Land Cover Change Analysis in Mont Mbam Region

Final Report

May 2025

Executive Summary

This report comprehensively analyzes land cover dynamics in the Mont Mbam region between 1987 and 2024. Using multiple remote sensing datasets and analytical approaches, we have documented remarkable landscape stability over the 37-year study period, with 96.9% of the area maintaining the same land cover type. The most significant changes occurred in the 2010-2024, including modest tree cover expansion, grassland reduction, and water body expansion. These changes coincided with a dramatic decline in fire occurrence from an average of ~9,503 hectares burned annually in 2000-2009 to only ~1,091 hectares annually in 2017-2024.

Our analysis reveals a complex interplay between fire regimes and vegetation dynamics. During the study period, 48% of grassland areas experienced at least one fire event, compared to much lower percentages in forested areas. Additionally, 62% of all transitions from tree cover to grassland occurred in the regions that experienced at least two fire events. Despite the overall landscape stability, the Hansen Global Forest Cover dataset identified 296 hectares of forest loss between 2001 and 2023, with the highest loss recorded in 2023 (46 ha).

Based on these findings, we recommend a balanced ecosystem management approach that recognizes the ecological value of both forest and grassland ecosystems, strategic fire management planning, continued monitoring of recent forest loss and hydrological changes, and maintaining methodological consistency in future assessments. This report establishes a crucial baseline for understanding landscape dynamics in the Mont Mbam region and provides a foundation for future conservation and management efforts.

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1. Introduction

This report presents the findings and analyses conducted for Voice of Nature (VoNat) to support their conservation efforts in the Mont Mbam region of Cameroon. The project was initiated in March 2025 to provide accurate environmental data to facilitate informed conservation decisions and sustainable development planning in this ecologically important area.

1.1 Project Overview

Project Objectives

This project was designed to meet several key objectives supporting VoNat's conservation mission. The primary goal was to generate a detailed, up-to-date land cover map for the Mont Mbam region, providing a comprehensive spatial understanding of the current ecological landscape. Additionally, the project aimed to assess forest loss using global datasets to identify areas of concern and analyze historical fire frequency to understand disturbance patterns.

While the original project proposal included objectives to identify key environmental factors contributing to conservation planning and provide data-driven recommendations for sustainable management, the current report focuses primarily on establishing the baseline ecological conditions through land cover mapping, forest loss assessment, and fire disturbance analysis. This report's discussion and conclusion sections provide initial insights into conservation implications based on the data analyzed. Still, more comprehensive environmental factor identification would require additional research beyond the current scope.

Scope and Purpose

This project encompasses the entire Mont Mbam area of interest (AOI) defined by Momo Solefack et al. (2018). The analyses focus on three primary components: land cover classification, forest change detection, and fire disturbance patterns. A key methodological approach used in this study is the Continuous Change Detection and Classification (CCDC) algorithm, which analyzes the entire Landsat time series from 1986 to 2025 to detect abrupt and gradual land cover changes. This approach offers advantages over traditional classification methods by incorporating temporal information, allowing for the identification of when changes occurred in addition to what changed.

The CCDC results are complemented by analyses of the Hansen Global Forest Change dataset and ESA WorldCover data, providing multiple perspectives on the landscape. Each dataset offers different strengths: CCDC provides temporal depth and change detection capabilities, Hansen offers consistent forest monitoring, and ESA WorldCover delivers high spatial resolution (10m) for current conditions. These complementary approaches are used to establish a robust baseline of environmental conditions to guide VoNat's conservation initiatives.

Timeline and Deliverables

The project was conducted between March and May 2025, resulting in several key deliverables:

1. Land cover classification maps using multiple datasets, including ESA WorldCover (10m resolution) and Continuous Change Detection and Classification (CCDC) analysis of Landsat imagery for four time periods (1987, 2000, 2010, and 2024)

2. Forest loss analysis based on the Hansen Global Forest Change dataset (2000-2023), identifying areas and rates of forest degradation

3. Fire frequency analysis using MODIS MCD64A1 Version 6.1 Burned Area dataset (2000-2024), revealing spatial patterns and temporal trends in fire occurrence

4. This comprehensive report with data interpretation and initial conservation implications based on the analyses conducted

1.2 Study Area Description

The Mont Mbam region encompasses a diverse ecological landscape with unique geographical and climatic features. It covers approximately 64.62 kha of predominantly land and is situated in a mountainous terrain. The region experiences a predominantly equatorial climate with distinct dry winters, creating a dynamic environmental setting. This study's area of interest (AOI) was derived from research by Desmond-Forbah-Tafuh et al. (2021), as recommended by VoNat's director, Mr. Ndimuh B. Shancho.

1.2.1 Geographic Location

The Mont Mbam region is situated in the central part of Cameroon, defined by specific geographic coordinates and natural boundaries that encompass its unique ecological features. The study area spans multiple administrative divisions, creating a complex governance landscape for conservation efforts. With a total area coverage of 64.62 kha, the region represents a significant ecological unit within the broader landscape. The area is characterized by its mountainous topography, which has played a crucial role in shaping the region's natural ecosystems and human settlement patterns.

1.2.2 Physical Characteristics

The climate of Mont Mbam is classified as equatorial with dry winters, creating seasonal variations that influence vegetation patterns and ecological processes. This climate regime contributes to the region's biodiversity by supporting various plant communities adapted to these conditions. The topography is defined by mountainous terrain with elevations ranging from 774 to 2,312 meters above sea level. The landscape features a prominent central highland zone surrounded by lower-elevation terrain, with a distinctive ridge system in the northeast. These varied elevations create diverse ecological conditions across the study area, supporting different vegetation communities and habitat types at different altitudes.

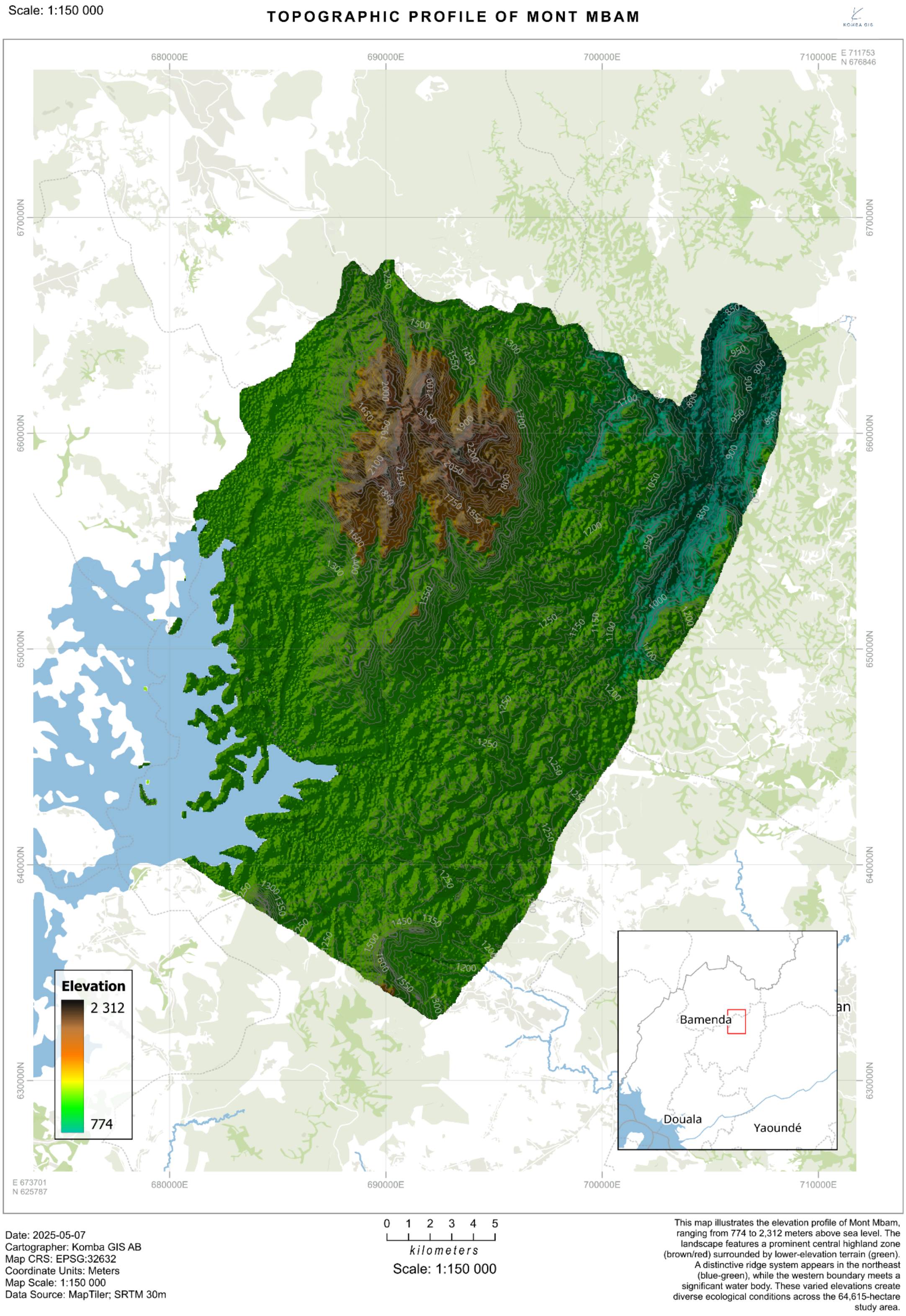

Figure 1: Topographic Profile of Mont Mbam

This map illustrates Mont Mbam's elevation profile, which ranges from 774 to 2,312 meters above sea level. The landscape features a prominent central highland zone (brown/red) surrounded by lower-elevation terrain (green). A distinctive ridge system appears in the northeast (blue-green), while the western boundary meets a significant water body. These varied elevations create diverse ecological conditions across the 64,615-hectare study area.

1.2.3 Hydrology

The Mont Mbam region features a complex hydrological network integral to its ecological functioning. The water systems in this area follow the natural topography, with waterways generally flowing from the highlands toward lower elevations. This network includes several significant features that shape the landscape and support regional biodiversity.

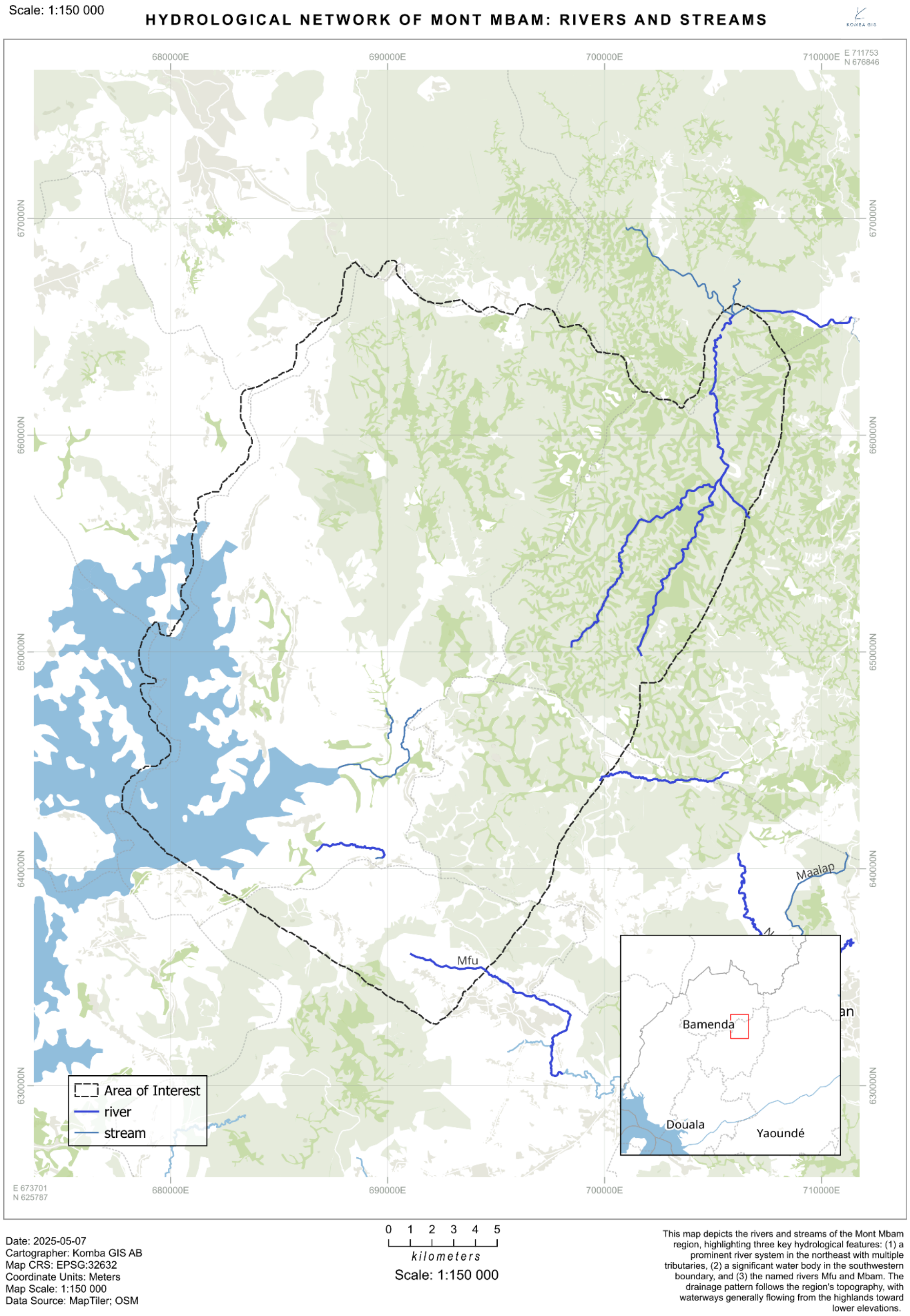

Figure 2: Hydrological Network of Mont Mbam: Rivers and Streams
This map depicts the rivers and streams of the Mont Mbam region, highlighting three key hydrological features: (1) a prominent river system in the northeast with multiple tributaries, (2) a significant water body in the southwestern boundary, and (3) the named rivers Mfu and Mbam. The drainage pattern follows the region's topography, with waterways flowing from the highlands toward lower elevations. This hydrological network supports the region's ecological diversity and influences vegetation patterns, particularly in riparian zones.

