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Land Cover and Land Use Dynamics in Cameroon's Forest-Savanna Transition Zone: Implications for the Conservation and Sustainable Management of the Minta Communal Forest

Dinâmica da Cobertura e Uso do Solo na Zona de Transição entre Floresta e Savana de Camarões: Implicações para a Conservação e Gestão Sustentável da Floresta Comunal de Minta

Ingrid Tsopmejio Temfack[1], Amandine Flore Ntonmen Yonkeu[1], Cédric Chimi Djomo[1,2], Hubert Kpoumie Mounmemi[3,4], Louis Zapfack[1], Darling Djoumene Wado[1], Guylène Ngoukwa[5] & Aurélien Richy Nkouankam Tchayep[1]

[1] University of Yaounde I, Department of Plant Biology, Laboratory of Botanic, Ecology and carbon stocks accessment, Yaounde, Cameroon
[2] Institute of Agricultural Research for the Development, Yokadouma, Cameroon
[3] University of Yaounde I, Institute of Wood Technology, Yaounde, Cameroon
[4] National Herbarium of Cameron, Yaounde, Cameroon
[5] Catholic University of Louvain, Faculty of Bioengeneering Sciences, Ottignies-Louvain-la-Neuve, Belgium

E-mails: ingridtemfack@yahoo.fr; yonaflore@yahoo.fr; chimicedric10@yahoo.fr; hubertmounmemikpoumie@yahoo.fr; lzapfack@yahoo.fr; darlingwado@gmail.com; guylnengoukwa@yahoo.fr; nkouankamtchayep@yahoo.com

Abstract

Sustainable management of communal forests remains a challenge for Cameroonian municipalities due to the inadequacy of available data reflecting the current reality of these forests. For this reason, several communal forests, particularly those in the forest-savanna transition zone, do not always benefit from adequate management measures. This study therefore set out to assess the spatial and temporal dynamics of land cover and land use in the Minta communal forest in order to provide useful information for decision-making on the sustainable management of its communal forest. The supervised classification was performed using Landsat Enhanced Thematic Mapper (ETM), Thematic Mapper (TM), and Operational Land Imager (OLI) satellite images based on a diachronic approach for land cover mapping for 2000, 2010, and 2021. The results show that seven types of land cover and land use were identified, namely: mature forests, secondary forests, swamp forests, fallow land, savannas, farms, and bare Land. Image classification was satisfactory, with overall accuracy and Kappa indices exceeding 70% and 80%, respectively, during the periods 2000–2010, 2010–2021, and 2000–2021 for the study area. Transition matrices showed a decline of approximately 20% of mature forests in favor of secondary forests, fallow land, farms and bare Land. Consequently from 2000 to 2021, mature forests had a deforestation rate of 0.67% and a degradation rate of 5.48%. These results are the combined effect of drivers such as logging, mining, agriculture, livestock farming, and climate change. In response to these threats, three sustainable management options are recommended to the municipality of Minta: (1) complete conservation of less degraded areas; (2) reforestation/restoration of highly degraded areas; (3) production of a land zoning plan for their forest cover, assigning each area an economic, social, or ecological function in order to meet expectations related to ecosystem sustainability.

Keywords: Sustainable management; Municipalities; Degraded areas

Resumo

A gestão sustentável das florestas comunais continua a ser um desafio para os municípios camaronenses devido à insuficiência de dados disponíveis que reflitam a realidade atual dessas florestas. Por esse motivo, várias florestas comunais, particularmente aquelas na zona de transição entre floresta e savana, nem sempre se beneficiam de medidas de gestão adequadas. Este estudo teve, portanto, como objetivo avaliar a dinâmica espacial e temporal da cobertura e uso do solo nas florestas comunais de Minta, a fim de fornecer informações úteis para a tomada de decisões sobre a gestão sustentável das suas florestas comunais. Foi realizada uma análise diacrônica

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utilizando classificação supervisionada em imagens Landstat 2000, 2010 e 2021 da área de estudo. Os resultados mostram que foram identificados sete tipos de cobertura e uso do solo, a saber: florestas primárias, florestas secundárias; florestas inundáveis, áreas em pousio, savannas, áreas agrícolas e solo exposto. A classificação das imagens foi satisfatória, com precisão geral e índices Kappa superiores a 70% e 80%, respetivamente, durante os períodos 2000-2010, 2010-2021 e 2000-2021 para a área de estudo. As matrizes de transição mostraram um declínio de aproximadamente 20% das florestas maduras em favor de florestas secundárias, terras em pousio, fazendas e terras nuas. Consequentemente, as florestas maduras tiveram uma taxa de desflorestação de 0,67% e uma taxa de degradação de 5,48%. Esses resultados são o efeito combinado de fatores como exploração madeireira, mineração, agricultura, pecuária e mudanças climáticas. Em resposta a essas ameaças, três opções de manejo sustentável são recomendadas ao município de Minta: (1) conservação completa das áreas menos degradadas; (2) reflorestamento/restauração das áreas altamente degradadas; (3) elaboração de um plano de zoneamento territorial para sua cobertura florestal, atribuindo a cada área uma função econômica, social ou ecológica, a fim de atender às expectativas relacionadas à sustentabilidade do ecossistema.

Palavras-chave: Gestão sustentável; Municípios; Áreas degradadas

1 Introduction

Land cover refers to the physical characteristics that involve the distribution of vegetation, water, soil, and other natural features, including those affected by human activities (Darem et al. 2023; Zekeng et al. 2019). For Surya et al. (2020), land use refers to how humans value land, focusing on its role in economic activities and infrastructure development. This is the reason why these concepts are very similar, even interdependent, and are often used simultaneously (Bui & Mucsi 2021). Thus, for effective ecosystem management, it is important to have up-to-date information on land cover and land use (LCLU) dynamics in the environments concerned (Zanguim et al. 2022). For several decades, remote sensing has provided fairly satisfactory results at consistent, multi-temporal, and extensive spatial scales, facilitating a better understanding of land use and land cover dynamics, particularly in areas where ground observations are limited (Almeida et al. 2025; Zhang et al. 2023). Satellite imagery and geospatial analysis can therefore be used to detect deforestation, forest degradation, and plant regeneration, as well as other spatial changes, with satisfactory temporal resolution and high spatial accuracy (Wu et al. 2025). Their findings contribute to the orientation of sustainable forest management approaches in developing countries (Wahelo, Mengistu & Merawi, 2024). Access to comprehensive and relevant information on land occupation and use is essential for effective decision-making, planning, and implementation of land use programs to meet the growing demand for basic human needs and well-being in the territories. This information is also essential for monitoring dynamic changes in land use, which are driven by changing needs due to demographic growth.

