hectares (1.33%), and Wowosunggu has the smallest area of 15.17 hectares (0.65%).

Moramo District Protected Forest was chosen as the study population because this area is part of a strategic ecosystem in Southeast Sulawesi that functions as a biodiversity buffer and provider of important environmental services, such as hydrological regulation and climate change mitigation. However, the area is experiencing significant degradation due to anthropogenic pressures, including illegal logging and plantation expansion. To date, studies on changes in vegetation density in this area are limited, particularly in remote sensing-based spatial-temporal approaches. Therefore, this study contributes to filling the scientific gap by providing spatial data-based analysis that can support conservation planning and more adaptive forest management policies. A map of the research location is shown in Figure 1.

In 2022, land use in the Moramo District Protected Forest is dominated by Secondary Dryland Forest, which covers 1,826.57 hectares, or 77.78% of the total area. This area plays a crucial role in the protected forest ecosystem and accounts for the largest share of land use in the area. Scrub followed with an area of 333.27 hectares or 14.19%, indicating the presence of open areas or bushes that also have a function in maintaining the balance of nature. Mixed Dryland Agriculture was recorded at 185.56 hectares or 7.90%, reflecting the presence of agricultural activities in the protected forest area, albeit with a smaller contribution. Meanwhile, Open Land covers only 3.01 hectares or 0.13%, indicating a very small open area in the area. Overall, while most of the land is used for forest and scrub, there is also a small portion used for agriculture and open areas in the Moramo District Protected Forest. These conditions may play a role in significantly affecting the level of vegetation density in the study area.

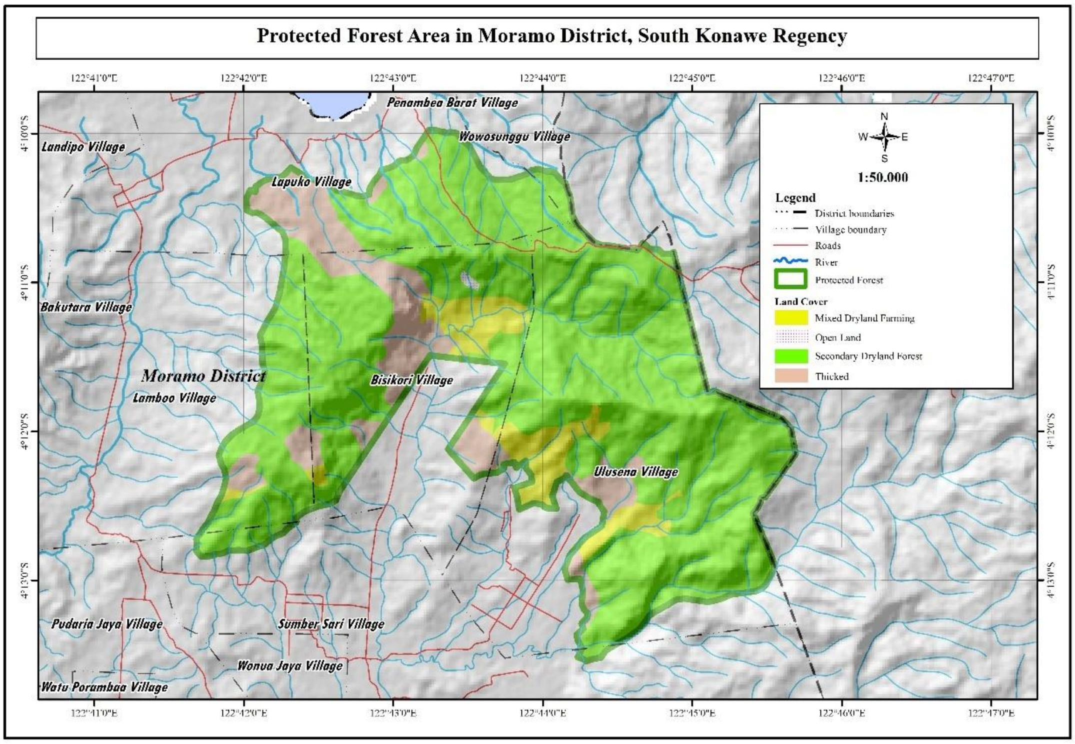



Fig. 1. Research location map

## 2.2. Material

The materials used in this research are forest area data according to the Decree of the Minister of Environment and Forestry No SK.6623 / p Year 2023, data on Village Boundaries throughout Indonesia in 2022, Landsat OLI 8 image data in 2013 and 2018 and Landsat OLI 9 image data in 2023 downloaded through the USGS (United States Geological Survey) web page. The tools used in this research are a unit of laptop/ PC for working media and supported by GIS software, GPS (Global Positioning System), and a Camera for documentation.

## 2.3. Data collection

This study utilises satellite imagery to monitor spatial changes in the vegetation of the Moramo District Protected Forest. Landsat 8 OLI images were acquired to provide an overview of vegetation conditions in the period 2013 and 2018, while Landsat 9 OLI images were taken to provide an overview of vegetation conditions in the period 2023. The image download process was done through the USGS Earth Explorer platform, which allows open access to remote sensing data of moderate quality and reliable accuracy.