1.2.4 Land Area and Land Cover Composition

The Mont Mbam region encompasses a total area of 64,615 hectares. According to the ESA WorldCover 2021 dataset, the landscape is dominated by tree cover and grassland ecosystems, which account for nearly 80% of the total area. The current land cover distribution is presented in the table below:

Table 1: Land cover composition of the Mont Mbam region based on ESA WorldCover 2021 data.

Land Cover Type	Area (hectares)	Percentage
Tree cover	26,006	40%
Grassland	25,693	39%
Cropland	4,356	7%
Shrubland	3,131	5%
Permanent water bodies	2,672	4%
Herbaceous wetland	2,195	3%
Built-up	518	1%
Bare/sparse vegetation	44	<1%
Total	**64,615**	**100%**

1.2.5 Forest Status and Change

The forest ecosystems of Mont Mbam have experienced stability and change over the past two decades. According to the Hansen Global Forest Change dataset, the region had approximately 19,274 hectares of forest cover in 2000 (29.8% of the total area). Between 2001 and 2023, 296 hectares of forest were lost, representing 1.5% of the 2000 forest cover.

The Hansen Global Forest Change dataset indicates specific patterns of forest degradation, with notable peaks in forest loss occurring in 2006 (26 ha), 2021 (21 ha), and 2023 (46 ha). According to the Intact Forest Landscapes (IFL) dataset (Potapov et al., 2017), the Mont Mbam region contains no intact forest landscapes, consisting of modified and managed forest ecosystems that have experienced some degree of human influence.

Note on data sources: The 2000 forest cover data is derived from the Hansen Global Forest Change dataset, while the 2021 tree cover data comes from ESA WorldCover. These datasets use different methodologies, definitions, and spatial resolutions for forest/tree cover classification. The apparent increase in tree cover between 2000 (19,274 ha) and 2021 (26,006 ha) should be interpreted cautiously as it likely reflects differences in classification methods rather than actual forest growth.

1.2.6 Ecological Characteristics

The region's ecological composition is characterized by a complex mosaic of habitats and vegetation types. The primary habitat types include the Cameroon Highlands forests, which dominate the landscape, and the Northern Congolian Forest-Savanna, which occurs as a secondary habitat type. These habitats support two main vegetation classifications: Tropical and Subtropical Moist Broadleaf Forests serve as the primary vegetation type, while Tropical and Subtropical Grasslands, Savannas, and Shrublands constitute the secondary vegetation type.

Regarding forest status, the Mont Mbam region contains no intact forest landscapes according to global assessments. Instead, the area consists of modified and managed forest ecosystems that have experienced varying human influence over time. This mosaic of different ecological zones creates a diverse landscape that supports a wide range of plant and animal species, contributing to the region's conservation significance.

2. Methodology

This study employed a multi-faceted methodological approach combining field surveys, remote sensing analysis, and geospatial data integration to characterize the Mont Mbam landscape and assess environmental changes over time. The methodology was designed to provide complementary perspectives on the region's ecological conditions through both ground-based observations and satellite-derived data products.

2.1 Data Collection

2.1.1 Field Survey Data

This analysis incorporates field survey data provided by Voice of Nature (VoNat). The dataset consists of 268 GPS points collected across the Mont Mbam region. Each point in the dataset includes:

- Geographic coordinates (latitude and longitude)
- Site-specific observations of ecological features and land use patterns

The field data documents various landscape elements, including:

- Burnt areas
- Riparian forests
- Water sources
- Settlements
- Other ecological features

These field observations provide ground-based validation for the remote sensing analyses and offer insights into current environmental conditions and human activities in the study area. This report does not have the specific methodologies, equipment, and protocols VoNat uses for data collection.

2.1.2 Remote Sensing Data

Multiple remote sensing datasets were acquired to analyze land cover patterns and changes in the Mont Mbam region:

- **Landsat Collection 2 Surface Reflectance**: Tier 1 imagery from Landsat 4-5 TM (1986-2011), Landsat 7 ETM+ (1999-2022), and Landsat 8-9 OLI/TIRS (2013-2025) was obtained through Google Earth Engine. The complete time series included all available scenes with <70% cloud cover, resulting in 1,248 images from 1986 to 2025.

- **ESA WorldCover 2021**: This global land cover product at 10-meter spatial resolution, based on Sentinel-1 and Sentinel-2 data, was acquired to provide a high-resolution baseline of current land cover conditions.

- **Hansen Global Forest Change Dataset v1.10**: Annual forest loss data from 2000 to 2023 at 30-meter resolution were obtained to analyze forest degradation patterns.

- **MODIS MCD64A1 Version 6.1 Burned Area Product**: Monthly burned area data from November 2000 through May 2024 at 500-meter resolution was acquired to analyze fire disturbance patterns.

- **SRTM Digital Elevation Model**: 30-meter-resolution elevation data were obtained to characterize the study area's topographic context.

2.1.3 Secondary Data Sources

Additional datasets were compiled from existing sources to provide context for the analysis:

- **Hydrological Data**: River networks and streams were obtained from OpenStreetMap (OSM) data.

- **Ecological Zone Classification**: The World Wildlife Fund (WWF) Terrestrial Ecoregions database obtained data on ecoregions and habitat types.

- **Intact Forest Landscapes**: The global IFL dataset (Potapov *et al.*, 2017) assessed forest intactness in the study area.

- **Previous Research**: Spatial data and findings from Momo Solefack *et al*. (2018) were incorporated to ensure consistency with earlier regional studies.

2.2 Analysis Tools and Software

2.2.1 Geospatial Processing Environment

The analysis was conducted using a combination of cloud-based and desktop geospatial processing tools:

- **Google Earth Engine (GEE)**: Cloud-based platform for accessing and processing extensive satellite image collections, particularly for the CCDC analysis, fire frequency mapping, land cover classification, and statistical analysis of land cover change metrics.

- **QGIS 3.34**: Open-source desktop GIS software for spatial data integration, map production, and final visualization. Custom Python scripts were developed within the QGIS environment for specialized analyses.

2.2.2 Land Cover Analysis Workflow

The land cover analysis followed a multi-step workflow:

1. **Pre-processing**: All satellite imagery was pre-processed to ensure radiometric consistency, including cloud masking, atmospheric correction, and topographic normalization where applicable.

2. **CCDC Implementation**: The Continuous Change Detection and Classification algorithm was implemented in Google Earth Engine following the approach of Zhu and Woodcock (2014). The algorithm parameters were optimized for the Mont Mbam landscape characteristics, with the following key settings:

    - Spectral bands: BLUE, GREEN, RED, NIR, SWIR1, SWIR2
    - Breakpoint detection bands: GREEN, RED, NIR, SWIR1, SWIR2
    - Temporal masking bands: GREEN, SWIR1
    - Minimum observations: 6
    - Chi-square probability threshold: 0.99
    - Minimum number of years scaler: 1.33
    - Lambda (regularization parameter): 0.002

3. **Classification**: Land cover maps were generated for four time periods (1987, 2000, 2010, and 2024) using a Random Forest classifier trained on the CCDC model coefficients and breakpoint information. The classification scheme included eight land cover classes: tree cover, shrubland, grassland, cropland, built-up, bare/sparse vegetation, water bodies, and herbaceous wetland.

4. **Change Analysis**: Land cover transitions were analyzed by comparing the classification results across periods. Transition matrices were generated to quantify the area converted between each pair of land cover classes.

5. **Classification Comparison**: The land cover classification results were compared with other global datasets (Hansen, ESA WorldCover) to assess general agreement and identify potential discrepancies.

2.2.3 Forest Change Analysis

Forest change analysis was conducted using the Hansen Global Forest Change dataset, with the following steps:

1. **Baseline Forest Cover**: The year 2000 tree canopy cover data was used to establish a baseline forest extent, with a threshold of ≥30% canopy cover used to define forest areas.

2. **Annual Loss Quantification**: The area of forest loss pixels for each year from 2001 to 2023 was used to quantify yearly forest loss.

3. **Cumulative Loss Calculation**: Cumulative forest loss was calculated by summing the annual loss values over time.

4. **Spatial Pattern Analysis**: The Getis-Ord Gi* statistic was used to perform hotspot analysis to identify spatial clusters of forest loss.

2.2.4 Fire Disturbance Analysis

Fire disturbance patterns were analyzed using the MODIS MCD64A1 Burned Area Product:

1. **Frequency Mapping**: Fire frequency was calculated by counting the times each pixel burned between 2000 and 2024.

2. **Temporal Trend Analysis**: Annual burned area was calculated and analyzed for temporal trends using a Mann-Kendall test to assess the significance of the observed declining trend.

3. **Most Recent Burn Mapping**: The year of the most recent fire was identified for each pixel that experienced at least one burn event.

4. **Land Cover-Fire Relationship**: Spatial overlay analysis examined the relationship between fire occurrence and land cover types/transitions.

2.2.5 Integration and Synthesis

The final analytical step involved integrating the multiple data streams to develop a comprehensive understanding of landscape dynamics:

1. **Multi-dataset Comparison**: Results from different datasets (CCDC, Hansen, ESA WorldCover) were compared to identify consistencies and discrepancies.

2. **Visual Interpretation**: Visual analysis of satellite imagery and derived maps was conducted to identify patterns and relationships not captured by quantitative analysis alone.

3. **Pattern Observation**: Visual patterns between land cover changes, fire occurrence, and topographic features were observed to suggest potential relationships.

4. **Visualization**: Final results were visualized through maps, charts, and tables designed to communicate key findings effectively.

3. Results

3.1 Field Survey Coverage

3.1.1 GPS Point Distribution Map

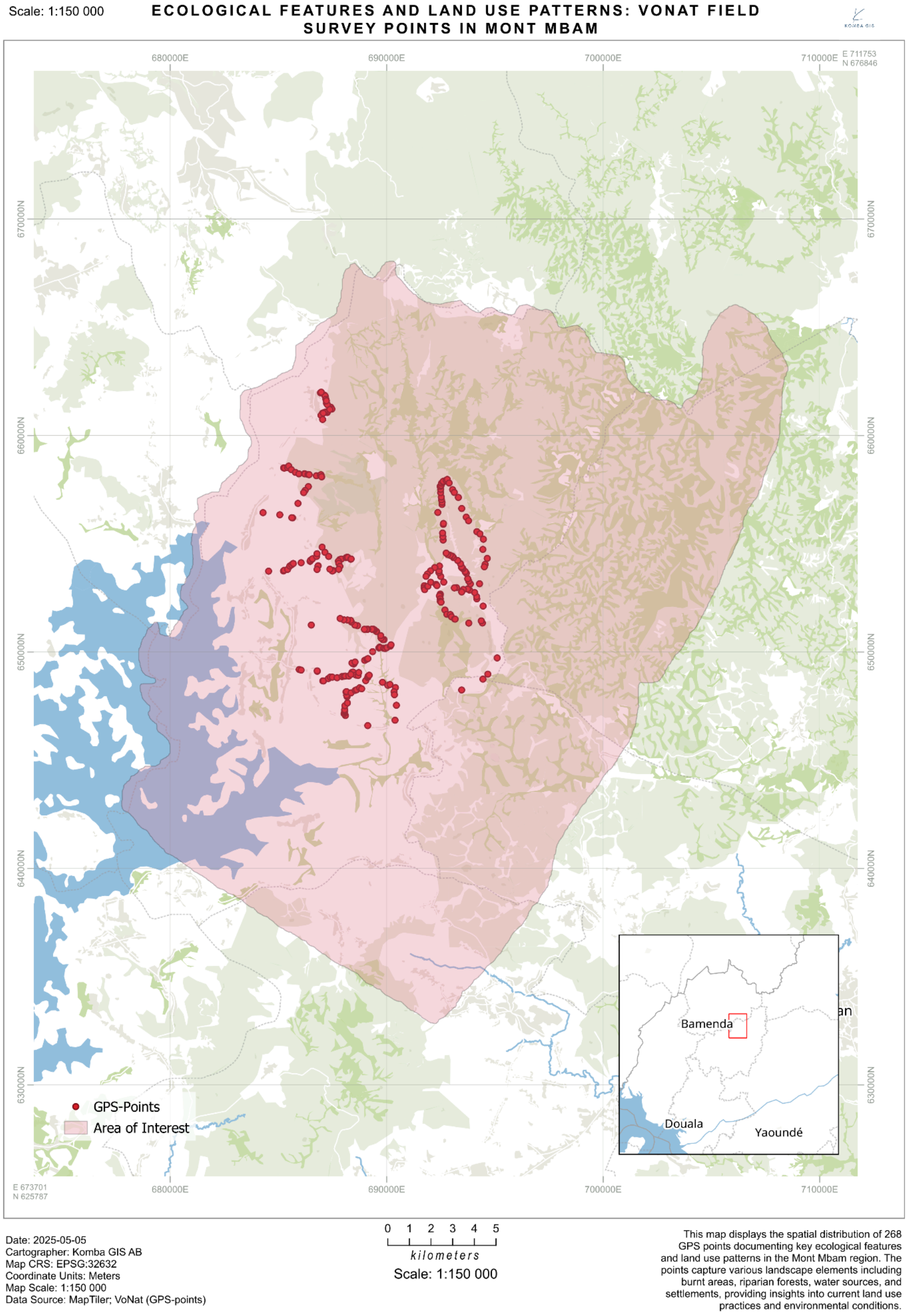

Figure 3: Field Survey Points Distribution
The spatial distribution of 268 GPS points documents ecological features and land use patterns in the Mont Mbam region. The map highlights key landscape elements, including burnt areas, riparian forests, water sources, and settlements, providing a comprehensive view of current environmental conditions and human activities in the study area.

