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Analysis of the Dynamics of Forest Landscape Fragmentation in Western Madagascar under the Influence of Migration

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Abstract— *Economic activities by migrant populations lead to changes in landscape structure and land use in non-forested areas. This article aims to analyse the spatial and temporal dynamics of forest fragmentation and to examine the influence of migration on the configuration of the forest landscape within the Menabe Antimena protected area between 2017 and 2022. The methods used include a diachronic analysis of satellite imagery using remote sensing. Following canopy classification, land-use classes were categorised as forest or non-forest. The results reveal that forest fragmentation shows a generalised increase of 13.94% within the protected area and 25.05% at its periphery, with an overall peak observed in 2022. Furthermore, the configuration of forest fragments is significantly correlated with migration inflows. The landscape is dominated by micro-fragments covering an area of less than 20 ha, which account for between 98.86% (16,197 out of 16,383 fragments) and 99.18% (20,622 out of 20,792 fragments) of the total within the protected area; and 99.08% (11,607 out of 11,715 fragments) to 99.30% (12,226 out of 12,312 fragments) outside the protected area. At the same time, fragment density increased from 2.32 to 3.92 fragments/ha, resulting in a significant change in the fragmentation index (from 0.60 to 0.87) for the 20–50 ha class. These results make a major contribution to the overhaul of national conservation strategies by demonstrating the need to incorporate internal population flows into protected area management plans.*

Keywords— Menabe Antimena Protected Area, Migration, Anthropogenic pressure, Fragmentation, Conservation, Forest fragmentation, Deforestation, Remote sensing, Landscape ecology, Madagascar, Dry forest, Climate-induced migration, Protected area management.

I. INTRODUCTION

Population growth and agricultural expansion, particularly in developing countries, are the main causes of deforestation and forest degradation (Jallat et al., 2021; Ahmed et al., 2023). Forests are among the natural resources whose preservation is a key concern for sustainable development, particularly given the importance of their numerous ecosystem services to both current and future generations (Wainger et al., 2010). Covering a total area of 10 million km² (Senior et al., 2019), tropical forests constitute one of the world's most ecologically important habitat types (Hending et al., 2025). They harbour more than half of the world's forest carbon and more than 80% of terrestrial biodiversity; they play a fundamental role in regulating the climate at both regional and global levels and provide countless services and products to people (Sist, 2025). Unfortunately, tropical forests are among the most threatened habitats in the world (Edwards et al., 2019). Due to factors ranging from large-scale forest conversion to the overexploitation of resources for subsistence purposes, tropical forests have been massively affected by agricultural activities that drive deforestation and forest degradation (Achard et al., 2004; Asner et al., 2009). Currently, most of the remaining tropical forests are fragmented into more than 130 million patches, with an average area of around 29 ha (Taubert et al., 2018). Forest fragmentation manifests itself through typical changes in the spatial structure of the landscape and is characterised by an increase in the number of patches, a reduction in their size, greater complexity in their shape and increased isolation between them (Ma et al., 2023; Peptenatu et al., 2023; Rahman and Islam, 2021). However, the spatial configuration of landscapes, including plot shape and connectivity, plays a crucial role in the provision of ecosystem services (Lamy et al., 2016). This observation highlights the significant impact of forest fragmentation, particularly in areas with high population density, on the continuity and effectiveness of these services (Hisham and Hua, 2026).

Climate-related events are forcing thousands of people to move within their own countries (Veron, 2020). This climate-induced migration directly alters population growth rates and demographic characteristics, both through the migration itself and by interacting with and amplifying other demographic processes (Hauer et al., 2024). As such, the issue of demographic pressures remains a major and pervasive concern in documents examining deforestation, land degradation, the loss and degradation of biodiversity, threats to peace, future stability, and global warming (Agrawal, 2018). In recent years, the forests of sub-Saharan Africa have been under increasing pressure, mainly due to demographic pressure and migration caused by climate change (Nicoletti et al., 2023; Vinke et al., 2022). In these countries, access to land is considered important for improving the incomes and food security of rural households (Holden and Otsuka, 2014; Muraoka et al., 2018). However, migrants often adopt unsustainable agricultural practices (Sunderlin and Pokam, 2002), including itinerant slash-and-burn agriculture. Changes in land use linked to human development are the main drivers of forest fragmentation. With population growth and economic expansion, forests are cleared for agriculture, urbanisation and infrastructure development (Perea, 2024).