## 2.4. Analytical techniques

Data analysis in this study was carried out in two main stages: the calculation of Normalized Difference Vegetation Index (NDVI) and NDVI change analysis. These two methods are used to identify and evaluate the dynamics of vegetation density in the Moramo District Protected Forest area spatially and temporally. The NDVI change calculation process is done through several stages. Radiometric correction to reduce atmospheric effects and improve image quality. Radiometric correction is a set of techniques designed to convert digital values captured by sensors into physical quantities of interest, such as radiance, reflectance, or surface temperature (Pons et al., 2014). After the radiometric correction process, the next step is to perform atmospheric correction, which aims to remove atmospheric effects caused by absorption and scattering of light by the atmosphere (Suyarso et al., 2023). Geometric Correction to adjust the pixel position to the actual geographical coordinates. Geometric correction is the process of transforming remote sensing imagery to ensure that it has the right characteristics, such as shape, scale, and projection. This process involves adjusting the position of pixels so that the corrected image represents objects on the Earth's surface according to the data recorded by the sensor. One example of the result of geometric transformation is the change in the shape of the coverage frame from a square to a parallelogram. This process is applied to raw digital imagery directly obtained from satellite recording and aims to correct systematic geometric errors. Geometric correction is performed by considering the types of errors, both systematic and random, that cause geometric distortion in the image (Arkham et al., 2023). Extraction of NIR and RED channels from satellite imagery. NDVI calculation using the equation (Gandri et al., 2023).

$$\text{NDVI} = \frac{NIR - Red}{NIR + Red} \quad \text{(Eq. 1)}$$

Where:
NDVI = Normalized Difference Vegetation Index
NIR = Near Infra Red (Band 5)
Red = Red light (Band 4)

Classification of NDVI values ranges from +1.0 to -1.0, with classification shown in Table 1. As USGS mentions on their website, NDVI values can be averaged over time to establish normal growing conditions in a region for a given time of year, which can be used to analyze vegetation condition as well as changes due to human activities such as deforestation, natural disturbance, or changes in plants' phenology.

Table 1. Classification of NDVI density values

| No. | NDVI range | Classification |
|---|---|---|
| 1 | -1.00 – 0.1 | No vegetation (barren rock, sand, or snow) |
| 2 | 0.2 – 0.5 | Sparse vegetation (shrubs, grasslands, senescing crops) |
| 3 | 0.6 -0.9 | Dense vegetation |

(USGS, n.d.)

Interpretation accuracy test is an analysis method obtained from field surveys with a tool in the form of a suitability table. The table contains interpretation location points, survey locations, and coordinates. Survey points were selected based on interpretation results that were considered less convincing by researchers, necessitating field surveys, including the existing vegetation density on the map and changes in current vegetation density. The Interpretation Accuracy Test Error Matrix is shown in Table 2.

Table 2. Interpretation accuracy test error matrix

| No | Coordinates (X, Y) | Image interpretation | Ground check | Level of correctness |
|---|---|---|---|---|
| 1. | $X_a$, $Y_a$ | Rice fields | Rice fields | Correct |
| 2. | $X_b$, $Y_b$ | Settlement | Terraces | Incorrect |
| 3. | Xn, Yn | etc. | etc. | etc. |

(Trinufi & Rahayu, 2020)

Ground checking is very important to do as the first step of accuracy testing. Ground checks are carried out in the research stage to see the truth of the results of land cover classification through the interpretation of satellite imagery that has been made. Ground truthing can be performed by measuring several sample points selected from each homogeneous NDVI class. The implementation of each class is sampled based on the homogeneity of its appearance and tested. The total number of checking results is 90 points, as shown in Figure 2.

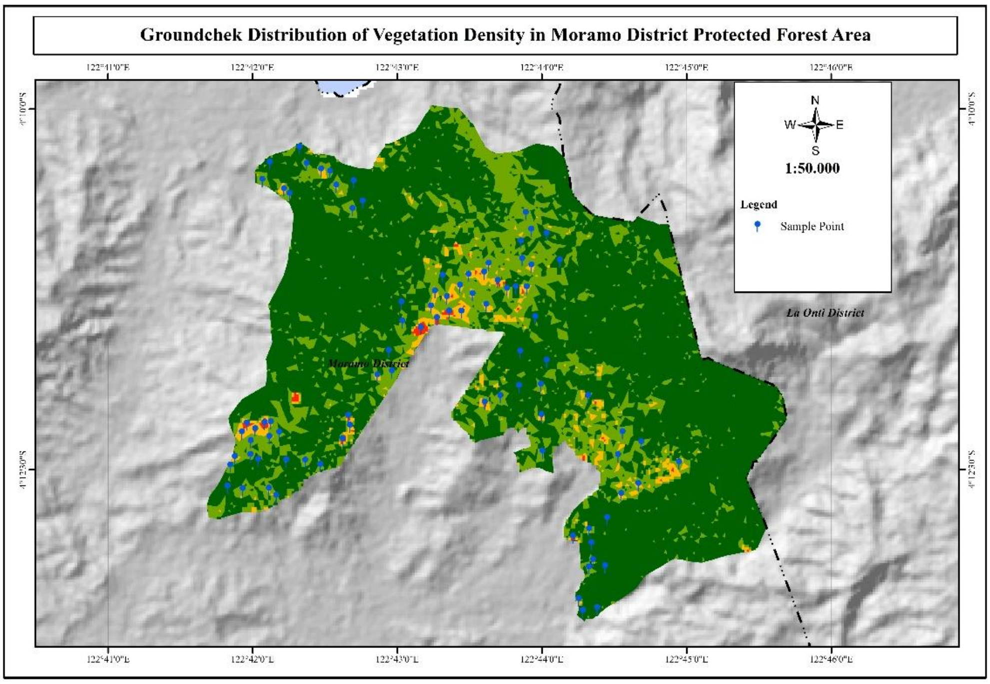



Fig. 2. Ground check points distribution

Based on the table of field survey results, it is expected to know the accuracy value of the interpretation using the formula:

$$\text{Level of correctness of interpretation} = \frac{Correct\ point}{Point\ surveyed}\ x\ 100\% \qquad \text{(Eq. 2)}$$