Due to their exceptional biodiversity, Africa's tropical rainforests offer invaluable potential for the socioeconomic development of their owners (Chimi et al. 2022). These forest ecosystems are of crucial importance to local populations, as they provide them with numerous goods (food, wood, fibers, medicines) and ecosystem services (Mapong-metsem et al. 2016; Ngoukwa et al. 2023). Despite their many advantages, these forests are facing increased anthropization, causing alarming degradation that continues to worsen, with a direct impact on the deterioration of their ecological, economic, and sociocultural functions (Babu et al. 2024). This anthropization is the result of the significant population growth that the world has experienced in recent decades, reinforced by rapid urbanization, which increases demand for natural resources and compromises the sustainability of ecosystems (Kookana et al. 2020). Considering the complex interaction between human actions and natural processes, changes in land occupation and use induced by human activity have significant consequences on nature's ability to maintain its vital abiotic and biotic resources (Zekeng et al. 2019; Vázquez 2023). For example, from 1990 to 2005, the forests of the Congo Basin experienced an increase in their deforestation rate from 0.09% to 0.17%, and in Cameroon, from 1990 to 2010, the deforestation rate is estimated at 18.1% (FAO 2014; Bozongo 2018).

Cameroon's Forest-Savanna Transition Forests (FSTF) are also vulnerable to these threats. Due to their geographical location in the northern part of the southern Cameroonian plateau, specifically north of the Center and East regions of the country and south of the Adamaoua region, these forests are at the confluence of the country's forests and savannas (Mertens, Ahononga & Yente. 2012). More specifically, the FSTF are an interface where large forest strips are interspersed with savanna islets. They are characterized by a diverse flora, mixing plant species typical of forests and savannas (Letouzey 1985; Ngo et al. 2022). These forests are highly coveted because of their unique landscape and are well suited to cattle farming, which is widespread in the area, along with its corollaries such as bush fires and overgrazing (Ngo et al. 2022; Tchoupou et al. 2021). The FSTF are therefore a complex ecosystem in which several forest and savanna species have found refuge, granting this area a significant ecological advantage for the entire nation (MINFOF 2018).

Despite these various advantages, the original forest cover of this area is threatened by the many human activities occurring there. It is in response to such threats that Sustainable Forest Management (SFM) has gradually established itself as the ideal approach to forest management, as it is recognized as the best strategy for responding quickly to current environmental emergencies (Leroy et al. 2014). SFM represents an ecologically sound forest management model, establishing indicators, criteria, and objectives that integrate economic, social, and environmental dimensions. Adopting this strategy demonstrates a country's commitment to balancing the use of forest resources with the preservation of their vital ecological functions.

In adopting SFM, Cameroon has completely restructured its constitutional and regulatory framework in order to plan and facilitate forest management and the effective implementation of sustainable practices (MINFOF 2013). One of the major manifestations of this adoption has been the transfer of forest management to local communities and municipalities through decentralization. This gave rise to concepts such as communal forests (CFs), which appear to be a local-level strategy for achieving these long-term objectives and the well-being of local communities (Loi forestière 2024; Poissonnet & Lescuyer 2005). CFs as a key role in land use and natural resource management; they are essential to the socioeconomic well-being of local communities (Ngoukwa et al. 2023) and provide important ecosystem services that are vital to the well-being of local populations (Mounmemi et al. 2022; Ngoukwa et al. 2023; Zekeng et al. 2021, 2023).

Nevertheless, CF management currently faces several obstacles, including a lack of expertise among community staff in analyzing forest data; managers' lack of knowledge about the quantity of available forest resources, which hinders effective planning; changes in land cover use that require constant adaptation of management strategies; and the population's lack of adherence to the vision embodied in the CF concept. These challenges are particularly worrying given that the management of several Cameroonian CFs lacks many aspects of sustainability, such as Doumé (Zekeng et al. 2019), Dimako (Mounmemi et al. 2020), and Belabo-Diang (Ngoukwa et al. 2025). In addition, various CFs do not have the equipment necessary for effective management planning and are therefore unable to accurately assess resource use. The Minta communal forest (MCF) is not exempt from this, which means that urgent action must be taken to ensure the sustainable management of its forest resources.

The MCF, which covers various ecosystems, plays a key role in Cameroon's commitment to sustainable forest management and community involvement. This forest serves as a reservoir of biodiversity and a source of income for local communities, but its true potential remains largely untapped. Despite efforts to promote sustainable forest management, the MCF faces significant challenges due to changes in LCLU by local communities and infrastructure development driven by the government; this poses a major threat to the biodiversity and essential ecological functions of this ecosystem. In fact, according to Yemefack and Alemagi (2016), 85% of key stakeholders in forest management reported that they were neither consulted nor informed prior to the creation of the CF. Before it classification, the MCF underwent selective logging between 1988 and 2000. But, after the sale of logging concession No. 08-01-186, the Fabrique Camerounaise de Parquets (FIPCAM) became the sole holder of a legal logging concession in the MCF (SIFCAM 2011). Over time, significant changes in LCLU, influenced by agricultural expansion, logging, and socio-economic development, have had an impact on vegetation cover and overall ecological integrity, necessitating a comprehensive review of their spatial and temporal dynamics in the MCF (Dicko et al. 2016).

Despite numerous studies on CFs, few have addressed aspects such as land use trajectories, LCLU, deforestation rates, degradation rates, and the impact of management and conservation on forest cover (Mounmemi et al. 2020; Ngoukwa et al. 2025; Zekeng et al. 2019). No study on LCLU has yet been conducted in the MCF. This research is in line with SDG 15, which aims to fight deforestation, desertification, and soil degradation. It is also in line with the 2063 African Union's Agenda and 2020-2030 Cameroon's National Development Strategy, which emphasize the rational use of wood and transparent management of communal and community forests. In addition, MCF contributes significantly to essential ecosystem services, including water cycle regulation, climate regulation, and carbon sequestration. Analysis of spatial and temporal dynamics makes it possible to assess the impact of LCLU changes on these essential services, providing useful data for the development of strategies that prioritize sustainable resource management (Zekeng et al. 2019). This study provides important information that will help Cameroon better implement the principles of SFM to which it is committed. It supports evidence-based policy decisions by striking a balance between conservation, community needs, and sustainable development. This study will also improve scientific understanding of the dynamics of communal forests, sustainable land use practices, and ecosystem resilience across the nation, highlighting the crucial role of research in global communal forest management for environmental sustainability and community well-being. The purpose of this study is to understand the spatial and temporal dynamics of LCLU in the MCF, while providing crucial information for land use planning and sustainable forest resource management.

2 Methodology and Data

2.1 Study Area

This study was performed in the Central Region of Cameroon, specifically in the municipality of Minta, located at 4°33'34" North latitude and 12°49'52" East longitude, in the Department of Haute Sanaga (Figure 1) (Yemefack & Alemagi 2016). The topography of the MCF is made up of more or less rugged plateaus ranging from 640 m to 680 m in altitude. The hydrographic layout is marked by rivers such as the Tia, Ngbwadjé, Dja, Longé, and Nyamendouga. The soils are ferralitic with a red texture and poor in nutrients with little humus. The vegetation is that of dense semi-deciduous forests with Ulmaceae and Malvaeae. The MCF is located in the transition zone between forests and savannas. It is composed of vast swathes of forest and savanna, as well as numerous fairly rich forest galleries along rivers (SIFCAM 2011). The climate is equatorial Guinean with four seasons: two dry seasons and two rainy seasons, with rainfall sometimes reaching 1,440 mm/year. Temperatures vary between 21 and 30°C throughout the year. The MCF was classified in 2010 by Decree No. 2010/2579/PM of September 17, 2010. It covers an area of 41,087 ha (PNDP 2015).