The establishment of protected areas is the cornerstone of conservation policies aimed at reducing biodiversity loss and ensuring the long-term conservation of nature, ecosystem services and the associated cultural values (Vimal et al., 2021). However, protected areas in Africa are generally highly vulnerable, due to their proximity to settlements and the impacts of human activities (Triplet, 2009). Furthermore, human migration to resource-rich border regions can be a significant driver of forest change and biodiversity loss (Jones et al., 2018), thereby threatening the integrity of protected areas (Scholte and De Groot, 2010).

As for Madagascar, although it is recognised as one of the world's most biodiverse countries and is classified as a biodiversity hotspot, with a very high rate of endemism, its biodiversity is under severe threat from human activities (Myers et al., 2000; Tovondrazane et al., 2020). As a result, the level of forest fragmentation has been steadily increasing since 1953 (Vieilledent et al., 2018) and, by 2024, forest cover will account for only 20.7% of the island's total land area (Rakotoarisoa et al., 2025).

Although the link between human migration and the degradation of natural resources has been recognised for some time, the role of migration in environmental change continues to attract growing interest in its many facets (Bechard, 2018). In recent years, the link between climate-induced human mobility and environmental health has attracted increasing attention. Deforestation, land loss and forest fragmentation are among the most significant environmental issues threatening forest ecosystems worldwide (Ravonjimalala, 2019). Nowadays, the fragmentation of natural forests, largely linked to human activities, agricultural practices and the expansion of road networks, is a recurring phenomenon faced by tropical countries (Hending et al., 2025; Mahapatra et al., 2025). Consequently, the fragmentation of these tropical forests and protected areas leads to a loss of habitat and biodiversity, as well as an increase in carbon emissions (Hansen et al., 2020).

The Central Menabe region is still home to the largest remnant of dry forest in western Madagascar. These forests harbour a rich biodiversity, including several local and regional endemic species (Zinner et al., 2014), the most famous of which are *Hypogeomys antimena*, the largest endemic rodent in Madagascar; *Microcebus berthae*, the world's smallest lemur (Wilmet et al., 2022; Markolf et al., 2019). Central Menabe has a long history of forest conversion to agricultural land, for both plantations and subsistence farming (Scales, 2011). The expansion of agricultural land and plantations, together with forest fires, is currently intensifying forest fragmentation, posing a profound and irreversible threat to forest ecosystems (Caron et al., 2023; Fischer et al., 2021).

Well known for its dense dry forests and mangroves, the Menabe region is renowned for having welcomed and integrated groups of migrants from all over Madagascar, particularly from the south, and is considered a prime destination for internal migration (IOM, 2024). Furthermore, this human mobility affects forest management in several regions of Madagascar

(Rabemananjara, 2014), including Menabe Antimena, but there is no evidence of spatial overlap or correlation with deforestation (Rakotonarivo et al., 2026). Within this protected area, migrants from the south settle and cultivate land cleared through slash-and-burn practices, or 'Hatsake', leading to significant deforestation and land grabbing, in defiance of conservation efforts and participatory ecosystem management with local communities (MEDD, 2022). The protected area recorded an annual deforestation rate of 0.85% (2000–2010) rising to 2.35% (2010–2014) (Salvaterra & INDRI, 2017), and is estimated at 4.27% per year (2018–2022); 2.50% (2022–2023) (Andrianambinina et al., 2025) due to the illegal cultivation of maize (*Zea mays*) and peanuts (*Arachis hypogaea*) (MEDD, 2022). Consequently, forest cover in Menabe Antimena decreased by 22.1% between 2017 and 2022 (Andrianandrasana et al., 2025).