Vegetation classification information from satellite image processing data is considered accurate if the classification results achieve an accuracy of≥ 80% or an error rate of < 20% compared to the field situation (Wulandari, 2017). NDVI change analysis was conducted to assess the dynamics of vegetation density change over the periods 2013, 2018, and 2023. The method used in this analysis was multi-temporal overlay, where NDVI maps from different years were compared to identify areas with increased or decreased vegetation density (Coppin et al., 2004).

## 3. Results and Discussion

Vegetation density refers to the number of individuals or mass of vegetation present in a given area. It can be measured in various ways, such as the number of trees per hectare, biomass per unit area, or density of vegetation cover. Meanwhile, changes in vegetation density are changes in vegetation cover that can indicate changes in environmental conditions, ecosystem health, or the impact of human activities or land conditions that experience changes in conditions at different times caused by humans, such as increasing population and accessibility (Wiguna et al., 2019). Vegetation density in such a large area was analyzed using a Remote Sensing approach using Landsat 8 imagery and the NDVI method. NDVI is calculated using data from the red and near-infrared bands in satellite images (Fitriani et al., 2023). Higher NDVI values indicate higher vegetation density.

*3.1 NDVI in Moramo District protected forest in 2013, 2018, and 2023*

Before presenting the spatiotemporal analysis of vegetation density based on NDVI data from the years 2013, 2018, and 2023, it is essential to ensure the reliability of the classification results. The results of the vegetation density classification accuracy test show that the image interpretation in these years demonstrates a high level of confidence. Validation was conducted through field surveys to compare the classification outputs with the actual on-site conditions. From a total of 90 observation points tested, an accuracy rate of 83.33% was obtained, as illustrated by Figure 3.

Based on the image interpretation accuracy standards, this value indicates that the classification results possess a good and reliable level of accuracy. According to Short (as cited in Nawangwulan et al., 2013), satellite image classifications with an accuracy rate above 80% are considered valid and suitable for further analysis. However, it is acknowledged that classification errors may still occur due to various influencing factors, including the quality of the imagery used, atmospheric variations at the time of acquisition, differences in vegetation moisture content, solar angle, and topographic effects on spectral reflectance (Zulkarnain et al., 2015). With this level of validation established, the analysis of vegetation density changes across the three time periods can now be conducted with confidence.

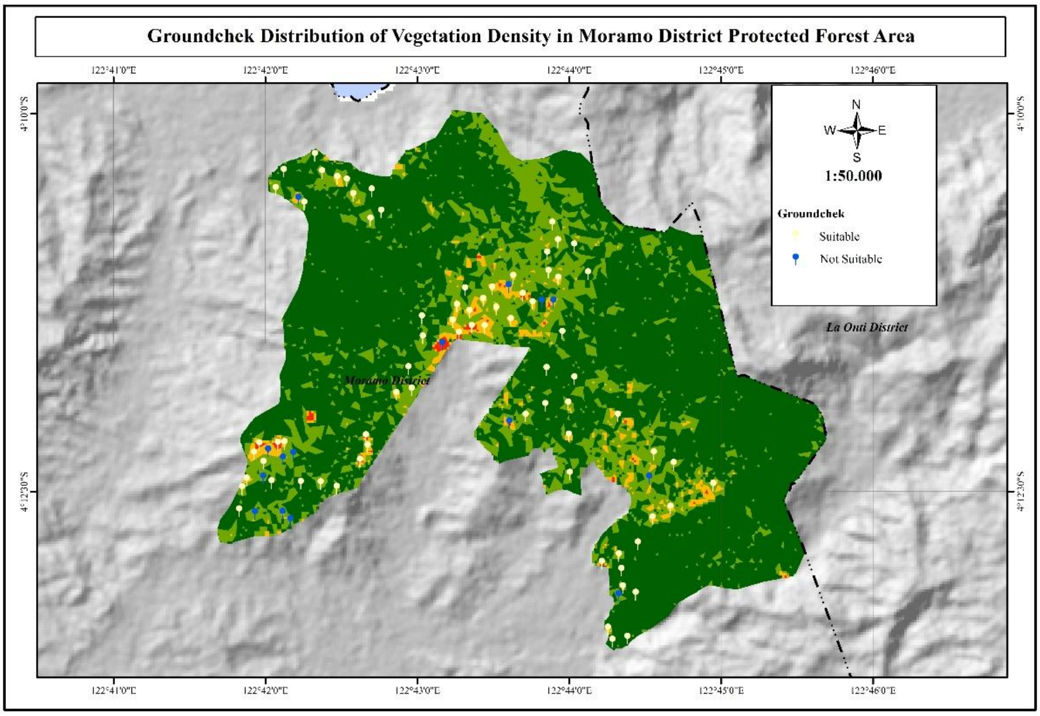



Fig. 3. Groundcheck result of vegetation density

This updated classification improves the accuracy of NDVI-based land cover interpretation by aligning spectral index values more closely with observed ground conditions. It also enhances the reliability of vegetation density analysis in the Moramo District and ensures consistency in subsequent spatiotemporal assessments. Based on the results of Landsat 8 imagery in 2013, 2018, and Landsat 9 imagery in 2023 in the Moramo District Protected Forest, vegetation conditions based on updated NDVI range are classified into 4 classes, namely non-vegetation, not dense, fairly dense, and dense. With a range of NDVI values (0.00-0.21) for non-vegetation classes, NDVI values (0.21-0.42) for Sparse Vegetation, a range of values 0.42-0.63 for moderately dense vegetation, and a range of NDVI values (0.63-0.85) for highly dense vegetation as shown in Figure 4. This classification is measured in hectares (Ha) for each year, as shown in Figure 4.