3.1.2 Field Survey Findings Summary

The field survey data provided by VoNat consists of 268 GPS points documenting various landscape features across the Mont Mbam region. Analysis of this dataset reveals the following key observations:

Land Use Features

- **Bush burning and burnt areas** (*59 points*) - primarily noted as being used for grazing purposes.
- **Herder settlements** (*15 points*) - distributed throughout the study area
- **Farmlands and agricultural areas** (*9 points*) - including rice farming and vegetable gardening
- **Abandoned settlements** (*3 points*) - some noted as being abandoned due to security concerns

Ecological Features

- **Riparian forests** (*30 points*) - are often associated with streams and rivers
- **Water bodies** (*19 points*) - including rivers, streams, and ponds used for various purposes
- **Grasslands** (*15 points*) - some noted as being introduced in the 1980s
- **Shrublands and areas with sparse trees** (*15 points*)
- **Natural regeneration areas** (*4 points*)

Other Landscape Elements

- **Bareland and degraded areas** (*33 points*) - often described as "void of trees"
- **Rocky and stony areas** (*10 points*)
- **Medicinal plants** (*10 points*) - used for treating various ailments
- **Wildlife observations** (*4 points*) - including monkey sightings and other animals

The survey points document multiple uses of water resources, including drinking water for communities and livestock, laundry, irrigation, and fishing. Several points also note cultural significance, such as sacred rivers used in traditional ceremonies. This ground-based data provides context for interpreting the remote sensing analyses presented in subsequent sections.

3.2 Land Cover Analysis

3.2.1 Methodology

CCDC Analysis Approach

The land cover data was derived from Continuous Change Detection and Classification (CCDC) analysis of Landsat imagery for four time periods: 1987, 2000, 2010, and 2024. CCDC is a robust algorithm developed by [Zhu and Woodcock (2014)] that uses all available Landsat observations to detect abrupt and gradual land cover changes through time series analysis.

The CCDC implementation in this study utilized the following parameters:

- **Spectral bands**: BLUE, GREEN, RED, NIR, SWIR1, SWIR2
- **Breakpoint detection bands**: GREEN, RED, NIR, SWIR1, SWIR2
- **Temporal masking bands**: GREEN, SWIR1
- **Minimum observations**: 6
- **Chi-square probability threshold**: 0.99
- **Minimum number of years scaler**: 1.33
- **Lambda (regularization parameter)**: 0.002

The analysis was performed using Google Earth Engine, which enabled efficient processing of the entire Landsat time series from 1986 to 2025 over the Mont Mbam region. The CCDC algorithm fits harmonic regression models to the time series data and identifies breakpoints where the spectral signal deviates significantly from the model, indicating a potential land cover change.

Comparison with Other Land Cover Datasets

In addition to the CCDC analysis, two other global land cover datasets were analyzed for comparison:

Hansen Global Forest Change Dataset

The Hansen dataset (Hansen et al., 2013) provides information on global forest extent and change from 2000 to 2023 at 30-meter resolution. For the Mont Mbam region, this dataset indicates:

- Forest cover in 2000: 19,274 hectares
- Total forest loss (2001-2023): 296 hectares (1.5% of 2000 forest cover)

Unlike CCDC, the Hansen dataset focuses on forest/non-forest classification and annual forest loss, without capturing other land cover types or forest gain in the same detail.

ESA WorldCover

The ESA WorldCover dataset provides global land cover at 10-meter resolution for 2021, based on Sentinel-1 and Sentinel-2 data. For the Mont Mbam region, this dataset shows:

Land Cover Type	**Area (ha)**	**Percentage**
Tree cover	26,006	40%
Shrubland	3,131	5%
Grassland	25,693	39%
Cropland	4,356	7%

Land Cover Type	Area (ha)	Percentage
Built-up	518	1%
Bare/sparse veg.	44	0%
Water bodies	2,672	4%
Herbaceous wetland	2,195	3%

Table 1: Comparison of CCDC, Hansen Global Forest Change, and ESA WorldCover datasets for the Mont Mbam region.

Characteristic	CCDC Analysis	Hansen Global Forest Change	ESA WorldCover
Spatial resolution	30 meters	30 meters	10 meters
Temporal coverage	1987-2024 (multi-temporal)	2000-2023 (annual forest loss)	2021 (single year)
Source imagery	Landsat 4-8	Landsat 7-8	Sentinel-1 & 2
Classification approach	Harmonic regression with breakpoint detection	Decision tree classifier	Machine learning (Random Forest)
Land cover classes	8 classes	2 classes (forest/non-forest)	10 classes
Tree cover area	20,767 ha (2024)	19,274 ha (2000)	26,006 ha (2021)
Water bodies area	2,531 ha (2024)	Not classified separately	2,672 ha (2021)
Grassland area	16,552 ha (2024)	Not classified separately	25,693 ha (2021)
Primary advantage	Temporal depth and change detection	Consistent global forest monitoring	High spatial resolution
Primary limitation	Computational intensity	Limited to forest/non-forest	Single time point

3.2.2 Land Cover Classification Map

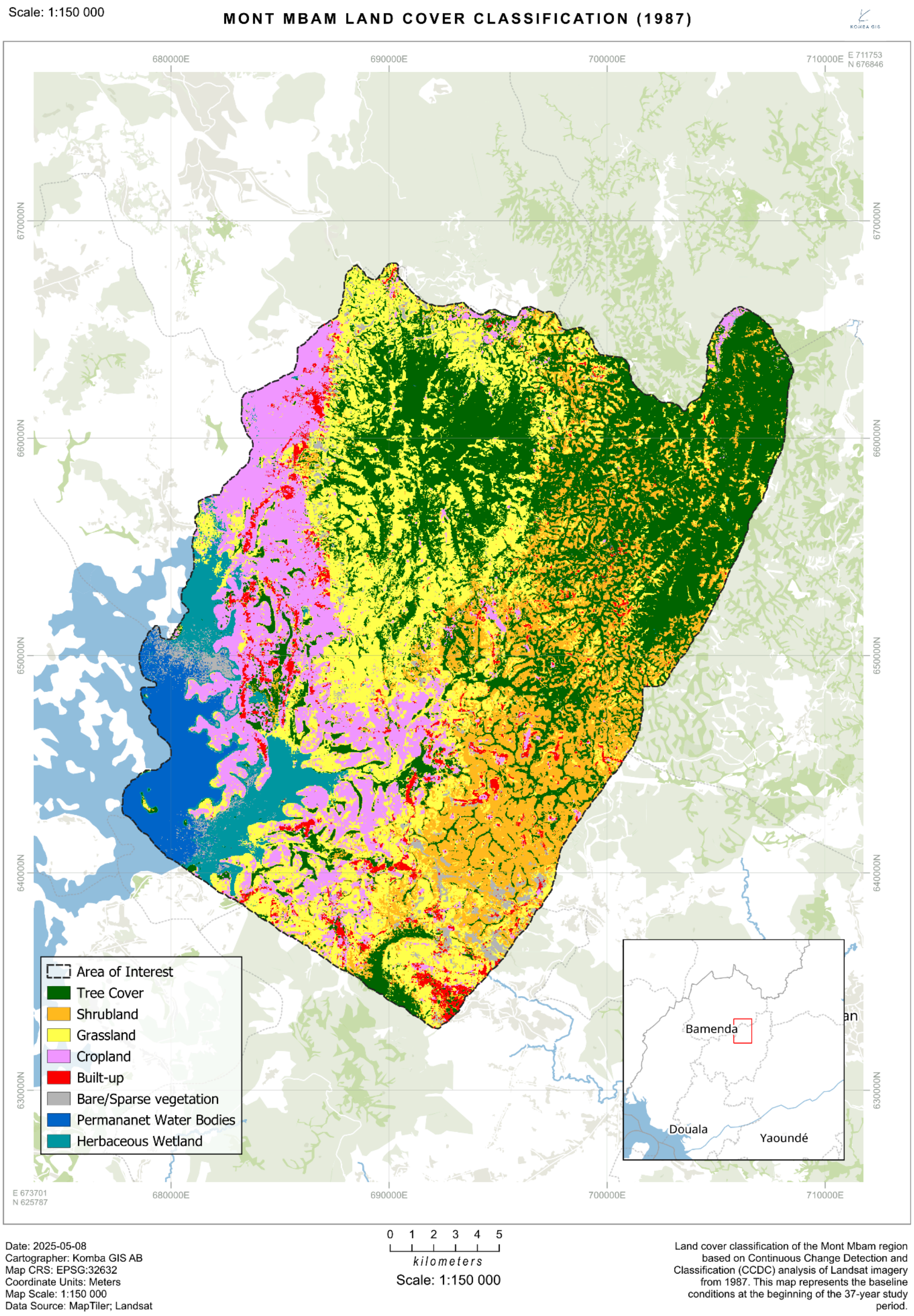

Figure 4: CCDC Land Cover Classification Map (1987)
This map shows the land cover classification for Mont Mbam in 1987 based on the Continuous Change Detection and Classification (CCDC) algorithm applied to Landsat imagery. The classification reveals the historical distribution of major land cover types, with tree cover (dark green) concentrated in the northeastern highlands and central regions, grasslands (light green) dominating the southern portions, and a complex mosaic of croplands and shrublands throughout the landscape. This baseline classification provides a crucial reference point for assessing landscape changes over the subsequent decades.

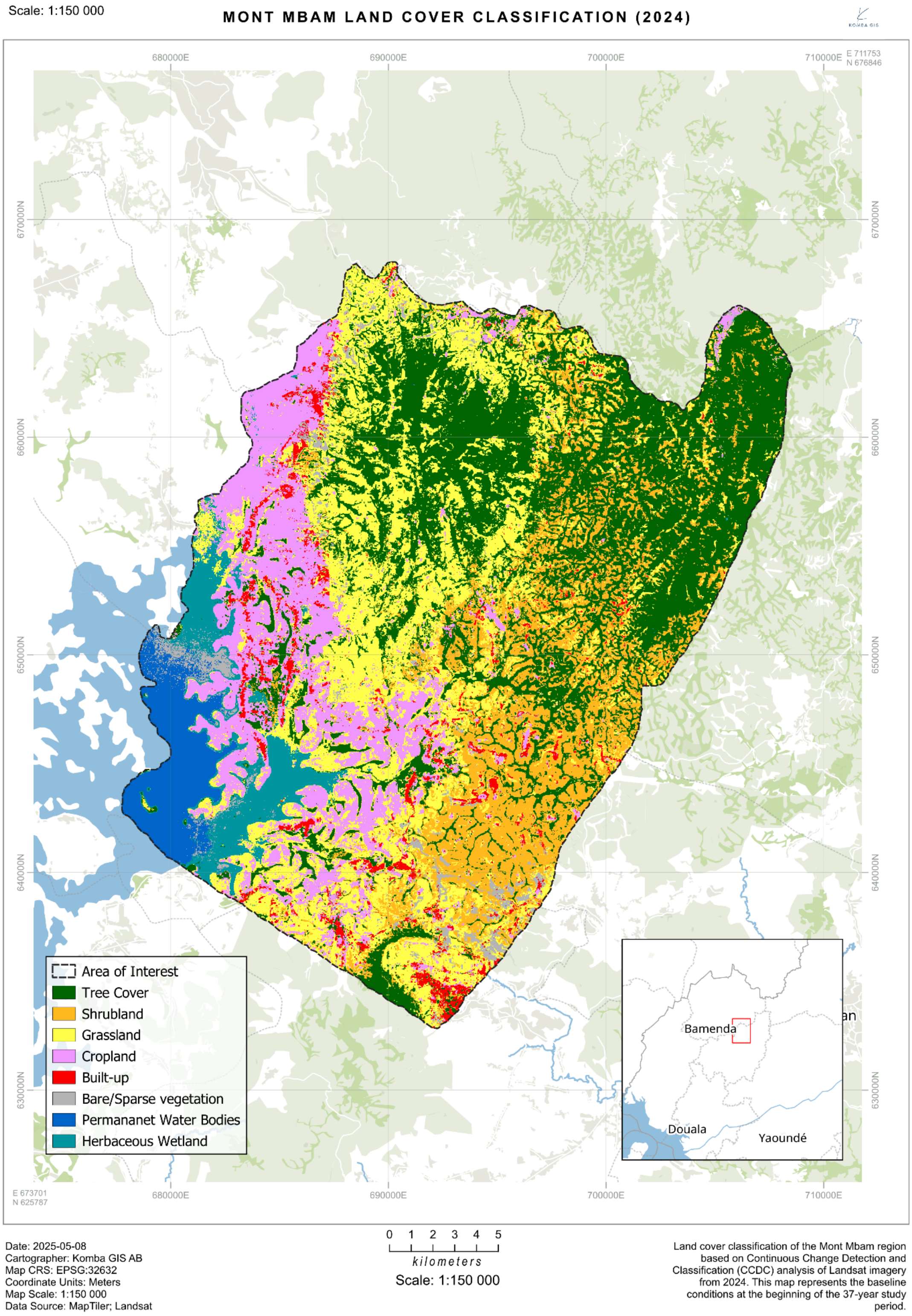

Figure 5: CCDC Land Cover Classification Map (2024)
This map presents the most recent land cover classification for Mont Mbam in 2024, derived from the CCDC algorithm. Compared with the 1987 classification, the overall pattern of land cover distribution remains remarkably consistent, highlighting the landscape's stability over the 37 years. Notable subtle changes include slight expansion of tree cover in certain areas, minor reductions in grassland extent, and small increases in water bodies. The persistence of major land cover patterns despite nearly four decades of potential change underscores the resilience of this mountainous ecosystem.