This reduction in forest area is accompanied by fragmentation, whereby forest plots are divided into several smaller plots (Taubert et al., 2018), and forests fragmented by human activities are at greater risk of further fragmentation or loss than those fragmented by natural causes (Wade et al., 2003). There is good evidence that forest fragmentation has a significant impact in maintaining ecosystem services and is generally recognised as a stressor for ecosystem stability (Fu et al., 2025; Li et al., 2022). In this regard, there is a significant lack of scientific analysis, particularly concerning the causal relationships between landscape spatial configurations and the ecosystem services provided by protected areas.

However, previous studies carried out within the Menabe Antimena protected area have not highlighted the heterogeneity, the degree of temporal and spatial fragmentation, the evolution and their correlation with migration patterns within and around their green belts. Many questions therefore remain unanswered, notably to what extent the migratory influx that occurred between 2017 and 2022 has altered the degree of fragmentation and the spatial configuration of the Menabe Antimena forest landscape. If this migration were to lead to an expansion of subsistence farmland, then the number of forest fragments would increase, as new arrivals clear the denser forest blocks to practise agriculture. Thus, the primary scientific aim of this research is to characterise and quantify the changes occurring in the forest landscape, and to examine the spatial and temporal dynamics of fragmentation in a dry forest in the western ecoregion of Madagascar between 2017 and 2022, whilst assessing its impact on ecosystem resilience. Secondly, to provide a scientific analysis of human migration flows as an independent predictor of vegetation dynamics within the protected area. The results of this study contribute to a better understanding of the relationship between forest fragmentation and agricultural expansion by migrant and indigenous populations, and will serve as a warning and a catalyst for mobilising all stakeholders to develop realistic development policies in the regions from which migrants originate and to devise effective strategies for forest sustainability.

II. MATERIALS AND METHODS

2.1 Study Areas

The ecoregion of western Madagascar is characterised by dry tropical forests and mangrove forests. The Menabe region (Figure 1), situated in western Madagascar, covers an area of 4,612,100 ha, with Morondava as its capital. It is a region rich in biodiversity, with various categories of protected areas, including: the Menabe Antimena Protected Area, the Ambondrombe Lake-Forest Complex, the Ambohijanahary Special Reserve, the Ambararata Londa Forest Station, the Andranomena Special Reserve, the Kirindy Mite National Park, the Mangoky Ihotry Wetland Complex, and, of course, the famous Alley of the Baobabs harmonious landscape.

The Menabe Antimena Protected Area (Figure 1), classified as a Category V Protected Harmonious Landscape according to the IUCN classification, is situated in the districts of Morondava and Belo sur Tsiribihina, at the geographical coordinates 19°56'37"S 44°40'46"E. It comprises three Ramsar sites: the Bedo wetlands (1,962 ha), the Ambondrombe wetlands (13,000 ha) and the Belo sur Tsiribihina mangroves (47,218 ha). Managed by the Fanamby Association, Menabe Antimena covers a total area of 216,011 ha, comprising a core area of 68,874 ha and a buffer zone of 141,126 ha (Goodman et al., 2018), with 57,689 ha of forest (27.47% of its total area) (Andrianambinina et al., 2025).

In recent years, the Menabe Antimena Protected Area has been facing rapid deforestation, resulting in the loss of around 30% of its dry forests (Markolf et al., 2019). Furthermore, it has seen a massive influx of survival migrants, particularly in the rural communes of Marofandilia, Beroboka Nord, Tsimafana, Tsarahotana and Antsoha, coming from the Androy region, the driest region in Madagascar. The Androy region has a Standard Precipitation Index (SPI) of up to (SPI $\leq$ -2), classifying it as an extremely dry region in the south of the country according to the table by McKee et al. (Panigrahi and Vidyarthi, 2024).