The economic life of the study area is dominated by activities such as subsistence and cash crop farming, with a strong emphasis on cocoa production, artisanal fishing, hunting with widespread poaching, domestic livestock farming of small ruminants and poultry, trade, and sometimes the collection of non-timber forest products. In addition, the presence of savannas encourages cattle farming by the Mbororo people (Yemefack & Alemagi 2016). Although the population is mainly made up of indigenous Bamvélé people, there are also non-indigenous people, ranging from nationals to foreigners.

2.2 Data Collection

To assess changes in LCLU in the MCF, a diachronic approach was used. This method involved using pre-existing data such as satellite images taken on different dates to trace the evolution of vegetation types. Multispectral satellite images from Landsat 7 and 8 sensors of the study area were downloaded from the US Geological Survey (USGS) Earth Explorer website and processed using ERDAS Imagine 2014 software. These images were chosen because of their availability and better spatial coverage of the area. Table 1 shows the characteristics of each of these images. Cartographic data were added to these satellite images to map LCLU in the MCF.

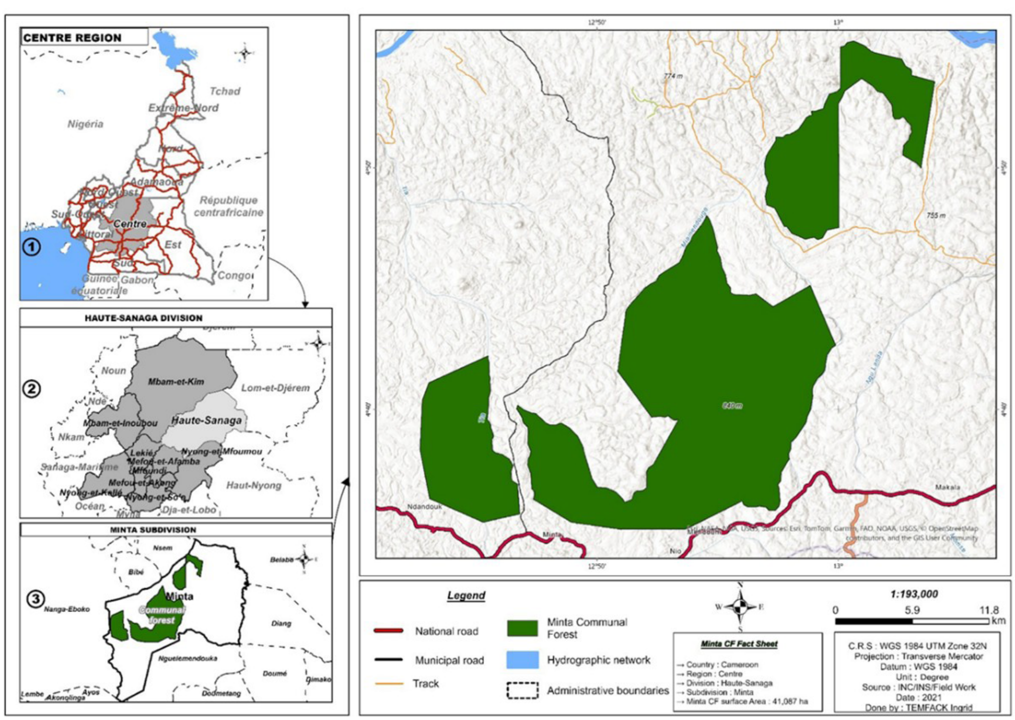

Figure 1 Map of the study area.

Table 1 Characteristics of the Landsat images used.

Satellites	Sensors	Scenes (Path-row)	Acquisition date	Number of bands	Resolution
Landsat 7	SENSOR_ID= "ETM"	185-057	2000-01-14	09	30 m
		184-057	2000-01-14	09	30 m
	SENSOR_ID= "ETM"	185-057	2010-02-16	09	30 m
		184-057	2010-0131	09	30 m
Landsat 8	SENSOR_ID= "OLI_TIRS"	185-057	2021-01-26	11	30 m
		184-057	2021-02-06	11	30 m

The choice of periodic assessment sequences in this study corresponds to the pre-classification (2000), classification (2010), and post-classification (2021) stages of this CF. In fact, from 1994 to 2000, forest management was marked by the granting of provisional agreements for logging in this municipality (PNDP 2015). Between 2000 and 2010 it was the classification period and the municipality implemented management measures that could help validate its management plan (Yemefack & Alemagi 2016). And from 2010 to 2021, it was the sustainable management period. These three dates therefore correspond to the indicated periods for assessing the effects of management methods on the spatiotemporal dynamic of the MCF.

Supervised classification using the Maximum Likelihood algorithm was chosen for image classification in this study. This method calculates the probability of a pixel belonging to a given class rather than another. The pixels were assigned to the class for which the probability was highest. This step consists of defining the training samples for the different land use units in order to assign them a name. The training samples were selected on the basis of several criteria, namely: they must belong to the classes identified on the maps and in the field (ground truth); they must be sufficiently representative of the study area; and they should be among the most relevant classes selected for this study. This is why seven training samples were selected for this study. A priori, it was agreed that a sample would be selected if it contained sufficient information for classification. Its validation was therefore carried out following expert opinion in the field. In fact, Tyukavina et al. (2025) state that, when sampling from a list using simple random or systematic sampling, each unit has equal probability of being selected for a study. Indeed, the processing of Landsat Enhanced Thematic Mapper (ETM), Thematic Mapper (TM), and Operational Land Imager (OLI) satellite images based on the multi-date diachronic approach allows for the mapping of land cover at various time scales. In this study, the implementation of this methodology made it possible to distinguish seven land use types: mature forests, secondary forests, swamp forests, fallow land, farms, savannas and bare land.

2.3 Satellite Image Processing

- **Preprocessing**

At this stage, several operations were carried out, such as radiometric corrections and geographical recalibration, performed after linear spreading of the histograms of each spectral band in order to improve contrast for better extraction of the study area. The objective of these operations was to homogenize image quality, as recommended by various authors (Lounis et al. 2010; Mounmemi et al. 2020). ERDAS Imagine 2014 software was used to perform these operations.

- **Processing**

- **Field mission:** it enabled the collection of biophysical data (identification of different land cover types), operational data (identification of different land use types), geospatial data (GPS control points), and ground truth data (informations to validate satellite image classification). The GPS data collected in the field, combined with data from Google Earth Explorer, served as a reference for 2021 in order to clearly identify the LCLU needed for supervised classification. The ultimate goal was to produce LCLU map that reflect the reality on the ground.
- **Unsupervised classification:** this involved classifying digital image data using computer processing. This processing is based solely on image statistics without the use of training samples. In order to extract the study sites, a color composition was created following various combinations. Training sites were then selected based on their spatial distribution and knowledge of the study site.
- **Supervised classification:** the maximum likelihood algorithm was applied to each Landsat composite image. This algorithm consisted of calculating the probability of a pixel belonging to a given class rather than another (Mezafack et al. 2022). This

method provides each pixel with a certainty index linked to this choice in addition to the class to which it has been assigned. This step is mathematically very satisfactory because the pixels are classified according to a probabilistic method that estimates that all classes have an identical a priori probability (Ghilardi et al. 2016). Vectorization enabled the precise delimitation, structuring, and temporal monitoring of homogeneous LCLU areas according to the nomenclature defined in this study, namely the different types of forests identified, fallow land, farms, and bare land.