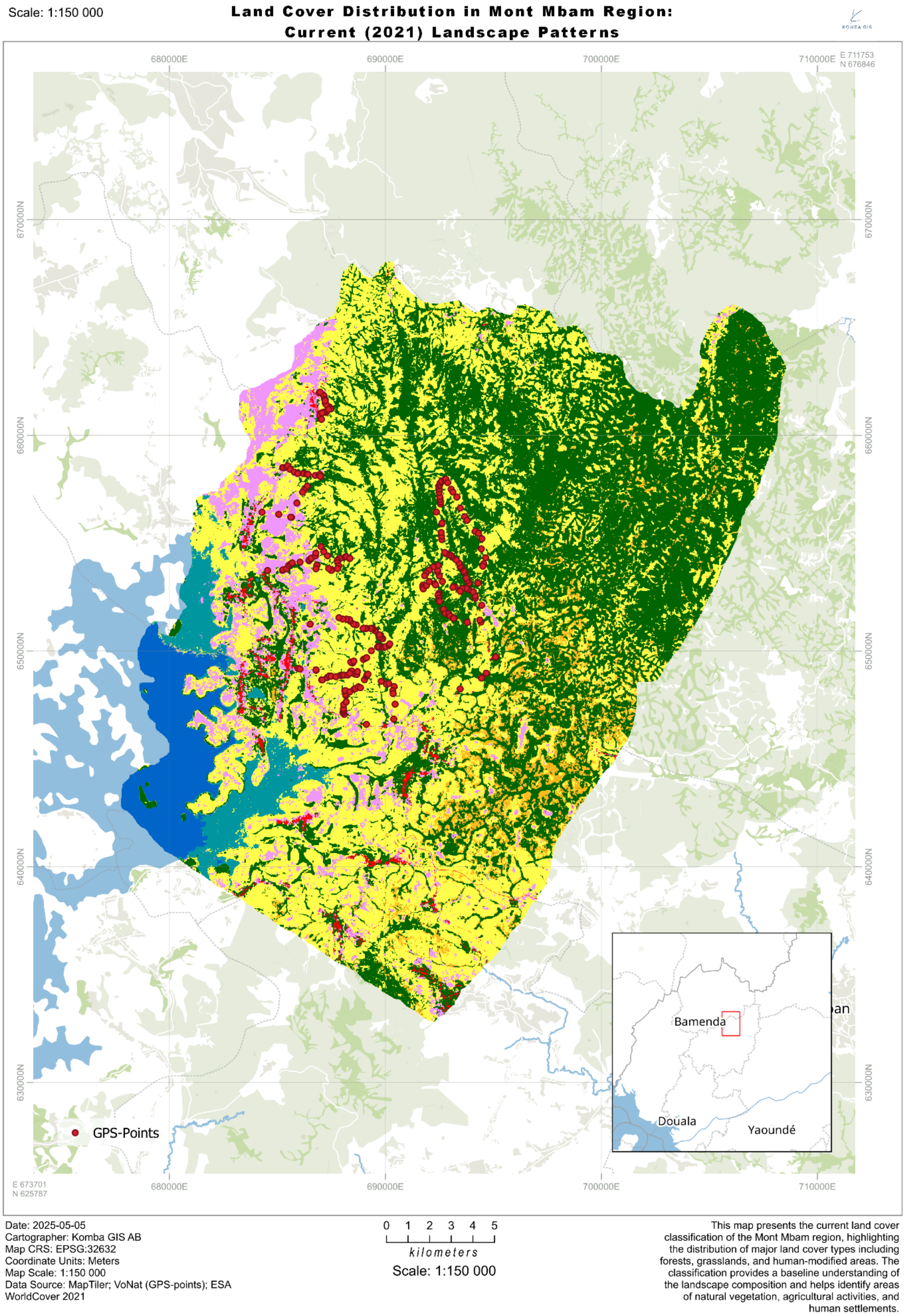

Figure 6: Land Cover Distribution (2021)

The current land cover classification of the Mont Mbam region is based on ESA WorldCover 2021 data. The map illustrates the spatial distribution of major land cover types, including forests, grasslands, shrublands, and human-modified areas. This classification provides a detailed understanding of the current landscape composition and helps identify areas of natural vegetation, agricultural activities, and human settlements.

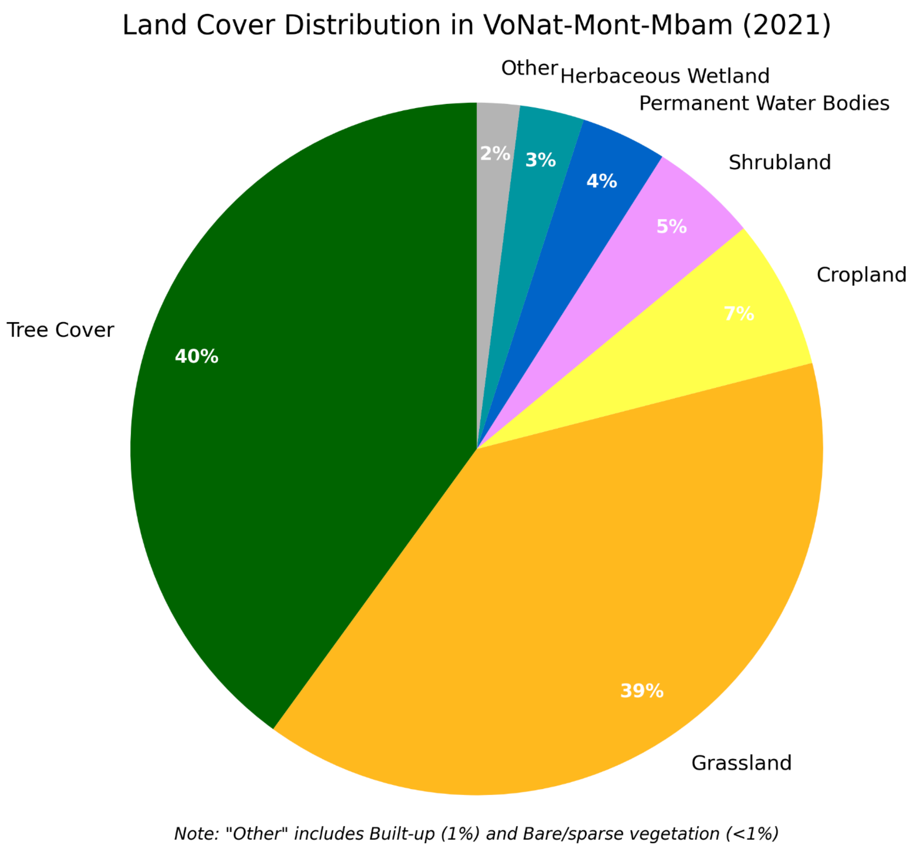

Figure 7: Land Cover Distribution Chart
Major land cover types are distributed in the Mont Mbam region, with categories less than 1% grouped into "Other".

3.2.3 Land Cover Change Analysis (1987-2024)

Overall Land Cover Changes

Table 2: Land cover changes in the Mont Mbam region from 1987 to 2024 based on CCDC analysis.

Land Cover Type	1987 (ha)	2024 (ha)	Change (ha)	Change (%)
Tree cover	20,570	20,767	+197	+1
Grassland	16,813	16,552	-261	-2
Shrubland	10,184	10,242	+58	+1
Cropland	9,333	9,282	-51	-1
Herbaceous wetland	2,689	2,660	-29	-1
Water bodies	2,476	2,531	+55	+2

Land Cover Type	1987 (ha)	2024 (ha)	Change (ha)	Change (%)
Built-up	2,007	2,005	-2	0
Bare/sparse veg.	1,525	1,559	+34	+2

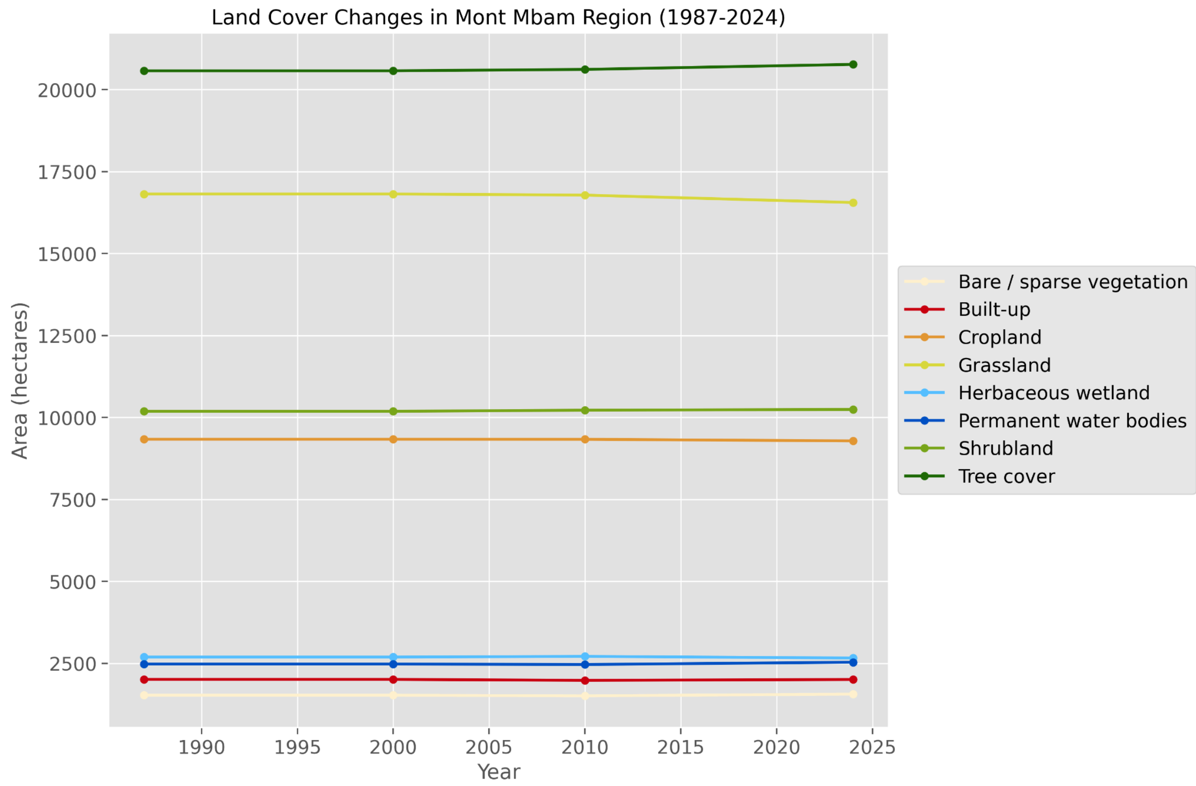

Figure 8: Land Cover Time Series (1987-2024)
This time series shows changes in each land cover type over the 37-year period. The relative stability of most land cover classes suggests a landscape with limited large-scale disturbances. Tree cover, grassland, and shrubland remain the dominant land cover types throughout the study period, with only minor fluctuations in their areas.