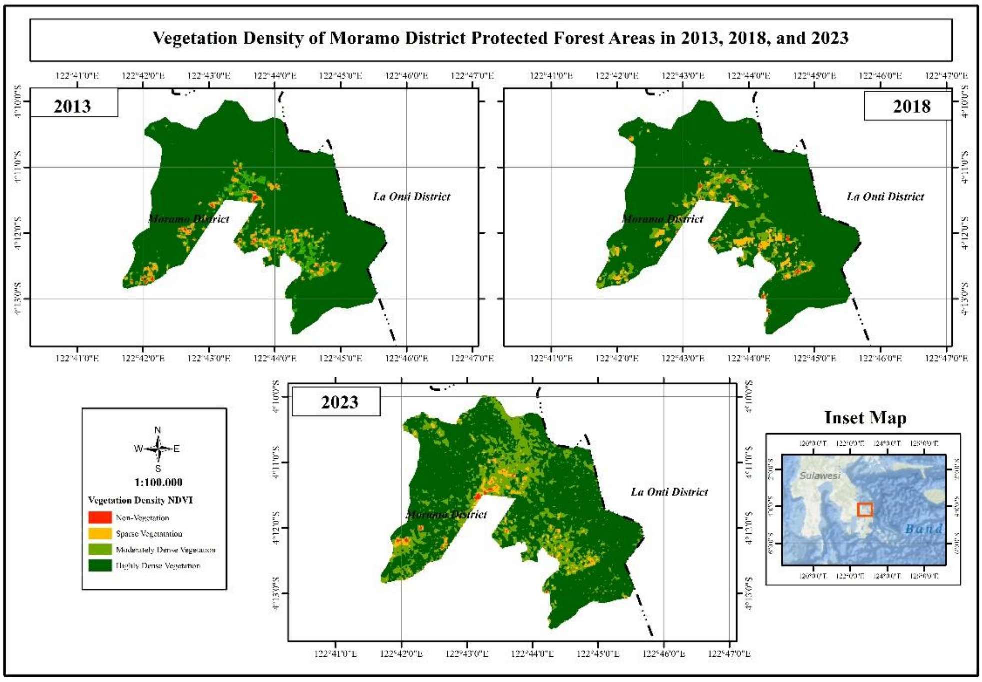



Fig. 4. Vegetation density of Moramo District protected forest area in 2013, 2018, and 2023

Based on field validation (ground checking) conducted in the Moramo Protected Forest, a refined NDVI classification scheme was developed to better reflect the actual land cover characteristics of the study area. The classification ranges are as follows.

Table 3. NDVI classification based on ground verification

| NDVI range | Classification | Description |
|---|---|---|
| -1.00 – 0.00 | Water bodies/cloud cover | Area covered by water surface or cloud masks |
| 0.00 – 0.21 | Non vegetation | Bare land, built-up areas, |
| 0.21 – 0.42 | Sparse vegetation | Grasslands, degraded areas, and low cover shrubs |
| 0.42 – 0.63 | Moderately dense vegetation | Transition forest |
| >0.63 | Highly dense vegetation | Dense natural forest with a closed canopy |

In 2013, the forested landscape was largely characterized by extensive areas of highly dense vegetation, particularly in the central, southern, and southeastern zones of Moramo District. These areas reflect intact forest conditions with minimal signs of anthropogenic disturbance. Sparse and non-vegetated patches were spatially limited and mostly located along peripheral edges, suggesting natural clearings or transitional zones.

By 2018, the spatial pattern began to shift, with a visible increase in sparse vegetation across several core areas, most notably in the central and southwestern portions of the district. This indicates the early onset of land cover degradation, likely driven by growing pressures such as illegal logging, shifting cultivation, or encroachment for infrastructure and settlement. The expansion of non-vegetated zones, although not yet dominant, reflects the cumulative impact of these disturbances.

The 2023 map demonstrates a further intensification of this trend. Highly dense vegetation has become significantly fragmented, replaced by widespread patches of sparse vegetation and bare land. Areas that were previously stable now exhibit signs of ecological stress, suggesting ongoing deforestation, reduced regrowth, and a weakening of forest resilience. The increasing fragmentation not only threatens biodiversity and carbon storage but also disrupts ecological connectivity and watershed protection functions.