- **Detection of changes between 2000-2010; 2010-2021; 2000-2021:** this process made it possible to detect changes in LCLU. According to Girard & Girard (1999), it is not always easy to assign a pixel to a given class, nor to associate a specific class with a survey in the field, hence the need to evaluate the overall effectiveness of the classification. The definition of classification quality was based on two approaches:

    - ♦ **Confusion matrix:** here, the accuracy of a classification corresponds to the percentages of correctly classified pixels, represented by the values on the diagonal. These matrices can be used to assess the relevance of the classification algorithm (Omari 2005; Tsewoue et al. 2020).

    - ♦ **Kappa coefficient:** this refers to a value slightly lower than the overall accuracy. Santos (2001) shows that the latter expresses the error rates to be avoided and which would be obtained during sampling that must be completely random. The Kappa index is calculated using the following formula (Equation 1):

$$Kappa = \frac{P0-Pc}{Pp-Pc} \times 100 \quad (1)$$

Where P0 is the observed correct proportion; Pc is the correct proportion minus chance; and Pp is the correct proportion when the classification is perfect.

- **Validation and mapping:** based on the overall accuracy and Kappa index obtained, the data was validated. Google Earth software was used to verify and convert the images into shape files. The shape file was overlaid on a high-resolution image to correct any confusion between the different land cover types. The land cover maps created with ArcGIS 10.5 provided the basic data for the land cover analysis. The methodological diagram outlines the different stages involved in processing the satellite images (Figure 2).

2.4 Analysis of Land Cover Data

The change detection matrix resulting from the comparison of LCLU surfaces between two dates was produced. Using this matrix, the gains, stable areas, and losses observed during this period were quantified. However, several annual rates facilitating land use analysis were calculated:

- **Annual spatial expansion rate (Tc):** changes were determined over three (3) periods: 2000-2010, 2010-2021, and 2000-2021. The formula of Bernier (1995) was used (Equation 2):

$$\mathrm{Tc} = \frac{\mathrm{LnS2-LnS1}}{\mathrm{(Date2-Date1)*Lne}} \times 100 \quad (2)$$

Where Ln = natural logarithm, e = base of natural logarithms (e = 2.71828), S1 = area of a class at date t1 and S2 = area of the same class at date t2.

- **Overall rate of change (Tg):** this is used to estimate changes in LCLU between date 1 (t1) and date 2 (t2). The overall rate of change makes it possible to detect changes for each LCLU for different periods (Njeugeut et al. 2021). It is determined by the following formula (Equation 3):

$$\mathrm{Tg} = \frac{\mathrm{S2-S1}}{\mathrm{S1}} \times 100 \quad (3)$$

Where S1 = area of a class at date T1 and S2 = area of a class at date T2.

- **Conversion rate (Tc):** this refers to the degree of transformation undergone by a LCLU when it is converted into another. It is obtained using a transition matrix (Issiako & Arouna 2018). The mathematical formula is as follows (Equation 4):

$$Tc = \frac{S_{it}-S_{is}}{S_{it}} x100 \quad (4)$$

Where: S_{it} = LCLU area at initial date t; S_{is}: area of the same LCLU remaining stable at date t_1.

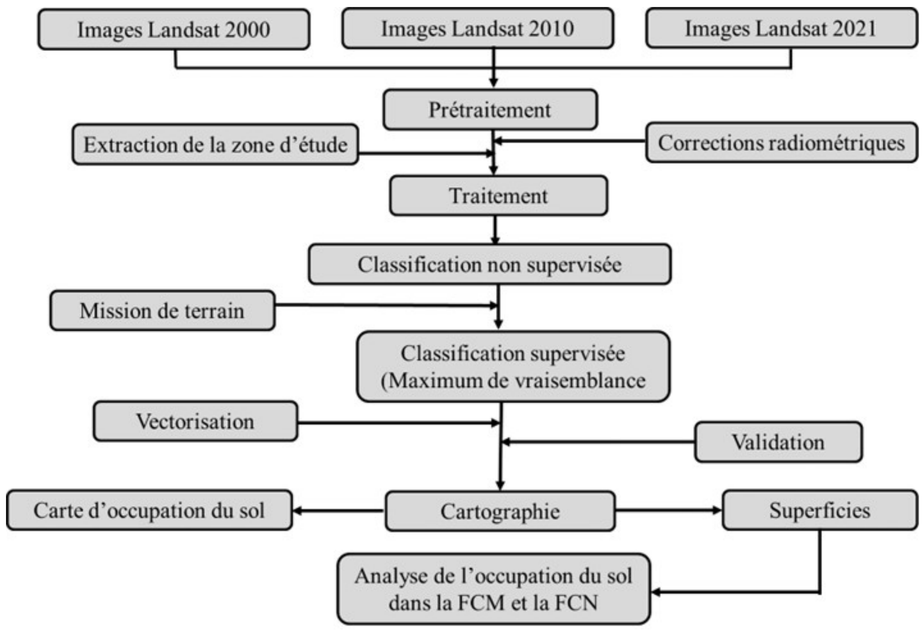

Figure 2 Summary of the methodology used for processing satellite images

- **Change rate of LCLU (Δs):** it refers to the variation speed the LCLU identified in the study area. The formula is (Ghilardi *et al*. 2016) (Equation 5):

$$\Delta_s = \frac{S_{p2} - S_{p1}}{t_2 - t_1} \tag{5}$$

Where: Δs = change rate of LCLU (progression or regression in ha/year): S_{P1}: area occupied by a specific LCLU during year 1 (ha): S_{P2}: area occupied by a specific LCLU during year 2 (ha); t_1: year 1: t_2: year 2.

- **Annual deforestation rate (R):** this represents the fraction of forest converted to land use types other than forest. It was calculated using the formula proposed by Zakari et al. (2018) and adjusted for the purposes of this analysis. The formula is Equation 6:

$$R = \frac{1}{t_2 - t_1} \ln\left(\frac{A_2}{A_1}\right) \text{ x } 100 \tag{6}$$

Where: R = deforestation rate: A_1 and A_2 represent the sum of the share of land use units for two years: ln: natural logarithm: t_1: year 1: t_2: year 2.

- **Annual degradation rate (TAD):** this represents the fraction of forest disturbed at a given time. It is calculated using the formula of Kamungandu (2009) (Equation 7).

$$TAD = \frac{\frac{S_2}{S_1}}{t} \text{ x } 100 \tag{7}$$

Where: S_1 = initial forest area; S_2 = forest area lost; t: number of years between two dates.