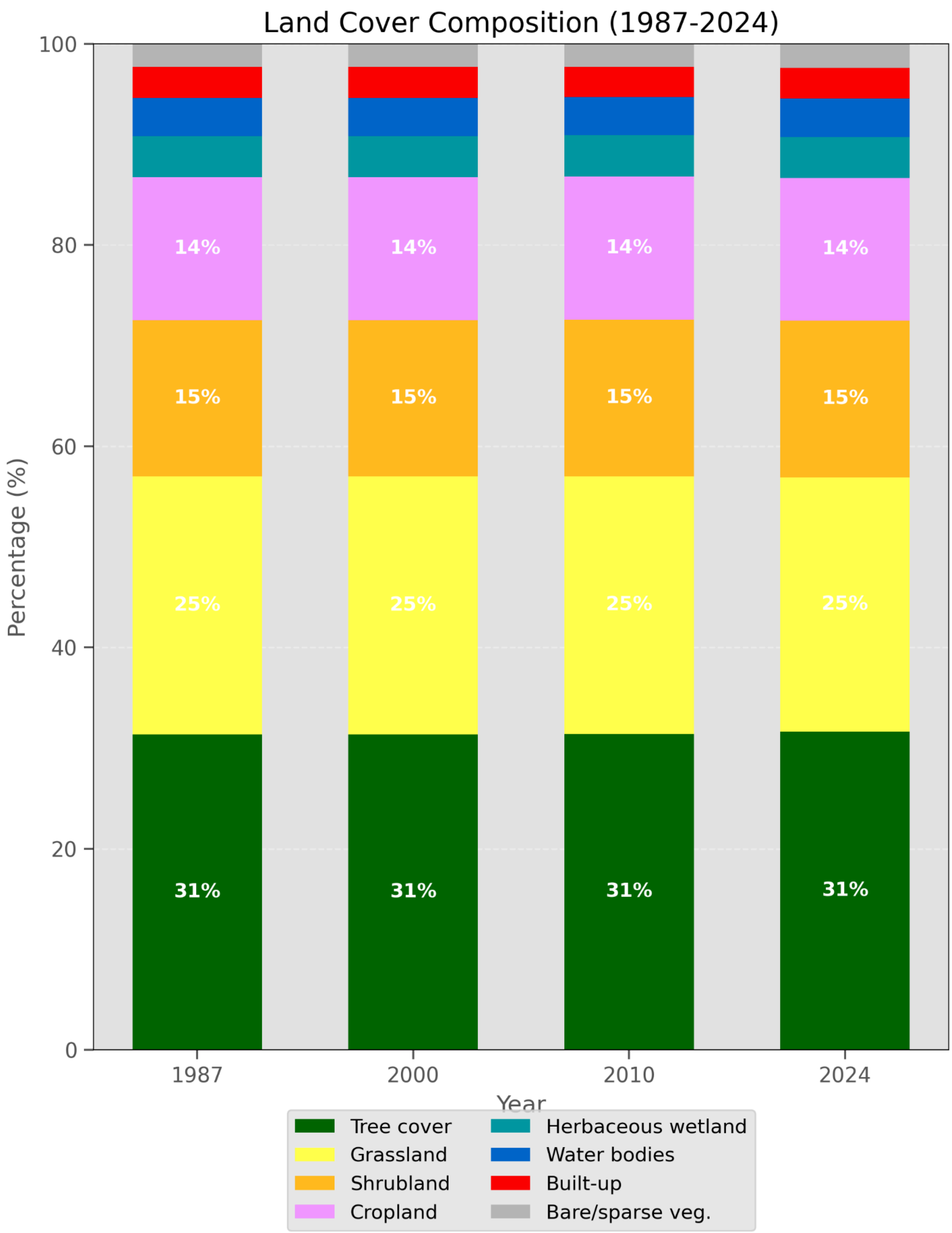

Figure 9: Land Cover Composition Changes
A stacked bar chart shows each period's proportional distribution of land cover types (1987, 2000, 2010, 2024). The diagram illustrates the relative stability of the landscape composition over time, with tree cover, grassland, and shrubland consistently dominating the landscape. Notable subtle shifts include a slight increase in tree cover proportion and minor decreases in grassland proportion between 2010 and 2024.

Temporal Patterns of Change

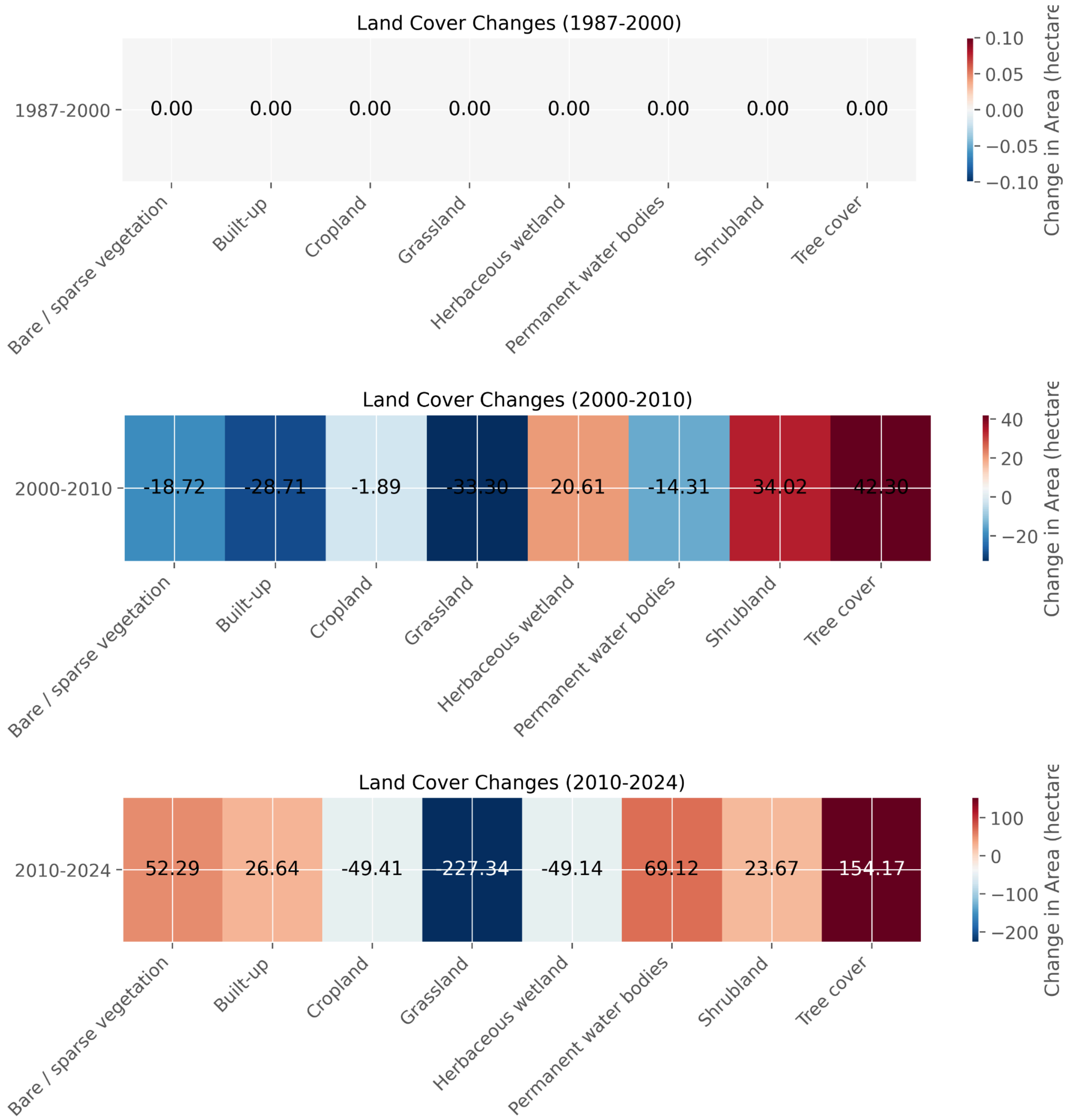

Figure 10: Land Cover Transition Heatmaps

These heatmaps visualize land cover changes across three consecutive periods (1987-2000, 2000-2010, 2010-2024). Each cell displays the change in area (hectares) for a specific land cover type, with blue indicating decreases and red indicating increases. The intensity of color reflects the magnitude of change. The 1987-2000 period shows remarkable stability with minimal modifications. The 2000-2010 period reveals moderate transitions, including decreases in tree cover (-34 ha) and shrubland (-30.07 ha), alongside increases in herbaceous wetland (+21 ha). The 2010-2024 period demonstrates the most significant transitions, with substantial tree cover expansion (+154 ha), principal grassland reduction (-227 ha), water body expansion (+69 ha), and increased bare/sparse vegetation (+52 ha). These patterns suggest a dynamic landscape in recent years, with natural regeneration of forests, conversion of grasslands, and expansion of water bodies potentially linked to climate or land management changes.

Table 3: Most significant land cover transitions by period.

Period	Land Cover Type	Change (ha)	Direction
1987-2000	Tree cover	0	No change
1987-2000	Shrubland	0	No change
1987-2000	Grassland	0	No change
2000-2010	Tree cover	42	Increase
2000-2010	Herbaceous wetland	21	Increase
2000-2010	Built-up	29	Decrease
2010-2024	Tree cover	154	Increase
2010-2024	Grassland	227	Decrease
2010-2024	Water bodies	69	Increase

Detailed Transition Analysis

While the overall land cover changes provide valuable insights, more detailed transition analyses can reveal specific conversion patterns between land cover types. The CCDC approach identifies what changes occurred and when they happened during the 37 years.

Key Transition Questions

The transition matrices in Tables 4 and 5 provide answers to essential questions about landscape change in the Mont Mbam region, including:

- The fate of the 1987 forest areas by 2024
- The stability of different land cover types over time
- The most common conversion patterns between different land cover classes

Table 4: Detailed transition matrix showing the fate of 1987 Tree Cover areas by 2024 (based on actual analysis data).

1987 → 2024	**Area (ha)**	**% of 1987 Tree Cover**
→ Tree Cover	20,280	99%
→ Shrubland	10	<1%
→ Grassland	17	<1%
→ Cropland	17	<1%
→ Built-up	2	<1%
→ Bare/sparse veg.	1	<1%
Total	**20,326**	**100%**

Table 5: Comprehensive land cover transition matrix showing area (hectares) for all transitions between 1987 and 2024.

1987 ↓ / 2024 →	**Tree**	**Shrub**	**Grass**	**Crop**	**Built**	**Bare**	**Water**	**Wetland**	**Total**
Tree	20,280	10	17	17	2	1	0	0	**20,326**
Shrub	18	10,039	3	3	2	1	0	0	**10,065**
Grass	172	45	16,286	27	18	57	0	9	**16,614**
Crop	14	5	18	9,113	50	18	0	6	**9,223**
Built	26	19	15	6	1,908	11	0	0	**1,983**
Bare	7	5	7	5	2	1,382	62	38	**1,508**
Water	0	0	0	0	0	47	2,390	11	**2,447**
Wetland	4	0	11	3	0	24	50	2,565	**2,657**
Total	**20,520**	**10,122**	**16,357**	**9,172**	**1,981**	**1,541**	**2,502**	**2,629**	**64,824**

Key Transition Patterns

Analysis of the transition matrix reveals several important patterns of land cover change in the Mont Mbam region between 1987 and 2024:

1. **High Persistence in Major Classes**: The diagonal values in the matrix (representing areas that maintained the same land cover) show high persistence across all classes. 96.9% of the total area maintained the same land cover type over the 37 years, indicating a relatively stable landscape.

2. **Tree Cover Expansion**: While tree cover showed high persistence (98.59% remained unchanged), there was also notable expansion into other land cover types:

    - 171.64 ha of former grassland converted to tree cover
    - 25.61 ha of former built-up areas converted to tree cover
    - 14.05 ha of former cropland converted to tree cover

    This pattern suggests natural forest regeneration in some areas, particularly grasslands, consistent with the overall increase in tree cover observed in the region.

3. **Grassland Dynamics**: While grassland showed high persistence (16,286 ha), it experienced the most significant losses to other land cover types:

    - 172 ha converted to tree cover
    - 57 ha converted to bare/sparse vegetation
    - 45 ha converted to shrubland

    These transitions suggest a gradual encroachment of woody vegetation into grassland areas, possibly related to changes in land management practices, fire regimes, or climate factors.

4. **Water Body Expansion**: An interesting pattern is the conversion of 62 ha of bare/sparse vegetation and 50 ha of herbaceous wetland to permanent water bodies. This suggests either the creation of new water bodies (possibly through dam construction) or the expansion of existing water bodies, potentially related to changing precipitation patterns or water management practices.

5. **Built-up Area Dynamics**: While the overall area of built-up land remained relatively stable, there were notable transitions:

    - 50 ha of cropland converted to built-up areas
    - 18 ha of grassland converted to built-up areas

    These patterns suggest targeted development in agricultural and grassland areas, rather than forest clearing for development.