Overall, the temporal analysis presents a clear downward trend in vegetation density and ecological integrity within the protected area. The progressive loss of forest cover underscores a critical need for improved monitoring, stricter enforcement of protection regulations, and community-based conservation strategies. Without urgent intervention, the Moramo Protected Forest risks a continued decline in its ecological functions and the long-term sustainability of its natural resources

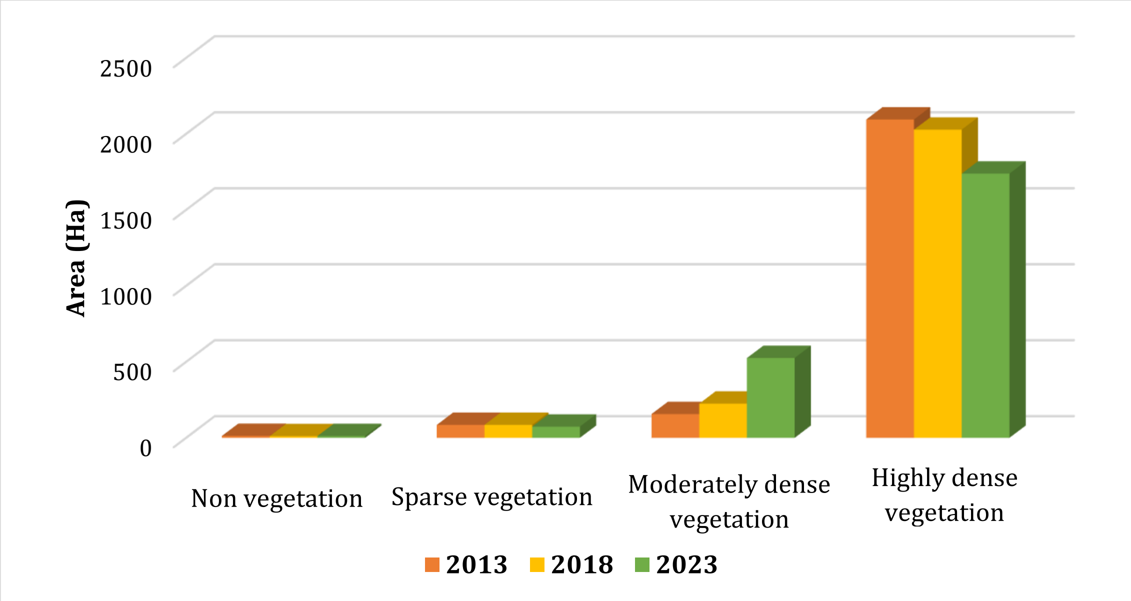



Fig. 5. Distribution of Normalized Difference Vegetation Index (NDVI) of Moramo District protected forest areas in 2013, 2028, and 2023

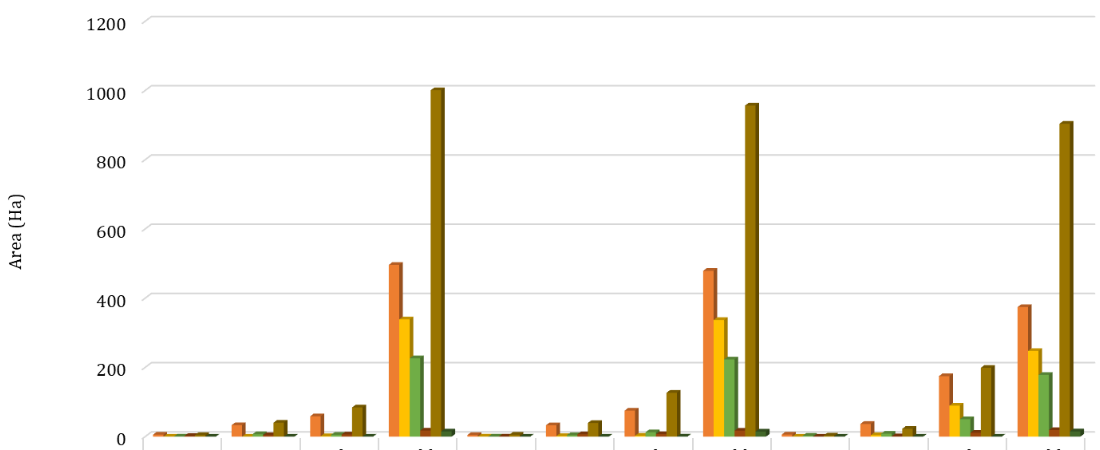
In 2013, the Moramo District protected forest was predominantly characterized by highly dense vegetation, covering approximately 2,094.52 hectares. This indicates a well-preserved forest ecosystem with a large proportion of closed canopy areas and healthy vegetation. The moderately dense vegetation class accounted for 156.33 hectares, reflecting areas likely composed of transitional forest zones or secondary growth. A small area of sparse vegetation was recorded at 84.90 hectares, which may correspond to degraded zones or regions undergoing natural regeneration. Non-vegetated areas, covering only 12.66 hectares, suggest minimal land cover disturbance, such as exposed soil, infrastructure, or bodies of water. Overall, the forest in 2013 showed a dominance of mature vegetation and minimal ecological disruption.

In 2018, the forest remained largely covered by highly dense vegetation, with an extent of 2,027.50 hectares, maintaining the forest's classification as a primarily intact ecosystem. The presence of moderately dense vegetation increased to 224.77 hectares, possibly indicating enhanced regeneration areas or regions experiencing partial canopy loss. Sparse vegetation was slightly higher, with 85.43 hectares, indicating some signs of low-density vegetation spread across the forest edge or human-affected zones. The non-vegetated area was 10.94 hectares, remaining a minor component in the overall land cover distribution. The year 2018 reflected a relatively stable vegetation condition, still dominated by forested land with healthy vegetative cover.