3 Results

3.1 Land Cover Status between 2000, 2010, and 2021

Analysis of land cover dynamics revealed seven (07) LCLU present in the MCF, namely: mature forests (MF), secondary forests or young secondary forests (SF), swamp forests (SwF), fallow land (Fal), savannas (Sa), farms (Far), and bare land (BL).

Observation of the various periods has shown that the distribution of LCLU has varied greatly over the years. FM remain the most common LCLU, accounting for 53.83% in 2000, 59.78% in 2010, and 46.72% in 2021. There has been a decline in SF, which fell from 5,945.26 ha in 2000 to 5,039.28 ha in 2010, to the benefit of MF; then an increase in SF from 5,039.28 ha in 2010 to 9,338.35 ha in 2021, to the detriment of MF. However, from 2000 to 2010, and then from 2010 to 2021, Fal, Far, and BL increased in area at the detriment of Sa. This means that the decline had a greater influence on land use dynamics in the FCM (Figure 3).

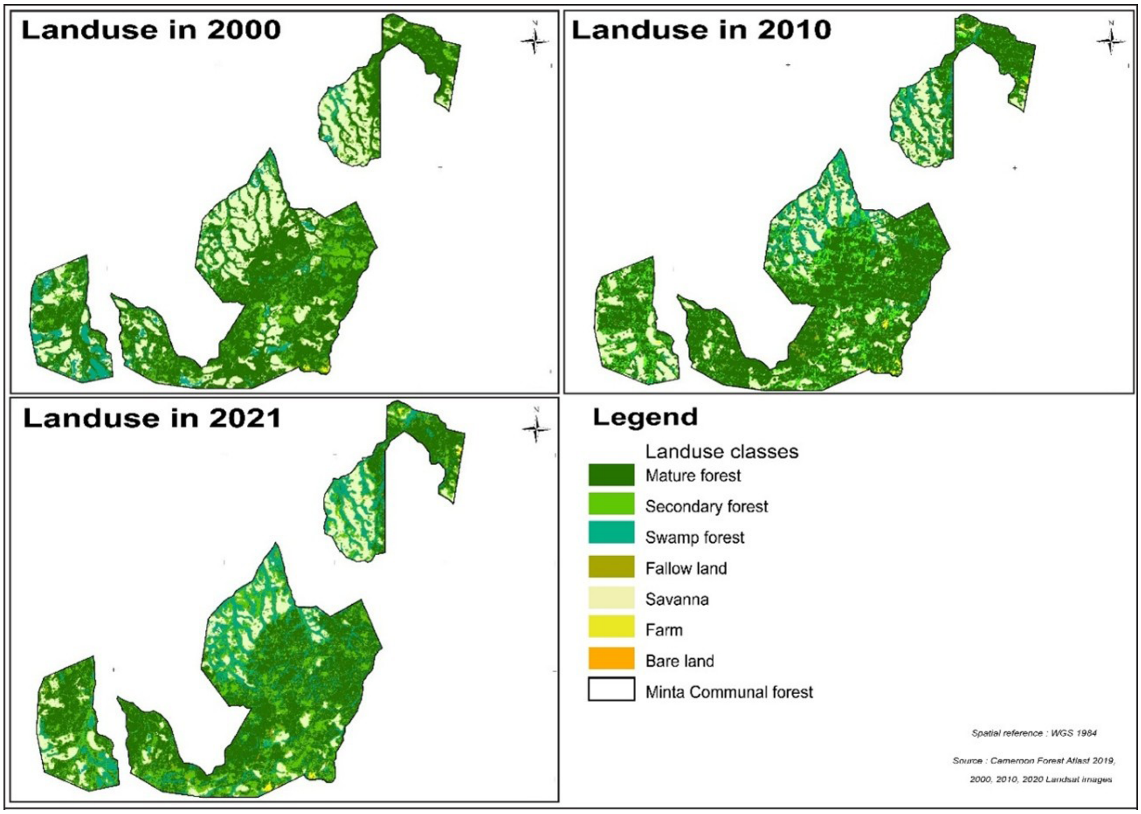

Figure 3 Dynamics of LCLU between 2000 and 2021 in the FCM.

3.2 Evaluation of Satellite Image Classification

In the MCF, the classification model between 2000, 2010, and 2021 has a Kappa coefficient above 77.25%, and the overall accuracy percentage is above 80%. This result indicates good agreement between the classification and the ground truth. Based on user accuracy, it appears that: the analysis model performed very well in 2000 for MF, SF, SwF, Fal, Far, and Sa, with over 90% for each except BL. This means that a pixel classified in these LCLU has a high probability of being correct. In 2010 and 2021, the results are almost the same except for MF and BL, which have an accuracy of around 80%. This result means that a pixel classified in these categories is more likely to be misclassified than those in SF, SwF, Fal, Far, and Sa. Accuracy by producer provides information on a model that performed well for many LCLU in 2000, 2010, and 2021. Only SWF had an accuracy of around 50% in 2010 and 2021. This means that the probability of a pixel assigned to this LCLU being misclassified is high. In terms of confusion, the most notable is that of BL in 2000, where among 27 pixels that were BL, 18 were classified as Sa and 9 as Far (Table 2).

3.3 Dynamics of LCLU Areas Between 2000, 2010, and 2021

Figure 4 shows that between 2000 and 2010, the areas of several LCLU increased, namely: MF (from 22,298.96 to 24,762.14 ha), SwF (from 3,193.74 to 3,327.36 ha), Fal (from 28.41 to 545.35 ha) and Far (from 44.25 to 161.39 ha), while those of SF (from 5,945.26 to 5,039.28 ha), Sa (9,874.39 ha to 7,553.81 ha) and BL (from 33.6 ha to 145.72 ha) decreased.

From 2010 to 2021, MF (from 24,762.14 to 19,352.46 ha), Fal (from 545.35 to 185.67 ha), Sa (from 7,553.81 to 5,422.05 ha) and Far (from 161.39 to 130.45 ha) declined, while SF (from 5,039.28 to 9,338.35 ha), SwF (from 545.35 to 6,848.23 ha), and BL (33.6 to 145.72 ha) increased.

During the period from 2000 to 2021, their areas decreased considerably, with MF falling from 22,298.96 to 19,352.46 ha; Sa from 9,874.39 ha to 5,422.05 ha, and Far from 161.39 to 130.45 ha. As for SF, SwF, Fal, and BL, their surfaces increased.

Table 2 Accuracy assessment for 2000, 2010, 2021 (MF: Mature forests; SF: Secondary forests; SwF: Swamp forests; Fal: Fallow land; Sa: Savannas; Far: Farms; BL: Bare land).