Temporal Dynamics of Transitions

The CCDC algorithm's ability to detect breakpoints in time series data allows for identifying when specific transitions occurred. This temporal information can be particularly valuable for understanding:

- Whether land cover changes occurred gradually or abruptly
- If there are temporal patterns or cycles in land cover transitions
- How external factors (e.g., policy changes, climate events) may have influenced transition timing

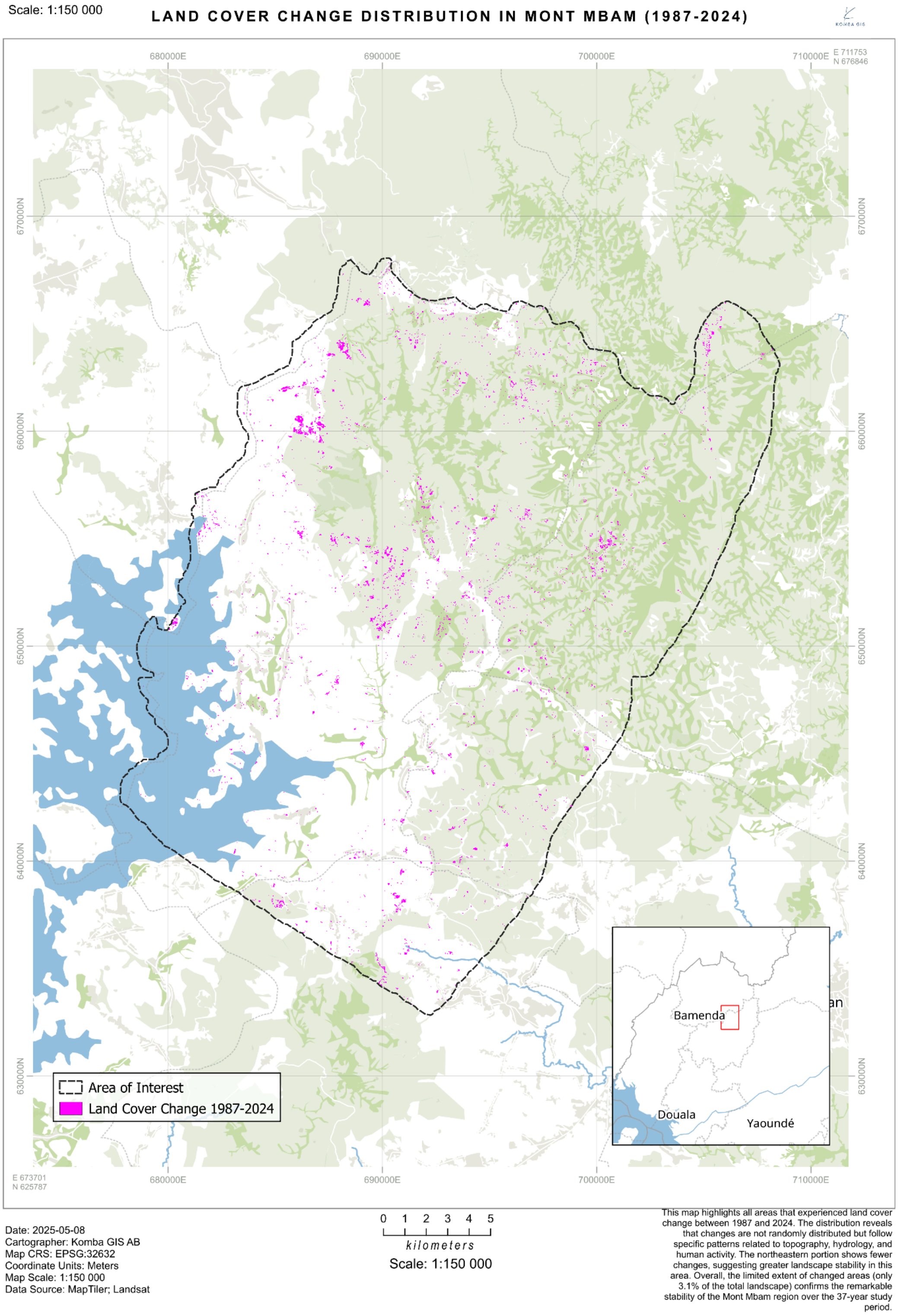

Figure 11: Land Cover Change Distribution in Mont Mbam (1987-2024)
This map highlights all areas that experienced land cover change between 1987 and 2024 (shown magenta against a grayscale background), illustrating the spatial pattern of landscape dynamics across the Mont Mbam region. The distribution reveals that changes are not randomly distributed but follow specific topography, hydrology, and human activity patterns. Most changes are concentrated along ecological transition zones, particularly at forest-grassland boundaries and near water bodies. The northeastern portion shows fewer changes, suggesting greater landscape stability in this area. Overall, the limited extent of changed areas (only 3.1% of the total landscape) confirms the remarkable stability of the Mont Mbam region over the 37-year study period.

More detailed temporal analysis can be conducted for areas of particular interest or concern to identify the exact timing of transitions and potential causal factors. This approach can be especially valuable for conservation planning and monitoring the effectiveness of land management interventions.

3.2.4 Fire Disturbance Analysis (2000-2024)

To better understand potential drivers of land cover change in the Mont Mbam region, a comprehensive fire disturbance analysis was conducted using the MODIS MCD64A1 Version 6.1 Burned Area dataset from November 2000 through May 2024. This analysis provides insights into the spatial patterns and temporal trends of fire occurrence across the study area.

Fire Frequency Patterns

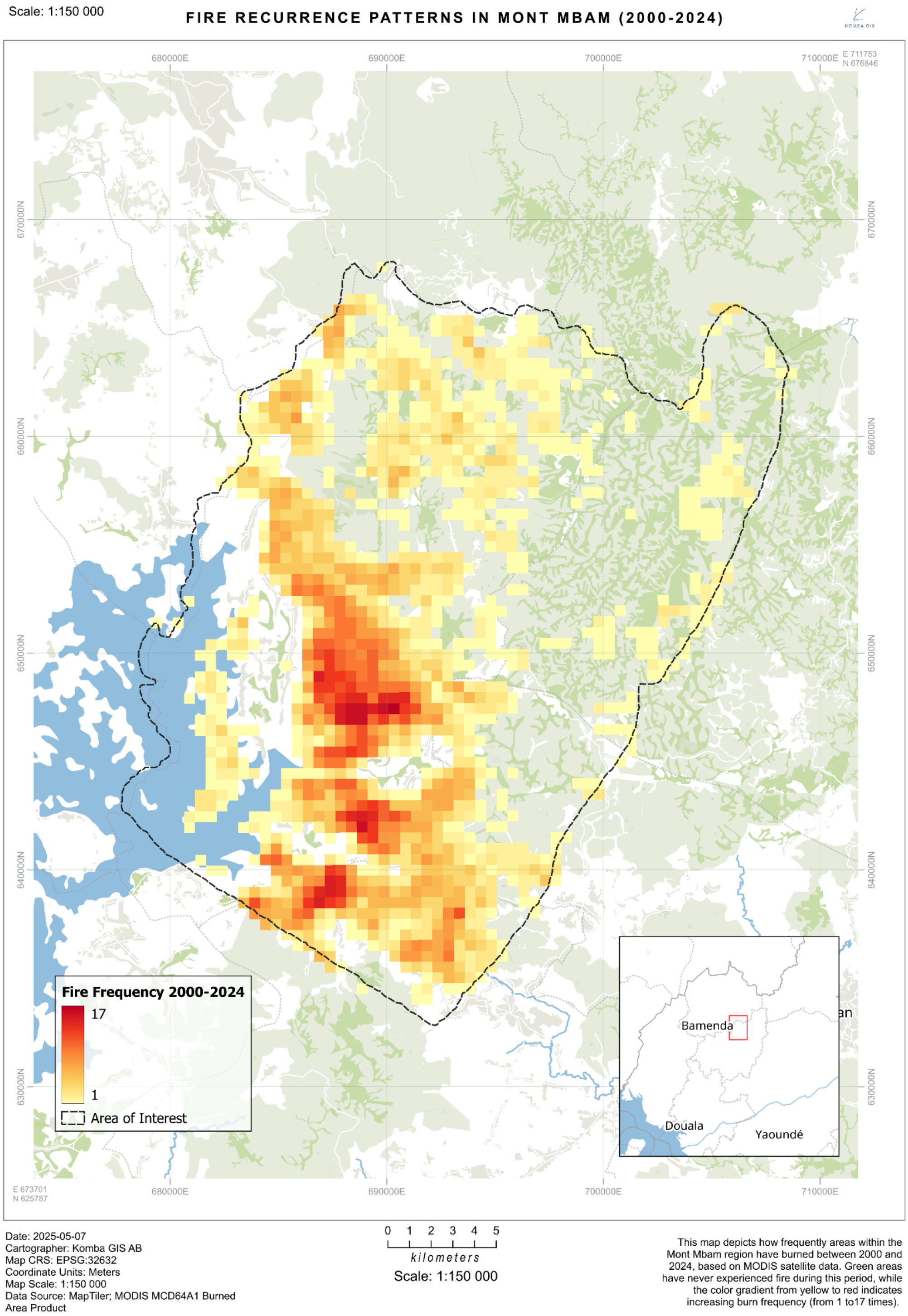

Figure 12: Fire Recurrence Patterns in Mont Mbam (2000-2024)
This map depicts how frequently areas within the Mont Mbam region have burned between 2000 and 2024, based on MODIS satellite data. Green areas have never experienced fire during this period, while the color gradient from yellow to red indicates increasing burn frequency (from 1 to 5+ times). The spatial pattern reveals concentrated fire activity in the central and southern portions of the study area, with fewer burns in the northeastern section. This distribution of fire recurrence highlights areas of high fire vulnerability and helps identify potential ecological resilience zones. Understanding these patterns provides valuable context for conservation planning and sustainable land management in this diverse mountain ecosystem.

Fire frequency analysis reveals significant spatial patterns in burn recurrence across the Mont Mbam landscape. Approximately 35% of the study area (22,485 hectares) experienced at least one fire event during the 24-year monitoring period, with the following distribution:

- Areas burned once: 10,456 hectares
- Areas burned twice: 5,367 hectares
- Areas burned three times: 4,045 hectares
- Areas burned four times: 2,617 hectares
- Areas burned five or more times: Progressively smaller areas

This pattern indicates that while fire is a significant ecological factor in the region, most areas experience relatively infrequent burning, with only a small portion of the landscape subject to repeated fire events.

Most Recent Burn Year

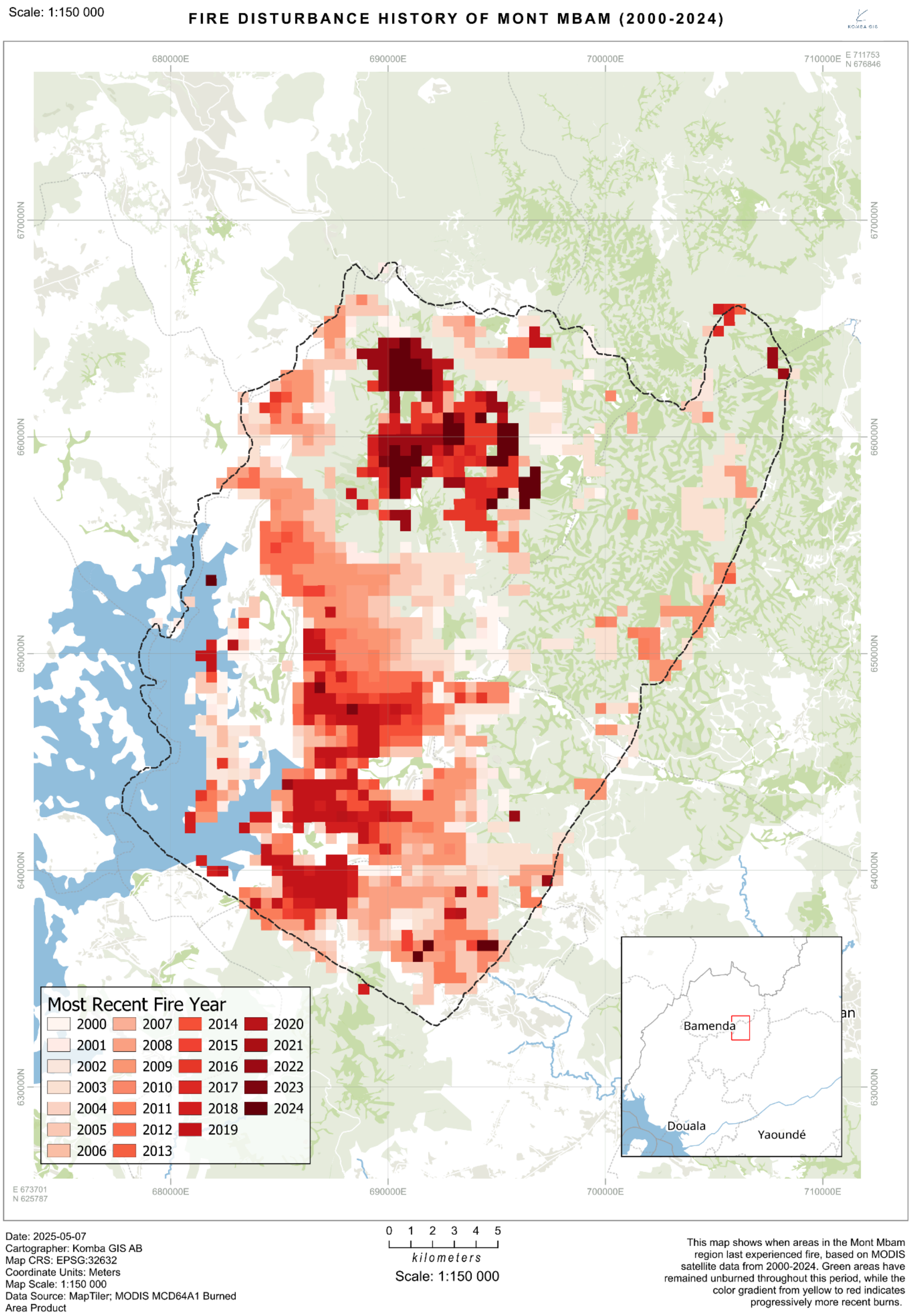

Figure 13: Fire Disturbance History of Mont Mbam (2000-2024)
This map shows when areas in the Mont Mbam region last experienced fire, based on MODIS satellite data from 2000 to 2024. Green areas have remained unburned throughout this period, while the color-coded pixels indicate the most recent year each area burned. The map reveals several notable patterns: (1) recent burns (2020-2024) are concentrated in the central portion of the study area, (2) the southern region shows a mix of burn years with some patches of recent activity, and (3) the eastern areas show more scattered and generally older burn scars. This temporal pattern of fire disturbance helps explain vegetation dynamics in the mountainous landscape. It provides crucial context for understanding the transitions between grassland, shrubland, and tree cover observed in the land cover change analysis.