By 2023, the highly dense vegetation category was recorded at 1,738.21 hectares, which still represents the largest share of the forest area. Notably, moderately dense vegetation saw a significant presence, covering 524.98 hectares, indicating a widespread area of mid-level canopy cover, possibly from regrowth or partial canopy thinning. Sparse vegetation was measured at 73.52 hectares, slightly lower than in previous years. The non-vegetated area remained limited, at 11.75 hectares, suggesting that open or disturbed land was still relatively contained. The forest in 2023 exhibited characteristics of structural variation within vegetation types but continued to maintain a predominantly green cover across the landscape.

*3.2 The spatial distribution of vegetation density across the protected forest areas in each village of Moramo District*

The analysis results based on spatial distribution per village, as shown in Figure 6, indicate that most changes occurred in Ulusena and Bisikori Villages. Each village shows a unique pattern of change influenced by land use, topography, and socio-economic activities. Ulusena Village holds the largest forest area in the district and has experienced the most substantial structural transformation. Highly dense vegetation declined from 1,000.72 ha in 2013 to 903.84 ha in 2023, while moderately dense vegetation surged from 84.35 ha to 198.86 ha. Field observations confirm widespread conversion of forest land into pepper plantations, a dominant local commodity. Additionally, the community's participation in the Social Forestry program under the Community Forest (HKm) scheme granted access to forest lands, promoting sustainable use. However, this access has also led to expanded cultivation, highlighting a duality where empowerment may conflict with conservation. Ulusena's topography, although less accessible in parts, still allows for gradual land clearing, especially in lower-elevation areas. This dynamic reflects a gradual degradation of dense forest and calls for targeted supervision and reforestation efforts to prevent further biodiversity loss and ecosystem imbalance.




| | In 2013 | | | | In 2018 | | | | In 2023 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Non Vegetation | Sparse Vegetation | Moderately dense vegetation | Highly Dense Vegetation | Non Vegetation | Sparse Vegetation | Moderately dense vegetation | Highly Dense Vegetation | Non Vegetation | Sparse Vegetation | Moderately dense vegetation | Highly Dense Vegetation |
| Bisikori | 5.64 | 33.16 | 58.87 | 496.16 | 4.7 | 32.95 | 75.15 | 479.05 | 6.15 | 36.73 | 174.74 | 374.22 |
| Lapuko | 0 | 0.09 | 1.27 | 338.77 | 0.24 | 1.74 | 2.58 | 336.96 | 0 | 4.36 | 89.7 | 247.46 |
| Lamboo | 0.28 | 7.03 | 5.46 | 226.31 | 0.15 | 4.34 | 12.6 | 223.01 | 2.5 | 8.74 | 50.44 | 178.47 |
| Sumber Sari | 2.05 | 4.31 | 6.38 | 17.63 | 0.24 | 6.84 | 7.29 | 17.18 | 0 | 1.02 | 11.18 | 19.11 |
| Ulusena | 4.69 | 40.31 | 84.35 | 1000.72 | 5.61 | 39.56 | 126.76 | 956.54 | 3.09 | 22.68 | 198.86 | 903.84 |
| Wowosunggu | 0 | 0 | 0 | 14.93 | 0 | 0 | 0.39 | 14.78 | 0 | 0 | 0.06 | 15.11 |

Fig. 6. The spatial distribution of vegetation density across the protected forest areas in each village of the Moramo District

Bisikori Village showed a significant reduction in highly dense vegetation from 496.16 ha in 2013 to 374.22 ha in 2023, paired with an increase in moderately dense vegetation from 58.87 ha to 174.74 ha. Ground validation indicates that extensive land conversion to cashew plantations is the key driver. While cashew agroforestry retains partial vegetative cover, it alters the native structure of the forest. Interestingly, Bisikori also exhibited scattered signs of natural regeneration and small-scale rehabilitation projects by community groups. These efforts, if integrated with sustainable land-use policies, could help offset some of the degradation trends. The village serves as a focal point of transition between natural and managed forests, making it a critical area for targeted intervention.

Lapuko Village experienced changes on a smaller but notable scale. Dense vegetation dropped from 338.77 ha to 247.46 ha, while moderately dense vegetation increased dramatically from 1.27 ha to 89.7 ha. Unlike other villages, Lapuko's unique condition lies in its relatively flat and accessible terrain, making it more vulnerable to rapid agricultural expansion. Cashew remains the dominant crop, and field reports suggest an increasing trend in land clearing without sufficient erosion control. Despite the smaller total forest area, the rapid transformation in vegetation density makes Lapuko an emerging hotspot for landscape-level monitoring and restoration.

Lamboo Village demonstrated a less extreme but still important transformation. Dense vegetation reduced from 226.31 ha to 178.47 ha, and moderately dense vegetation expanded from 5.46 ha to 50.44 ha. What is unique about Lamboo is its stable non-vegetated area (approximately 0.25 ha in 2023), suggesting limited soil exposure and perhaps more sustainable agroforestry practices. The moderate changes indicate a gradual, possibly reversible, transition influenced by low-intensity farming. Lamboo offers a potential model for balancing community farming needs with ecological preservation.

Sumber Sari Village recorded one of the smallest yet most stable forest cover profiles. Dense vegetation slightly increased from 17.63 ha to 19.11 ha, and moderately dense vegetation rose from 6.38 ha to 11.18 ha. What sets Sumber Sari apart is the visible absence of major conversion pressures. Field visits noted minimal plantation activity and limited human disturbance, likely due to the village's remoteness and reduced economic dependence on forest land. This makes Sumber Sari a key conservation area with potential as a biodiversity refuge and ecological benchmark for the district.