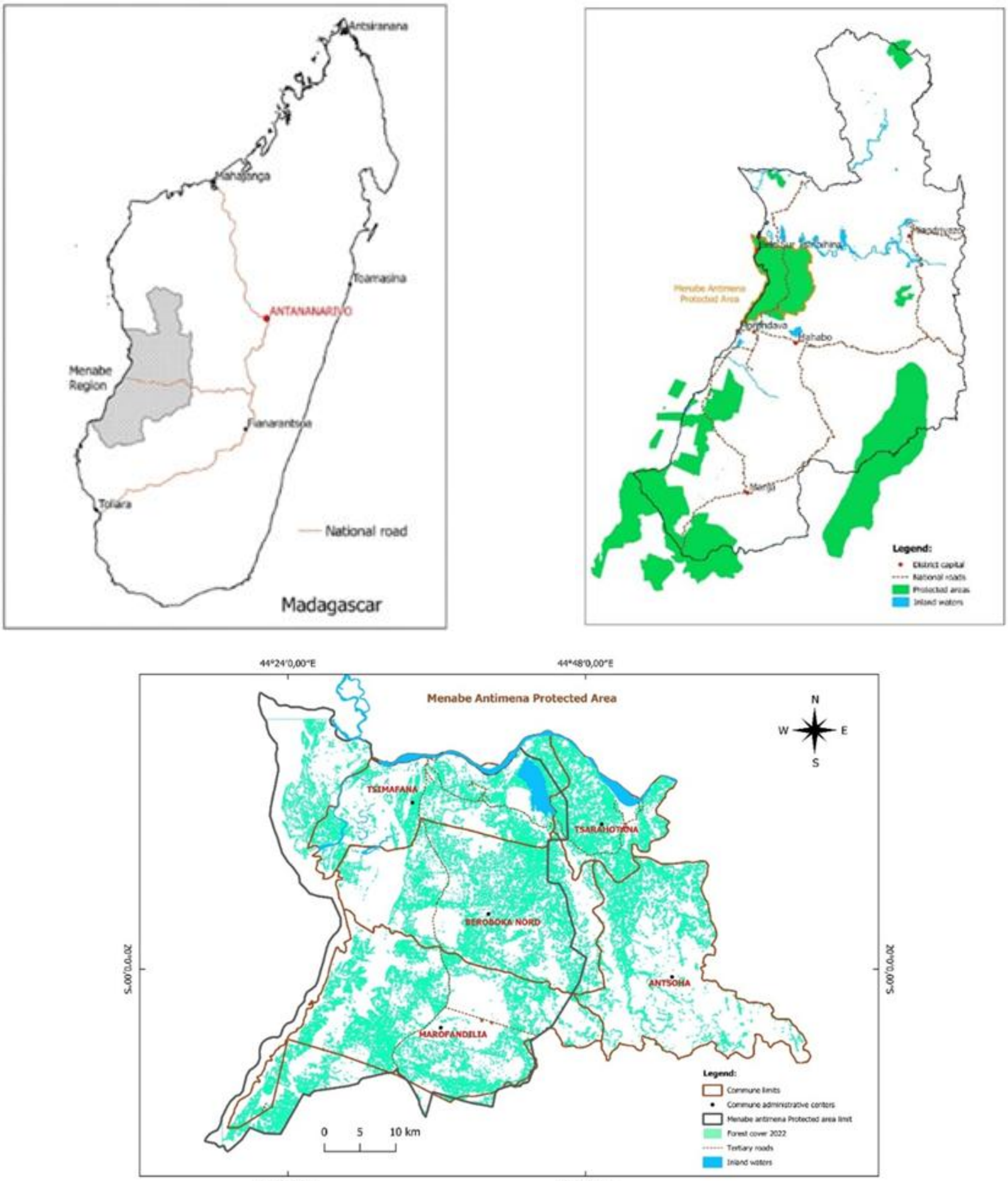


FIGURE 1: Location map of the study areas. Top left: Map of Madagascar showing the location of the Menabe region. Top right: Location map of protected areas within the Menabe region, including Menabe Antimena. Bottom: Map of the Menabe Antimena Protected Area and the five rural communes selected as study sites.

2.2 Data Collection

2.2.1 Unit of Analysis

The unit of analysis selected is the commune, the administrative division constituting the region in Madagascar. The geographical boundaries of the communes, modelled as polygons, were extracted from the official database of the Foiben-Taosarintanin'i Madagasikara (FTM) using QGIS 3.34.11 software. The annual socio-demographic and environmental variables for 2017–2022 were spatially aggregated within the territorial boundaries of the communes selected as study sites.