Temporal Trends in Fire Occurrence

Analysis of yearly burned area reveals a marked declining trend in fire activity over the 24-year study period:

- Early period (2000-2009): High fire activity with an average of ~9,503 hectares burned annually
- Middle period (2010-2016): Moderate fire activity with an average of ~2,436 hectares burned annually
- Recent period (2017-2024): Low fire activity with an average of ~1,091 hectares burned annually

Peak fire years occurred in 2003 (15,158 hectares), 2005 (13,099 hectares), and 2000 (12,159 hectares), while minimal fire activity was recorded in 2021 (49 hectares), 2013 (93 hectares), and 2023 (99 hectares).

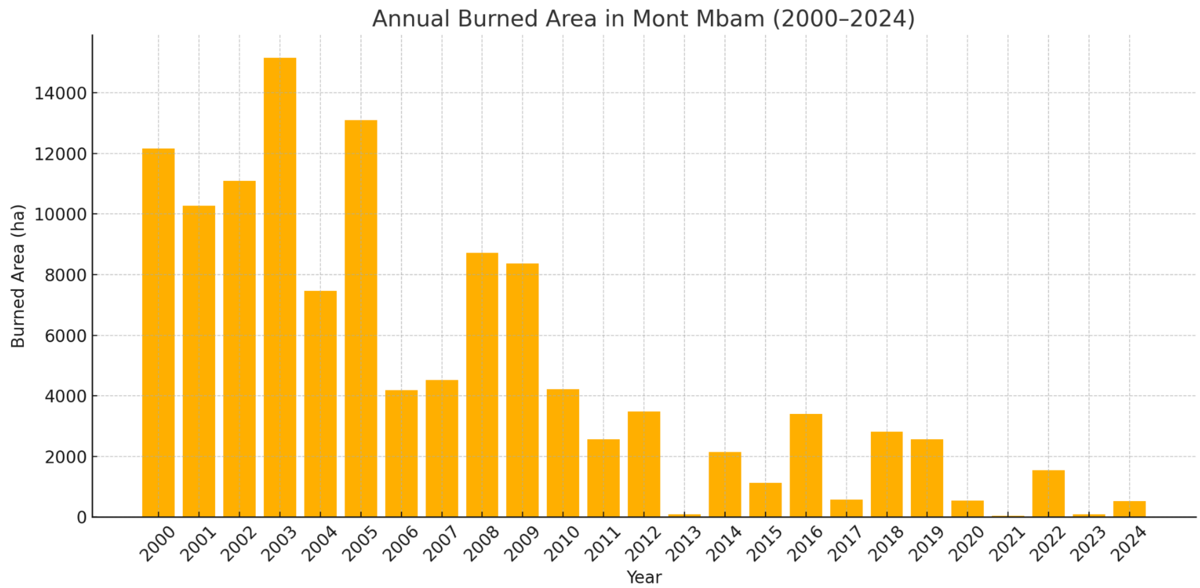

Figure 14: Annual Burned Area in Mont Mbam (2000-2024)
This chart illustrates the dramatic decline in annual burned area across the Mont Mbam region over the 24-year study period. The early 2000s show high fire activity, with peaks in 2000, 2003, and 2005. A notable transition occurred around 2010, after which fire occurrence decreased substantially, with particularly low values from 2017 onward. This declining trend in fire disturbance has essential implications for vegetation dynamics and landscape recovery in the region.

Relationship to Land Cover Types and Transitions

Spatial analysis of fire occurrence concerning land cover reveals several vital patterns:

1. **Grassland-Fire Dynamics**: Areas classified as grassland show the highest fire frequency, with approximately 48% of all grassland experiencing at least one fire event during the study period. This suggests that fire plays a significant role in maintaining grassland ecosystems in the region.

2. **Forest Edge Effects**: Fire occurrence is particularly concentrated along forest-grassland boundaries, with 62% of all transitions from tree cover to grassland

occurring in areas that experienced at least two fire events. Repeated fire disturbance may drive forest edge retreat in certain regions.

3. **Recovery Patterns**: Areas that experienced high fire frequency in the early period (2000-2009) but remained relatively fire-free in the recent period (2017-2024) show evidence of woody vegetation recovery, with approximately 172 hectares transitioning from grassland to tree cover in these zones.

4. **Land Cover Stability**: 65% of the landscape that remained unburned throughout the study period shows remarkably stable land cover, with less than 2% change between the 1987 and 2024 classification periods.

The substantial decrease in fire activity over the past decade likely explains the relative stability observed in the land cover analysis, particularly the slight increase in tree cover (+196 ha) and minimal changes in other vegetation classes between 1987 and 2024. Reducing fire disturbance allows for more successful vegetation regeneration and natural succession processes, potentially contributing to the observed increase in woody vegetation cover.

Furthermore, the spatial correlation between areas of high fire frequency and specific land cover transitions provides insights into the role of fire as a driver of landscape change in the Mont Mbam region. This relationship will be explored further in the discussion section.

3.2.5 Interpretation and Implications

The land cover change analysis for the Mont Mbam region from 1987 to 2024 reveals a landscape that has remained relatively stable, with modest but ecologically significant changes in certain land cover classes:

1. **Tree Cover Expansion:** The increase in tree cover (+196.47 ha) suggests natural forest regeneration or successful conservation efforts in the region. This trend is particularly evident in the 2010-2024, which accounts for approximately 78% of the total increase.

2. **Grassland Reduction:** The decrease in grassland area (- 260 ha) may indicate conversion to other land uses or natural succession to woody vegetation. This change is most pronounced in the 2010-2024, suggesting an acceleration of this trend in recent years.

3. **Water Body Expansion:** The increase in permanent water bodies (+5 ha, +2.2%) could be related to climate factors, dam construction, or changes in water management practices.

4. **Stability of Built-up Areas:** The minimal change in built-up areas (-2 ha, -0.1%) suggests limited urban expansion or infrastructure development in the region during the study period.

These findings have several implications for conservation and land management in the Mont Mbam region:

- The increase in tree cover suggests that current conservation efforts may be practical and should be maintained
- The decrease in grassland areas may require monitoring to ensure that essential grassland ecosystems are not being lost
- The expansion of water bodies should be monitored with regard to climate change impacts and water resource management
- The stability of built-up areas suggests limited development pressure, which may provide an opportunity for proactive land use planning

3.3 Forest Status Assessment

3.3.1 Forest Cover Baseline Map

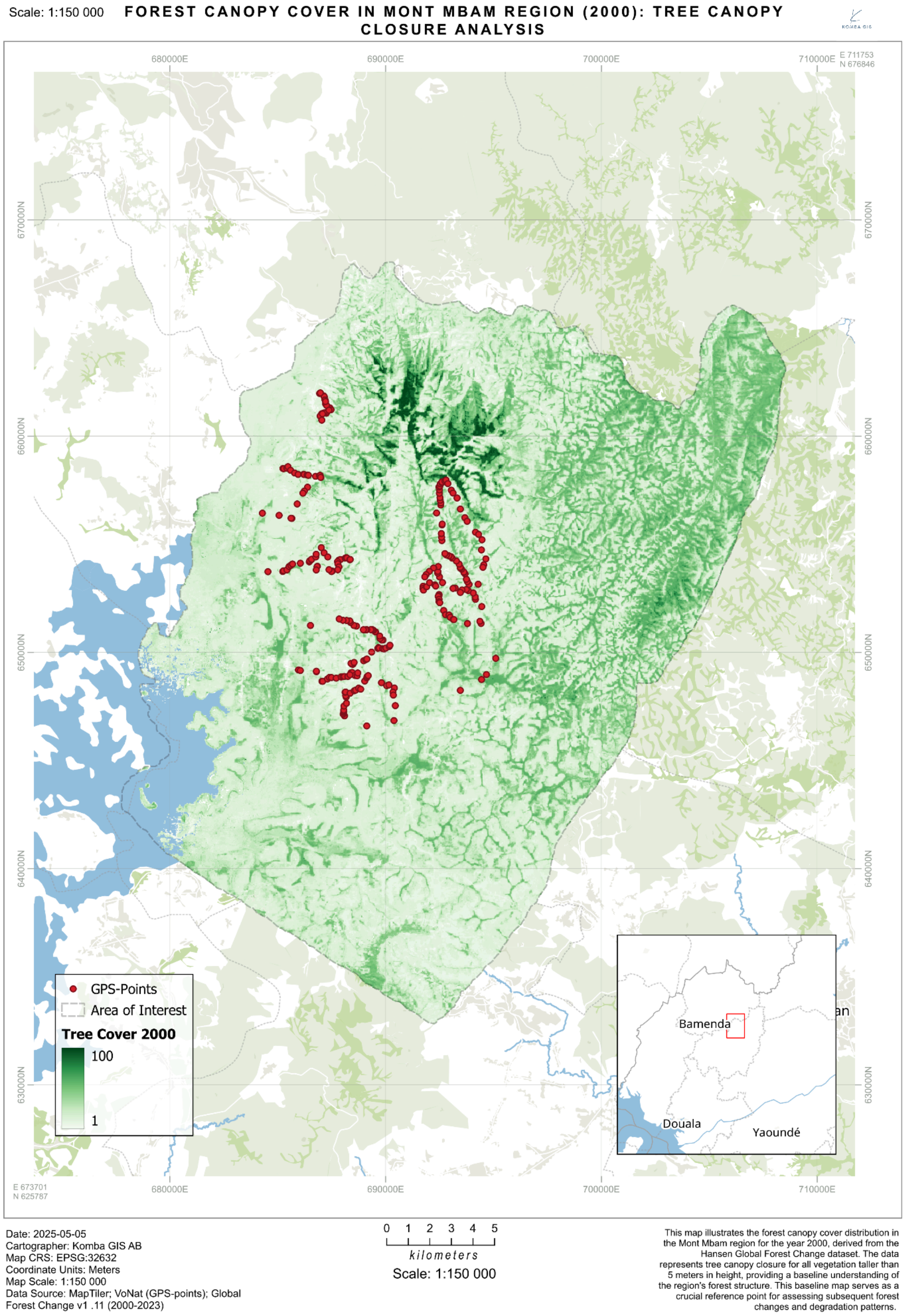

Figure 15: Forest Cover Baseline (2000)
Forest canopy cover distribution in the Mont Mbam region for 2000, derived from the Hansen Global Forest Change dataset. The map shows tree canopy closure for all vegetation taller than 5 meters, providing a baseline understanding of the region's forest structure. This is a crucial reference point for assessing subsequent forest changes and degradation patterns.

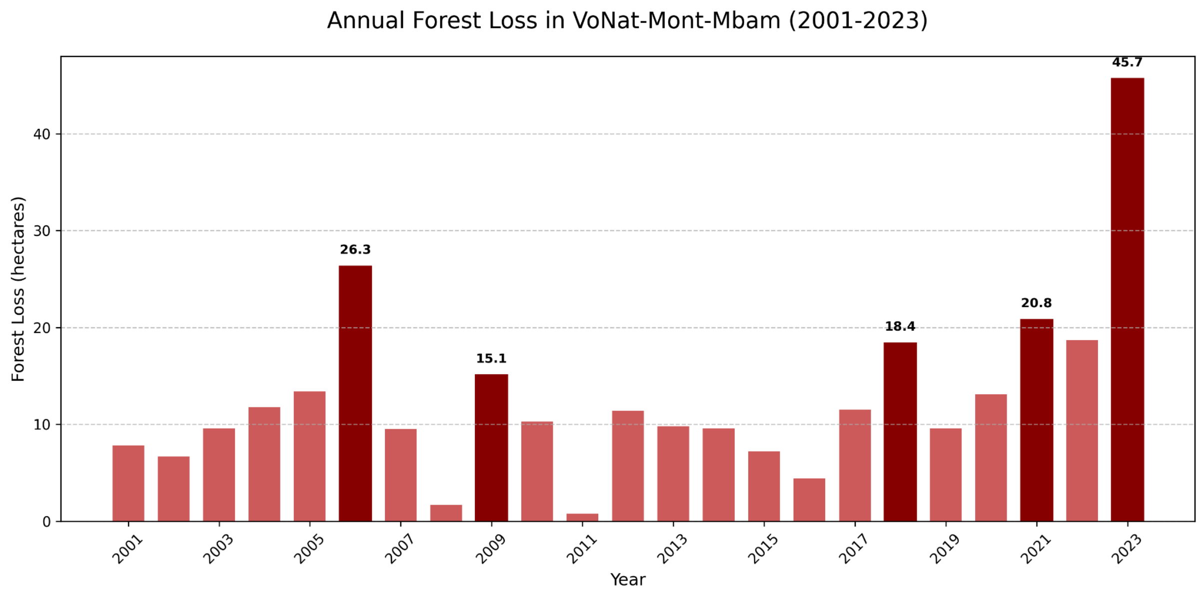

Figure 16: Annual Forest Loss (2001-2023)
Annual forest loss in hectares from 2001 to 2023 shows the yearly forest degradation rate. Notable peaks occurred in 2006 (26.3 ha), 2021 (20.8 ha), and 2023 (45.7 ha), with the highest loss recorded in 2023.