Wowosunggu Village consistently had the smallest recorded vegetative area but showed subtle positive change. Dense vegetation increased slightly from 14.93 ha to 15.11 ha, and moderately dense vegetation was recorded at 0.06 ha in 2023. While the total forest area is minimal, Wowosunggu’s unchanged non-vegetated and sparse categories indicate minimal disturbance. This could be attributed to cultural land-use preferences or physical inaccessibility, presenting an opportunity for conservation-focused land planning.

From an ecological standpoint, the overall decrease in dense vegetation across several villages has serious implications for the health of the Moramo Protected Forest. Dense forests play a crucial role in carbon sequestration, maintaining soil fertility, and regulating hydrological processes (Bonan, 2008). Reduced canopy cover increases the risk of erosion, lowers water retention capacity, and threatens native wildlife habitat (Jainuddin, 2023). Figure 4 presents spatial vegetation changes between 2013, 2018, and 2023, confirming these trends.

Each village in the Moramo District exhibits a unique trajectory of vegetation change, driven by a combination of environmental, economic, and social factors. These transformations not only reshape forest ecosystems but also impact ecological and community resilience. To address this, a landscape-based management approach is needed, one that harmonizes conservation with community livelihood, enforces land-use planning, and supports reforestation efforts. Monitoring vegetation density will remain a key metric for guiding policy, evaluating interventions, and safeguarding the long-term sustainability of Moramo’s forest landscapes. Tables 4 and 5 present the matrix of vegetation density changes for the periods 2013–2018 and 2018–2023, respectively.

The analysis of Tables 4 and 5 reveals a decade-long pattern of significant vegetation density changes in the protected forest areas of Moramo District, Southeast Sulawesi, from 2013 to 2023. These tables not only demonstrate the scale of transformation but also offer deeper insight into the dynamics of forest degradation at a sub-regional level. In 2013, the area categorized as Highly Dense Vegetation stood at 2,094.52 hectares, forming the ecological core of the protected forest. However, by 2018, a total of 129.08 hectares had experienced a downward transition: 103.69 hectares shifted into Moderately Dense Vegetation, 22.67 hectares into sparse vegetation zones, and 2.72 hectares became Non-Vegetated. This indicates a notable deterioration in forest structure, where over 6% of the most ecologically valuable forest class had degraded in just five years.

Table 4. The matrix of changes in vegetation density of protected forests in the Moramo District in 2013-2018

| | | Year 2018 (ha) | | | | |
|---|---|---|---|---|---|---|
| | Class | Non vegetation | Sparse vegetation | Moderately dense vegetation | Highly dense vegetation | Total |
| Year 2013 (ha) | Non vegetation | 3.06 | 5.73 | 1.96 | 1.91 | 12.66 |
| | Slightly vegetation | 2.47 | 32.43 | 28.06 | 21.94 | 84.90 |
| | Moderately dense vegetation | 2.69 | 24.6 | 91.06 | 37.98 | 156.33 |
| | Highly dense vegetation | 2.72 | 22.67 | 103.69 | 1965.44 | 2094.52 |
| | Total | 10.94 | 85.43 | 224.77 | 2027.27 | 2348.41 |

The loss is indicative of weakening forest integrity and a potential disruption in ecosystem services tied to carbon storage, hydrological regulation, and habitat stability. This degradation trend intensified between 2018 and 2023. Table 4 shows that an alarming 405.72 hectares of highly dense vegetation further regressed into Moderately Dense Vegetation, over three times the degradation rate observed in the previous period. The area of highly dense vegetation consequently declined to 1,738.16 hectares by 2023, confirming a net loss of 356.36 hectares across the decade. While such lands may still be classified as forested, the decline in canopy density represents a form of "silent degradation", where structural forest quality diminishes even in the absence of total clearance.

Table 5. The matrix of area changes in vegetation density of protected forests in the Moramo District in 2018-2023

| | | Year 2023 (ha) | | | | |
|---|---|---|---|---|---|---|
| | Class | Non vegetation | Sparse vegetation | Moderately dense vegetation | Highly dense vegetation | Total |
| Year 2018 (ha) | Non vegetation | 3.06 | 2.47 | 2.69 | 2.72 | 10.94 |
| | Slightly vegetation | 4.82 | 32.43 | 25.51 | 22.67 | 85.43 |
| | Moderately dense vegetation | 1.96 | 28.06 | 91.06 | 103.69 | 224.77 |
| | Highly dense vegetation | 1.91 | 10.56 | 405.72 | 1609.13 | 2027.27 |
| | Total | 11.75 | 73.52 | 524.98 | 1738.16 | 2348.41 |

Conversely, the area classified as moderately dense vegetation increased sharply, from 156.33 hectares in 2013 to 524.98 hectares in 2023. While this growth might superficially suggest recovery or regeneration, it is in fact primarily driven by the downward transition of higher-density vegetation classes. This reflects a passive form of degradation rather than active reforestation. The sparse vegetation class showed a small increase between 2013 (84.90 ha) and 2018 (85.43 ha), followed by a reduction to 73.52 ha in 2023. This decline could reflect some natural recovery or reclassification of areas into moderate-density zones due to partial vegetative regrowth or improved spectral signatures. The non-vegetated category remained relatively stable throughout the decade, with only a minor change from 12.66 ha in 2013 to 11.75 ha in 2023. This consistency suggests that full deforestation was not the predominant trend; instead, the forest experienced gradual canopy thinning and internal fragmentation, both critical indicators of forest health decline.