Confusion matrix in 2000									
TOS	**MF**	**SF**	**SwF**	**Fal**	**Sa**	**Far**	**BL**	**Total**	**Users' accuracy (%)**
MF	935	6	1	0	0	1	0	943	99.15
SF	3	234	2	0	0	3	0	242	96.69
SwF	5	4	254	0	0	0	0	263	96.57
Fal	0	1	0	121	0	0	0	122	99.18
Sa	0	0	0	5	1472	0	6	1483	99.25
Far	0	0	0	0	3	490	0	493	99.39
BL	5	0	4	0	18	9	171	207	82.60
Total	948	245	261	126	1493	503	177	4530	0
Producers' accuracy (%)	98.62	95.51	97.31	96.03	98.59	97.41	96.61	0	81.16
Kappa: 77,25 %									
Confusion matrix in 2010									
MF	1000	3	229	0	0	1	0	1233	81.10
SF	3	200	2	0	0	3	0	208	96.15
SwF	1	2	246	0	0	0	0	249	98.79
Fal	0	1	0	111	0	0	0	112	99.10
Sa	0	2	4	5	1423	0	6	1440	98.81
Far	0	0	0	0	3	466	0	469	99.36
BL	5	0	4	0	18	0	180	207	86.95
Total	1009	208	485	116	1444	470	186	3918	0
Producers' accuracy (%)	99.10	96.15	50.72	95.68	98.54	97.02	96.77	0	92.54
Kappa: 90,12 %									
Confusion matrix in 2021									
MF	956	1	302	0	0	1	0	1260	75.87
SF	1	197	8	0	0	3	0	209	94.25
SwF	2	4	233	0	0	0	0	239	97.48
Fal	0	1	0	125	0	0	0	126	99.20
Sa	0	0	1	5	1455	0	6	1467	99.18
Far	0	0	0	0	0	500	0	500	100
BL	1	0	4	0	10	1	196	212	92.45
Total	960	203	548	130	1465	505	202	4013	0
Producers' accuracy (%)	99.58	97.04	42.50	96.15	99.31	99.00	97.02	0	91.25
Kappa: 85,74 %									

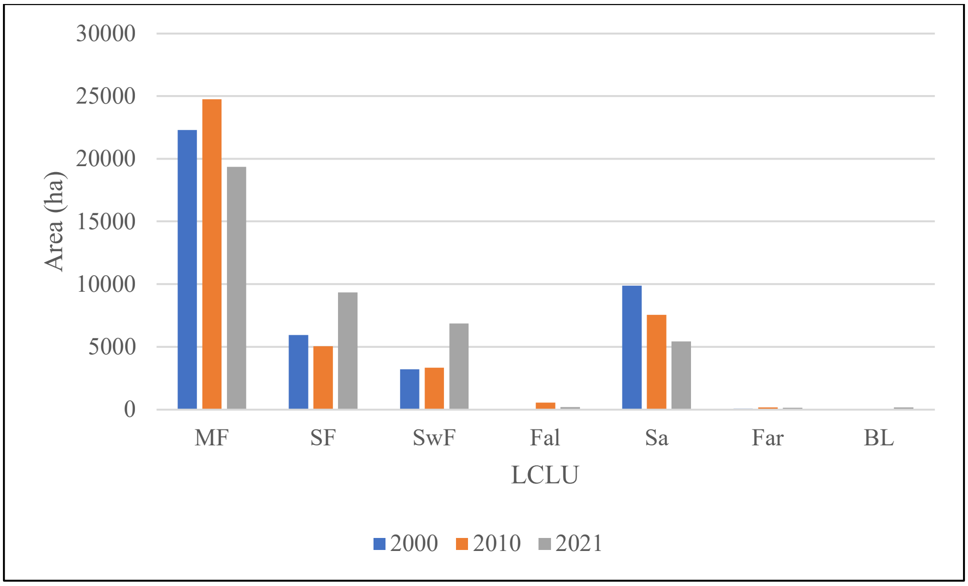

Figure 4 Changes in LCLU areas between 2000, 2010, and 2021 in the FCM (MF: Mature forests; SF: Secondary forests; SwF: Swamp forests; Fal: Fallow land; Sa: Savannas; Far: Farms; BL: Bare land).

3.4 Overall Rate of Change and Annual Rate of Spatial Expansion of Different LCLU Between 2000, 2010 and 2021

It should be noted from the outset that the annual average rates of spatial expansion follow the same trend as the overall change rates. Between 2000 and 2010, Sa had a negative overall change rate of -23.50%; then -28.22 between 2010 and 2021 and -45.09% between 2000 and 2021. This result indicates that strong pressure is being exerted on savannas by populations. In addition, during the period 2000-2010, MF and Fal had overall change rates of 11.05% and 1819.57% respectively; these rates fell between 2010-2021 (-21.85% and -65.95%) but increased between 2000-2021 (-13.21% and 553.54%) although these rates remained negative. SwF is the only LCLU that had only positive and increasing change rates during the following periods: 2000-2010 (4.18%), 2010-2021 (105.82%), 2000-2021 (114.43%) (Table 3).

3.5 Detection of Changes Between 2000 and 2021

- **Transition matrix**

Several changes were observed during the period from 2000 to 2021 in the MCF (Table 4). FMs declined by 8,730.6 ha in favor of all other LCLU identified in the MCF. However, Sa were converted to Far and BL. BL increased by 145.72 ha, and this is evidence of deforestation.

- **Intensity of change by LCLU between 2000 and 2021**

In general, three types of change affected the LCLU during this period. These include gains, losses, and stability. However, only Fal did not experience stability (0%) in their land area between 2000 and 2021. MF experienced the most significant losses (21.07%) and stability (32.75%). SF recorded the most remarkable gains (18.28%) (Figure 5).

- **Conversion rate and change rate of LCLU between 2000 and 2021**

Figure 6 shows that Fal (84.18%) had the highest conversion rate, while the lowest was found in Sa (-82.1%), followed by MF (-15.2). The other LCLU, namely SF, SwF, Far, and BL, had positive conversion rates of 36.37%, 53.35%, 66.13%, and 74.06%, respectively. These results mean that the interventions orchestrated in the MCF converted MF and Sa into SF, SwF, Fal, Far, and BL.

The Sa had the highest change rate (212.01 ha/year), followed by MF (140.29 ha/year), which means that the changes are more visible in the areas formerly occupied by the Sa and MF than in the SF, SwF, Fal, Fal, and BL.

Table 3 Overall rate of change and annual rate of spatial expansion of LCLU between 2000, 2010, and 2021 in the study area (MF: Mature forests; SF: Secondary forests; SwF: Swamp forests; Fal: Fallow land; Sa: Savannas; Far: Farms; BL: Bare land).

LCLU	2000-2010		2010-2021		2000-2021	
	Tg	Tc	Tg	Tc	Tg	Tc
MF	11.05	1.05	-21.85	-2.24	-13.21	-0.67
SF	-15.24	-1.65	85.31	5.61	57.07	2.15
SwF	4.18	0.41	105.82	6.56	114.43	3.63
Fal	1819.57	29.55	-65.95	-9.80	553.54	8.94
Sa	-23.50	-2.68	-28.22	-3.01	-45.09	-2.85
Far	264.72	12.94	-19.17	-1.93	194.80	5.15
BL	-11.39	-1.21	333.69	13.34	284.28	6.41

Table 4 LCLU transition matrix in ha between 2000 and 2021 (MF: Mature forests; SF: Secondary forests; SwF: Swamp forests; Fal: Fallow land; Sa: Savannas; Far: Farms; BL: Bare land).