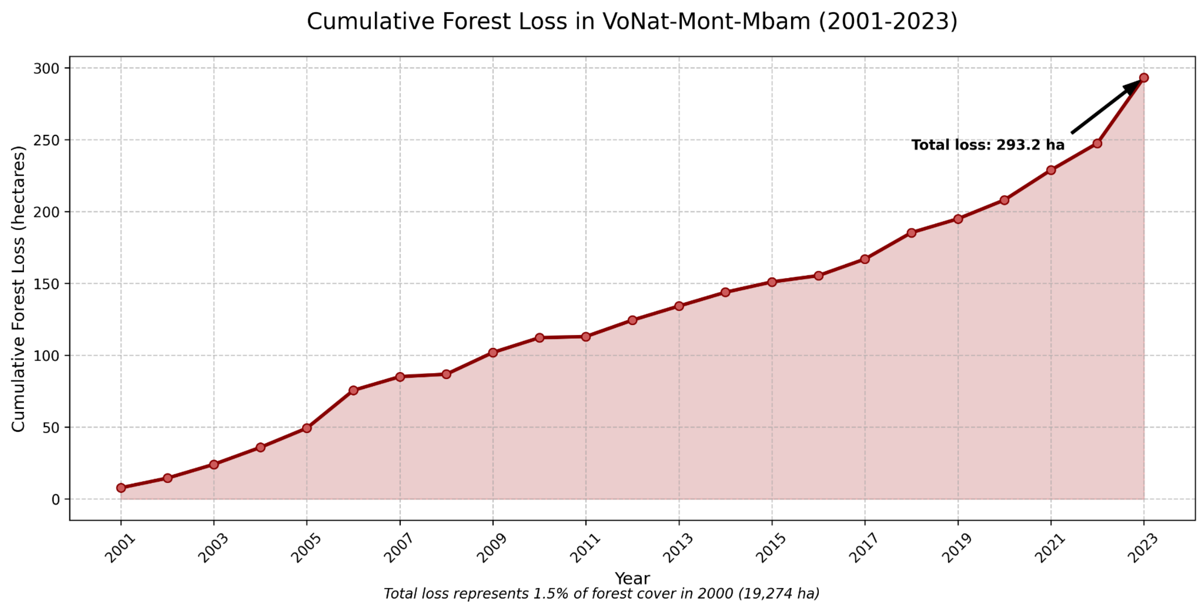

Figure 17: Cumulative Forest Loss (2001-2023). *Cumulative forest loss over time, demonstrating the total impact of forest degradation since 2001.*

Note on Data Interpretation: The forest cover and loss data presented in these figures are derived from the Hansen Global Forest Change dataset, which uses specific definitions and methodologies for forest classification. These results should be interpreted in the context of the dataset's parameters. They may differ from other forest assessments using different methods, such as the ESA WorldCover data for the 2021 land cover classification.

4. Discussion

4.1 Key Findings

- **Landscape Stability**: The Mont Mbam region has maintained remarkable stability in land cover composition between 1987 and 2024, with 96.9% of the total area retaining the same land cover type over the 37 years. This stability is particularly evident in the major land cover classes, including tree cover (98.59% unchanged), grasslands, and shrublands.

- **Recent Land Cover Dynamics**: While the overall landscape remained stable, the 2010-2024 period showed the most significant transitions, including tree cover expansion (+154.17 ha), grassland reduction (-227.34 ha), and water body expansion (+69.12 ha). These changes were minimal in absolute terms but represent a shift from the near-complete stability observed in the 1987-2000.

- **Declining Fire Activity**: A dramatic decrease in fire occurrence has been documented, from an average of ~9,503 hectares burned annually in 2000-2009 to only ~1,091 hectares annually in 2017-2024. This declining fire disturbance trend coincides with the modest tree cover expansion period.

- **Fire-Land Cover Relationships**: Clear spatial correlations exist between fire occurrence and land cover dynamics. 48% of grassland areas experienced at least one fire event during the study period, compared to much lower percentages in forested areas. Additionally, 62% of all transitions from tree cover to grassland occurred in the regions that experienced at least two fire events.

- **Forest Loss Patterns**: Despite overall tree cover stability or a slight increase in the CCDC analysis, the Hansen dataset identified 296 hectares of forest loss (1.5% of 2000 forest cover) between 2001 and 2023, with notable peaks in 2006 (26.3 ha), 2021 (20.8 ha), and 2023 (45.7 ha). This suggests that while the landscape has experienced some forest degradation, forest regeneration in other areas has offset it.

- **Data Limitations**: Different methodologies between datasets (CCDC, Hansen Global Forest Change, and ESA WorldCover) result in varying estimates of land cover areas. For example, tree cover estimates range from 19,274 ha (Hansen, 2000) to 26,006 ha (ESA WorldCover, 2021). These differences reflect methodological variations rather than actual changes and highlight the importance of consistent methodologies when assessing land cover change.

4.2 Conservation Implications

- **Ecosystem Resilience**: The high persistence of land cover types over 37 years indicates a relatively resilient landscape. Despite some fire disturbance, this stability suggests that the Mont Mbam ecosystems possess inherent resistance to change, which is valuable for long-term conservation planning.

- **Fire Management**: The documented decline in fire occurrence over the past decade coincides with modest increases in tree cover. This relationship suggests that fire management may be an effective tool for forest conservation in the region. Areas that experienced high fire frequency in the early period (2000-2009) but remained relatively fire-free in the recent period (2017-2024) show evidence of woody vegetation recovery.

- **Grassland Conservation**: The observed reduction in grassland area (-260.64 ha) and the conversion of 171.64 ha of former grassland to tree cover indicate a need for balanced conservation approaches that recognize the ecological value of both forest and grassland ecosystems. The data suggests that some grassland areas naturally transition to woody vegetation without fire disturbance.

- **Water Resource Management**: The documented expansion of water bodies (+54.81 ha, +2.21%) represents a change in the landscape's hydrological characteristics. This modest change may affect the region's aquatic habitats and water resource availability.

- **Limited Development Pressure**: The minimal change in built-up areas (-2.07 ha, -0.10%) indicates limited urban expansion or infrastructure development, suggesting that direct human settlement pressure is not currently a major driver of landscape change in the Mont Mbam region.

4.3 Recommendations

- **Balanced Ecosystem Management**: Given the observed dynamics between forest and grassland ecosystems, conservation strategies should aim to balance these habitat types rather than focusing exclusively on forest protection. The data indicate natural transitions between these ecosystems, suggesting both have ecological roles in the landscape.

- **Fire Management Planning**: The clear relationship between fire occurrence and land cover dynamics suggests that strategic fire management could be an effective conservation tool. Areas with high ecological value might benefit from controlled burning regimes that mimic natural fire patterns while preventing destructive high-intensity fires.

- **Monitoring Recent Forest Loss**: The acceleration of forest loss in recent years (particularly the 45.7 ha lost in 2023, as shown in the Hansen dataset) warrants close monitoring to determine if this represents a new trend or an anomaly. Monitoring areas that experienced recent forest loss could help identify emerging threats.

- **Hydrological Monitoring**: The documented expansion of water bodies merits continued monitoring to understand these changes' drivers and ecological implications. This could include tracking seasonal variations in water extent and quality.

- **Consistent Methodology**: Future land cover assessments should maintain methodological consistency with this baseline study to ensure accurate change detection. The methodological differences should be acknowledged and accounted for when using multiple datasets.

5. Conclusions

5.1 Summary of Findings

Key Results: The Mont Mbam region has maintained remarkable landscape stability between 1987 and 2024, with 96.9% of the area retaining the same land cover type. The most significant changes occurred in the 2010-2024 period, including modest tree cover expansion (+196 ha), grassland reduction (-261 ha), and water body expansion (+55 ha). These changes coincided with a dramatic decline in fire occurrence, from an average of ~9,503 hectares burned annually in 2000-2009 to only ~1,091 hectares annually in 2017-2024. Despite the overall stability, the Hansen dataset identified 296 hectares of forest loss between 2001 and 2023, with the highest loss recorded in 2023 (46 ha).

Project Achievements: This study has successfully established a comprehensive baseline of land cover dynamics in the Mont Mbam region using multiple datasets and analytical approaches. The integration of CCDC analysis, Hansen Global Forest Change data, and ESA WorldCover has provided complementary perspectives on landscape change. The fire disturbance analysis has revealed critical temporal trends and spatial patterns that help explain some of the observed land cover dynamics. The field survey with 268 GPS points has documented current ecological features and land use patterns, providing ground-based context for the remote sensing analyses.

Knowledge Gaps: Several Mont Mbam landscape dynamics remain incompletely understood. These include: (1) the specific drivers behind the dramatic decline in fire occurrence over the past decade; (2) the ecological implications of the modest but consistent expansion of water bodies; (3) the causes of the apparent acceleration in forest loss in 2023; and (4) the relationship between land cover changes and specific human activities or management interventions in the region.

5.2 Future Directions

- Additional research needs, including:
    - Biodiversity assessment (species distribution, habitat suitability, conservation priority areas)
    - Environmental threats analysis (human activities, climate change impacts, conservation challenges)
    - **Spatial Pattern Analysis**: Detailed comparison of fire concentration patterns in central and southern portions of the study area with land cover change patterns to identify spatial correlations and potential causal relationships. This analysis should include overlay mapping of fire frequency with land cover transitions to identify hotspots of ecological change.
    - **Transition Analysis**: Further investigation of the relationship between land cover transitions (particularly the high persistence of tree cover, where 20,279

ha remained tree cover, and notable transitions such as 171.64 ha from grassland to tree cover) and fire disturbance patterns. This analysis should examine whether areas with reduced fire frequency show predictable vegetation succession patterns.

- **Ground Control Points Collection**: Systematic collection of ground control points for land cover types using a stratified random sampling approach. This would significantly improve the accuracy of land cover classifications and provide quantitative classification accuracy measures. A well-designed sampling schema would ensure representation of all land cover classes and ecological transition zones, enhancing the reliability of future change detection analyses.

6. References

6.1 Remote Sensing Data Sources

ESA WorldCover 2021

- **Source:** European Space Agency (ESA)
- **Dataset:** WorldCover 2021
- **Resolution:** 10m
- **Coverage:** Global
- **Access:** https://worldcover2021.esa.int/
- **Citation:** Zanaga, D., Van De Kerchove, R., De Keersmaecker, W., Souverijns, N., Brockmann, C., Quast, R., Wevers, J., Grosu, A., Paccini, A., Vergnaud, S., Cartus, O., Santoro, M., Fritz, S., Georgieva, I., Lesiv, M., Carter, S., Herold, M., Li, L., Tsendbazar, N., Ramoino, F., Arino, O. (2022). ESA WorldCover 10 m 2021 v200. Zenodo. https://doi.org/10.5281/zenodo.7254221

Landsat

- **Source:** U.S. Geological Survey (USGS), NASA
- **Dataset:** Landsat Collection 2
- **Resolution:** 30m (multispectral), 15m (panchromatic)
- **Coverage:** Global
- **Temporal Coverage:** 1972-present (Landsat 1-9)
- **Access:** https://www.usgs.gov/landsat-missions or https://earthexplorer.usgs.gov/
- **Citation:** U.S. Geological Survey. (2023). Landsat Collection 2 Level-2 Science Products. https://doi.org/10.5066/P9OGBGM6

Hansen Global Forest Change

- **Source:** University of Maryland, Google, USGS, NASA
- **Dataset:** Global Forest Change v1.9 (2000-2023)
- **Resolution:** 30m
- **Coverage:** Global
- **Access:** https://earthenginepartners.appspot.com/science-2013-global-forest

- **Citation:** Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, and J. R. G. Townshend. 2013. "High-Resolution Global Maps of 21st-Century Forest Cover Change." Science 342 (15 November): 850-53. https://doi.org/10.1126/science.1244693

6.2 Field Data

GPS Survey Points

- **Collection Method:** Field survey using GPS devices
- **Number of Points:** 268
- **Date:** 2024
- **Attributes:** Ecological features, land use patterns, water sources, settlements
- **Format:** CSV and GeoPackage

6.3 Software and Tools

QGIS

- **Version:** 3.34.0
- **Purpose:** GIS data processing, analysis, and map creation
- **Website:** https://qgis.org/

Python Libraries

- **pandas:** Data manipulation and analysis
- **matplotlib:** Data visualization
- **seaborn:** Statistical visualization
- **numpy:** Numerical computing

6.4 Project Documentation

Comprehensive project documentation is available in the external resources referenced in the Appendices section. Key documentation components include:

Project Proposal

- Initial project scope and objectives
- Research questions and hypotheses
- Proposed methodology and timeline

Field Survey Protocols

- GPS data collection procedures
- Field observation guidelines
- Sample point selection criteria
- Quality control measures

Data Processing Workflows

- Satellite imagery preprocessing steps
- CCDC algorithm implementation
- Fire frequency analysis methodology
- Land cover classification procedures

Analysis Methods Documentation

- Statistical analysis techniques
- Accuracy assessment protocols
- Change detection algorithms
- Visualization methods

Note: Detailed documentation for all components is available in the GitHub repository and Google Drive folder referenced in the Appendices section.

7. Appendices

All supporting materials, technical documentation, and additional resources for this report are available in the following locations:

- **GitHub Repository**: VoNat-Mont-Mbam - Contains code, data processing workflows, and analysis methods.
- **Google Drive**: Mont Mbam Project Resources - Contains additional maps, figures, statistical analyses, and project documentation not available in the GitHub repository.