The implications of these patterns are significant. Dense forests play a foundational role in maintaining ecological functions such as carbon sequestration, microclimate regulation, water filtration, and biodiversity support. The degradation of highly dense vegetation directly threatens these services. As Brockerhoff et al. (2017) explain, the fragmentation and degradation of primary forests alter species composition, disrupt ecological processes, and reduce overall ecosystem resilience. In the case of Moramo, this trend signals mounting anthropogenic pressure, ranging from illegal logging and agricultural expansion to infrastructure development and shifting land use practices.

Hallaj et al. (2024) further emphasize that vegetation density transitions are closely correlated with human-induced disturbances, which not only alter forest structure but also influence local livelihoods and contribute to regional climate vulnerabilities. The findings from Moramo reflect broader national trends. According to the Ministry of Environment and Forestry (2023), Indonesia saw deforestation of approximately 104,000 hectares in 2022 alone, much of it due to agricultural and plantation expansion. Similarly, Curtis et al. (2018) report that over 77% of global tropical forest cover loss is linked to agricultural conversion, placing Moramo within the context of a global ecological challenge.

Beyond the loss of forest quantity, the shift in vegetation density reflects increasing forest fragmentation, where continuous forest landscapes are broken into smaller, isolated patches. While Moramo retains substantial tree cover, the internal ecological quality is deteriorating. FAO (2022) reports that such fragmentation reduces forest connectivity, impairs natural regeneration, and weakens resistance to environmental stressors. Supporting this, Betts et al. (2019) and Haddad et al. (2015) found that fragmentation exacerbates forest fire risk, increases edge effects, and disrupts microclimatic stability—all of which accelerate the degradation cycle. In Moramo's case, the reclassification of Highly Dense areas into lower-density categories exemplifies this shift toward fragmented and vulnerable ecosystems. This transformation also has critical implications for carbon storage and climate regulation. Highly vegetated forests are key carbon sinks, and their degradation reduces the district's carbon storage capacity significantly. The loss of 356.36 hectares of Highly Dense Vegetation represents a substantial decrease in biomass and carbon retention. According to Baccini et al. (2017), tropical forest degradation directly contributes to increased greenhouse gas emissions, thereby intensifying climate change impacts and creating a negative feedback loop for remaining forest ecosystems.

Hydrologically, the decline in dense canopy cover influences water regulation. As noted by Locatelli et al. (2015), healthy forest canopies help retain rainfall, improve infiltration, and reduce surface runoff. Their loss can lead to increased erosion, sedimentation of waterways, and instability in seasonal water availability. Bruijnzeel (2004) supports this, stating that vegetation loss can result in more frequent flooding during rainy seasons and exacerbate drought conditions in dry periods—an increasingly likely scenario in Moramo given the observed vegetation shifts.

Socioeconomically, these ecological changes are double-edged. While agricultural expansion (e.g., oil palm, cashew, cloves, and pepper cultivation) provides short-term income to communities, unsustainable practices risk undermining long-term ecosystem services and resilience. As Curtis et al. (2018) and Meyfroidt et al. (2018) caution, reliance on monoculture systems in such expansions makes both ecosystems and communities more vulnerable to environmental and market shocks.

Addressing these complex challenges requires an integrated and adaptive landscape management approach. Agroforestry systems and sustainable land-use practices offer potential pathways to balance ecological conservation with local development. These approaches promote biodiversity, stabilize microclimates, and diversify local economies. Simultaneously, policy mechanisms—including incentive-based conservation schemes, community-based forest governance, and enforcement of land-use regulations essential to stem ongoing degradation. Monitoring technologies like NDVI and high-resolution remote sensing can play a pivotal role in early warning, decision support, and participatory conservation.

The vegetation density changes observed in the Moramo District between 2013 and 2023 represent a slow but significant ecological transformation. Although large-scale deforestation is limited, the consistent decline in forest quality through density reduction is no less critical. This form of degradation erodes ecosystem functionality, disrupts hydrological and climatic stability, and diminishes socio-ecological resilience. Mitigating this trend demands a coordinated response involving policy reform, technological innovation, and meaningful local engagement. With timely and inclusive interventions, the Moramo District can chart a path toward sustainable coexistence between nature and people.

## 4. Conclusions

Based on the results of the study, it can be concluded that the density class of protected forest vegetation in Moramo District is classified into 4 classes, namely non-vegetation, not tight, fairly tight, and tight. In the period 2013-2018, the largest decrease in area was the tight vegetation class of 67.25 hectares (2.86%). Whereas in the following period, 2018-2023, the tight vegetation class continued to decrease by 289.11 hectares (12.31%). While the largest increase in area occurred in the fairly dense vegetation class in the 2013-2018 period, which increased by 68.45 hectares (2.91%), and in the next period 2018-2023 the class that experienced the largest increase in area was the fairly dense class of 300.21 hectares (12.78%).

This shift reveals a unique trend: degradation is occurring not through deforestation, but through vegetation thinning, signaling a reduction in forest quality without dramatic land clearance. This pattern highlights a more insidious ecological threat, structural forest decline masked by green cover stability. The implications are far-reaching: diminished carbon storage, disrupted hydrological function, and increased ecosystem vulnerability. The data emphasize the urgent need for targeted restoration, sustainable land-use enforcement, and early intervention to prevent further fragmentation and preserve long-term ecological and socio-economic resilience in Moramo.

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## Author Contribution
All authors contributed equally to the study design, data collection, analysis, interpretation, and manuscript writing. They reviewed and approved the final version, ensuring accuracy and integrity of the research findings.

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