Years		LCLU in 2021								
	Layers	MF	SF	SwF	Fal	Sa	Far	BL	Total 2000	Losses
LCLU in 2000	MF	**13568.05**	3980.91	4493.28	55.76	95.47	80.1	25.08	22298.65	**8730.6**
	SF	3339.87	**1770.4**	649.53	47.82	101.8	23.55	12.21	5945.18	**4174.78**
	SwF	722.49	659.52	**958.84**	20.49	812.54	2.83	17.7	3194.41	**2235.57**
	Fal	6.04	18.5	2.02	0	1.74	0.13	0	28.43	**28.43**
	Sa	1695.85	2872.45	743.77	54.53	**4408.8**	8.33	90.55	9874.28	**5465.48**
	Far	7.08	24.37	0.11	0.62	0.02	**11.86**	0.12	44.18	**76.5**
	BL	13.08	18.05	0.71	0.59	1.66	3.64	**0.06**	37.79	**37.73**
	Total 2021	19352.46	9344.21	6848.23	179.81	5422.04	130.44	145.73	**41422.92**	
	Gains	**5784.41**	**7573.8**	**5889.42**	**179.81**	**1013.23**	**118.58**	**145.72**		

Figure 5 Intensity of change by LCLU between 2000 and 2021 (MF: mature forests; SF: secondary forests; SwF: swamp forests; Fal: fallows; Sa: savannahs; Far: Farms; BL: Bare Land)

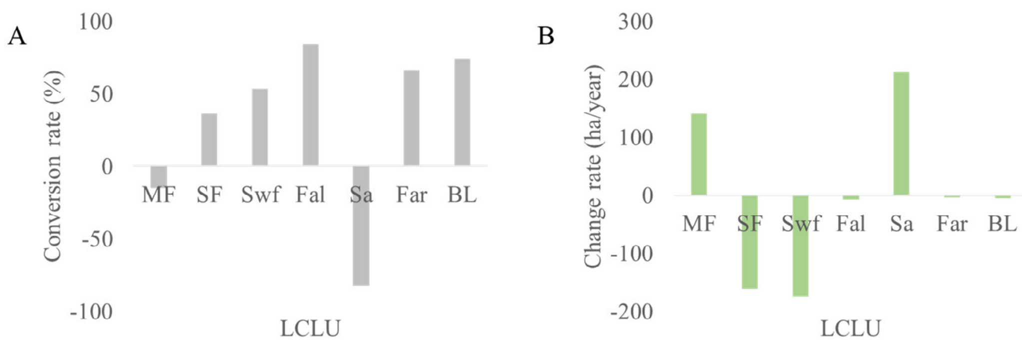

Figure 6 Conversion rate (A) and rate of change (B) of LCLU between 2000 and 2021 (MF: Mature forests; SF: Secondary forests; MF: Swamp forests; F: Fallow land; S: Savannas; C: Crops; SD: Bare land)

- **Deforestation rate and degradation rate of forest LCLU between 2000 and 2021**

MF have the highest deforestation rate at 0.67%. This result shows that MF are the most coveted forest layer compared to SF and SwF, which had deforestation rates of -2.15% and -3.63% respectively.

As for the degradation rate, the highest was found in MF (5.49%), followed by SF (3.03%) and SwF (2.22%). These results show that each of these LCLU is losing its forest composition (Figure 7).

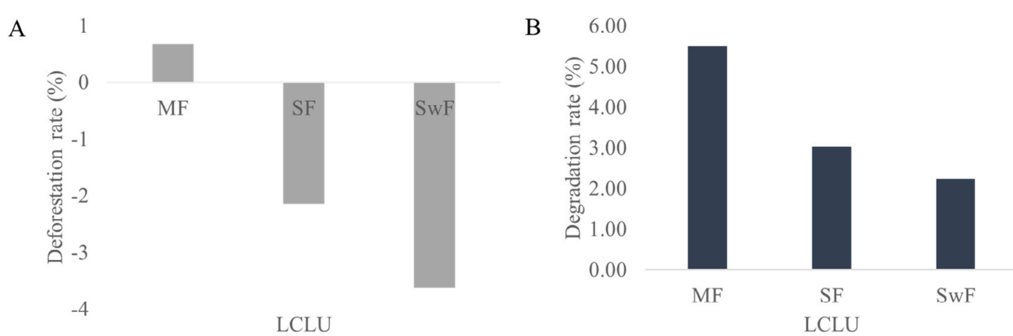

Figure 7 Deforestation rate (A) and degradation rate (B) of forest LCLU between 2000 and 2021 (MF: Mature forests; SF: Secondary forests; MF: Swamp forests; F: Fallow land; S: Savannas; C: Crops; SD: Bare land)

4 Discussion

4.1 Classification and Mapping of the MCF's LCLU

The methodological approach used in this study consisted of supervised maximum likelihood classification enabled the production of maps of sufficient quality (Mezafack et al. 2022). This method is one of the most relevant methods for studying LCLU through remote sensing (Kpedenou et al. 2016; Zhou et al. 2019). It is also the most representative, as it uses reference control areas to define the different LCLU types (Nagendra, Pareeth & Ghate 2006; Wiatkowska, Słodczyk & Stokowska. 2021; Zanguim et al. 2022). It must be acknowledged that supervised classification using maximum likelihood, which involves applying basic photo interpretation techniques, still presents difficulties in differentiating between homogeneous plots when selecting training sites (Avakoudjo et al. 2014; Mamane et al. 2018; Tsewoue et al. 2020). However, several authors agree that the results obtained using this method are still acceptable and satisfactory.

In addition, the overall accuracy in this study is above 80% and the Kappa index is above 77%. Only SwF had an accuracy around 50% in 2010 and in 2021. This confirms the difficulty in correctly detecting this class. To further improve the quality of their images, it would be beneficial to include data on texture and relief. Nevertheless, referring to the analyses presented by Pontius (2000), who estimates that the results of an image with a Kappa index above 50% are statistically acceptable, we can say that the results of this study are acceptable. Values similar to those in this study have been found in other ecosystems in the Congo Basin, such as Fotso et al. (2019), Mezafack et al. (2022), Ngoukwa et al. (2025), Tsewoue et al. (2020).

4.2 Dynamics of LCLU in the Study Area

Remote sensing tools help to reconstruct past landscapes and the dynamics to which they were subjected (Ngo et al. 2022). Transition matrices revealed a sharp decline in MF (± 20%) in favor of SF, Fal, Far, and BL. Similarly, in the Doumé and Dimako FCs, similar results were obtained by Zekeng et al. (2019) and Mounmemi et al. (2020), where the evolutionary trend was essentially regressive, with dense forests with high tree density being converted into other LCLU. These results are attributable to uncontrolled logging, which has continued to be practiced for decades in the MCF despite the existence of a management plan. They are also thought to be the result of the limited implementation of conservation or reforestation strategies for degraded areas, as well as the municipality's inability to adequately monitor FIPCAM (Fabrique Camerounaise des Parquets) activities due to a lack of qualified personnel in this domain. In contrast, an 18.28% increase in SF was found, indicating a regenerating environment and steady forest stand dynamics. However, this recent expansion of SF can sometimes hide internal degradation of the forest environment, which is nevertheless detectable on satellite images and confirmed by field investigations (Momo et al. 2018; Mounmemi et al. 2020).

LCLU dynamics of MCF are contrary to those observed in the protected areas of the forest-savanna transition zone. In Mbam and Djerem National Park, Fotso et al. (2019) found that dense forests tend to take precedence over other vegetation formations, particularly savannas and open forests, over the years. This difference can be explained by the fact that this park is a protected area and therefore highly degrading activities such as logging and mining are prohibited there. This is a call to municipalities to resort to practices such as reforestation, combating illegal logging, as well as regulating the creation of mining quarries and monitoring legal logging. In addition, the vegetation dynamics in the MCF show a certain loss of Sa (13.19%) in favor of BL. This result is similar to that found by Ngo et al. (2022) in the Mpem and Djim National Park. These similarities are thought to be due to overgrazing caused by the widespread pastoral activities in the transition zone. In short, these various results show that the managers responsible of these ecosystems must adapt their management plans to the specific realities of these ecosystems in order to ensure sustainable management.

4.3 Drivers of change in LCLU in the Forest-Savanna Transition Zone

Analysis of LCLU map from 2000, 2010, and 2021 revealed the dynamics of certain LCLU between these three years. Data collected in the field and the use of the diachronic method, which involves using satellite images to analyze LCLU dynamics, made it possible to identify the following drivers of change: logging and mining, the creation of plantations, livestock farming, and climate change (FAO 2014; Zanguim et al. 2022). Since the MCF was classified, logging has continued to intensify, accompanied by the creation of roads for timber transport (SIFCAM 2011; Tsewoue et al. 2020). The establishment of agricultural plantations is the main cause of forest loss, particularly cocoa and coffee plantations. It is a major driver of deforestation and vegetation degradation (Avakoudjo et al. 2014; Feudjio et al. 2023). This severe degradation and conversion of forest into agricultural plantations is attributable to the population living in the FCs, who practice slash-and-burn agriculture for their subsistence (Ngoukwa et al. 2025; Zekeng et al. 2019). Livestock farming is responsible for the degradation and loss of several hectares of savanna and forest due to overgrazing, with bush fires most often lit by herders at the end of the dry season to encourage early growth of forage plants (Tchoupou et al. 2021; Ngo et al. 2022). However, these results are similar to those of the FAO (2014), which stated that 90% of deforestation is caused by unsustainable agricultural practices. This dynamic is accompanied by biodiversity loss and land degradation (Nguimdo 2017; Chimi et al. 2022). This observation highlights the anthropogenic influence on forests, thus raising the issue of the distribution of the benefits generated by these forests in the era of sustainable management of CF, which aims to ensure the well-being of local populations.

Climate change occurs at several levels, firstly in the overall modification of physical conditions favorable to the maintenance and growth of plant formations (Gansaonré, Zoungrana & Yanogo, 2020). But it also occurs by weakening the living conditions of populations, which leads them to put pressure on natural ecosystems and hence the changes observed (Chimi et al. 2022; Tene et al. 2023). Changes in LCLU can also have climatic origins when the ecological zone no longer receives the minimum rainfall required for the spontaneous regeneration of plant formations, which is increasingly observed in the forest-savanna transition zone (Adjonou et al. 2010).

4.4 Implications of Studying LCLU Dynamic for the Conservation and Sustainable Management of FSTF

This study shows that LCLU dynamics analyses can provide a more comprehensive overview of the elements of LCLU that are involved in changes and forest decline. This analysis also helps to understand the various interactions between these LCLU, which is particularly important for spatial planning. The conversion of forests and savannas into highly anthropized systems such as Far, Fal and BL can be identified and monitored through trajectory analyses. Subsequently, conservation, reforestation, and zoning management policies can be developed to guide these changes in more sustainable directions. In fact, Mounmemi et al. (2020) found that the expulsion of populations from the Dimako CF contributed to a forest area gain of 100.59 ha/year between 2000 and 2015. Neglecting such measures can also drive remarkable changes in the socio-cultural environment of the ecosystem, impact the production of ecosystem services, and lead to a loss of biological diversity and carbon stocks. Therefore, it is essential and recommended that local communities should be involved in the planning and management process for this area, as they can play an important role in changes in LCLU and may also be affected by these changes. To reduce the pressure exerted by the populations in the MCF, its managers can first organize awareness-raising meetings for them on the purpose of creating a CF and its role in maintaining a healthy environment, since more than 80% of local residents say they were not consulted when the CF was created (Yemefack & Alemagi 2016). Once awareness has been raised, the municipality can also proceed with the reforestation of its CF and may later deport the populations from the CF in order to preserve this ecosystem.

To curb these changes, which are negatively affecting LCLU in the MCF, three management options are possible and recommended to the municipality: either conserving less degraded areas by prohibiting certain activities (logging, agriculture, livestock farming, mining); or reforesting or rehabilitating degraded areas; or implementing a zoning plan for their CF, thereby assigning each area an economic, social, or ecological function in order to meet expectations related to the SFM.

5 Conclusion

At the end of this study, which aimed to analyze land use dynamics in the MCF between 2000, 2010, and 2021, it appears that LCLU in this CF has undergone several changes due to various factors that have contributed to the degradation of this ecosystem. Consequently, the municipal executive is called upon to urgently address each of these drivers of degradation in order to save this ecosystem, which could lose its biodiversity and several ecosystem services it provides over the years. Indeed, reforestation that follows the pace of logging would boost the regeneration index, which is very low in the MCF. Furthermore, since the municipality is engaged in the sustainable management process, which requires all stakeholders to be involved in forest management not only at the decision-making and implementation levels, but also in terms of sharing the benefits derived from CF management, the municipality of Minta is encouraged to emphasize this sociological component of sustainable forest management. Therefore, it will improve the living standard of its populations, which have been largely neglected to date. Finally, the municipality of Minta must ensure that the purpose of the CF, which is to produce timber, is respected while ensuring the sustainability of these forests. Consequently, it is strongly recommended that deforestation activities such as agriculture and mining be stopped in order to contribute to the effectiveness of SFM, to which the entire nation is committed.

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Author contributions

Ingrid Tsopmejio Temfack: conceptualization; formal analysis; writing original draft; writing review and editing; supervision; visualization. **Amandine Flore Ntonmen Yonkeu:** conceptualization; formal analysis; writing review and editing. **Cédric Chimi Djomo:** formal analysis; methodology; validation; writing review and editing. **Hubert Kpoumie Mounmemi:** formal analysis; methodology; writing review and editing. **Louis Zapfack:** conceptualization; formal analysis; methodology; validation; writing review and editing; supervision. **Darling Djoumene Wado:** methodology; writing review and editing. **Guylène Ngoukwa:** methodology; writing review and editing. **Aurélien Richy Nkouankam Tchayep:** methodology; writing review and editing.

Conflict of interest

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