The data analysed in this study included predictive variables relating to population dynamics, migration statistics and economic activities, in order to assess their influence on the independent variable, namely the fragmentation of forest cover within and around the Menabe Antimena protected area. The analysis of these variables was preceded by field surveys carried out between May and August 2023 to collect and validate the data required for this research.

In order to assess the relationship between human mobility and vegetation dynamics in the Menabe Antimena protected area, we collected and analysed statistical data on the general population and on migrants from the South at the study sites, as well as remote-sensing data from 2017–2022. Where appropriate, analyses of the links between human migration and changes in the spatial structure of the vegetation landscape will be carried out to characterise the level of fragmentation within the protected area.

2.2.2 Migration Data

For the analysis of migration flows, demographic data from official municipal registers on population dynamics, analysed using the methodology applied by Andrianandrasana et al. (2025), were used. It enables the determination of the annual migration intensity rate, which serves as a tool for quantifying the scale of migratory movements relative to the total population studied over the period 2018–2022.

Data from the 2017 population census are not available in official records, either at municipality or national level. The recorded figures were cross-checked against those published in the register of Madagascar's Third General Population and Housing Census of 2018 (RGPH-3) to ensure their consistency in this study.

2.2.3 Forest Data

The forest cover data used in this section are identical to those used by Andrianandrasana et al. (2025). However, this article focuses on assessing forest quality, specifically on analysing the dynamics of forest fragmentation across the entire Menabe Antimena protected area, as well as at the level of the municipalities where the migrant communities are located. To identify forest within the Menabe Antimena protected area, we used a specific forest cover density threshold of 29%, classifying areas with canopy cover below this threshold as non-forested and those at or above it as forested, as recommended and used by Rafanoharana et al. (2023); Andrianambinina et al. (2024); Andrianandrasana et al. (2025). Forest fragments were identified using remote sensing, involving the use of satellite imagery to detect isolated or defined wooded areas. These algorithms were applied using GIS-based image processing. Time series of forest cover maps were utilised to quantify the six years (2017–2022) of forest fragmentation in Menabe Antimena by applying an effective clustering algorithm to determine the size, number and spatial configuration of all observed forest fragments.

In order to scientifically validate the results of the image processing with rigorous statistical robustness across the 216,011 ha of the protected area, a hybrid validation approach combining in situ observations and photo-interpretation was implemented. Twenty (20) polygons were delineated in the field as training control sites, strategically distributed between areas of dense forest and areas with open canopy, both within and outside Menabe Antimena. In order to achieve spatial representativeness in accordance with the standards set by Congalton (1991) and Olofsson et al. (2014), this sample was supplemented in ArcGIS 10.8.2 with a network of stratified random points. Points located in areas that were difficult to access were systematically validated through photo-interpretation of high-resolution historical imagery (Google Earth Pro). This comparative temporal analysis made it possible to definitively compare the automated classifications derived from image processing with the biophysical reality of the soil. Finally, ArcGIS's automatic confusion matrix calculation tool (Compute Confusion Matrix) was used to rigorously generate the overall accuracy rate and the Kappa coefficient.

2.2.4 Overlap between the Menabe Antimena Protected Area and the Rural Municipalities Studied

The five rural municipalities selected as study sites are those where the majority of migrants occupying the Menabe Antimena Protected Area and its green belts are located. A total of 81.38% of Menabe Antimena is attached to these communes, and the rural commune of Marofandilia, followed by the commune of Tsimafana, are the communes most covered by the protected area, with 94.17% and 91.63% of these communes, respectively, lying within the protected area. As for the rural commune of Tsarahotana, only 6.24% of the municipality lies within the protected area, whilst the commune of Antsoha comprises the entire green belt of Menabe Antimena (Table 1).

For the analysis of forest fragmentation dynamics, forest blocks located within municipalities that overlap with those of the protected area's forests are not counted alongside those of the rural municipalities outside the protected area.

TABLE 1
DISTRIBUTION OF THE PROTECTED AREA ACROSS THE STUDIED RURAL COMMUNES

Rural Communes	Total Area of the Commune (ha)	Area Covered by the PA (ha)	PA Coverage Proportion (%)
Antsoha	52,222.62	0	0
Beroboka Nord	63,982.93	55,463.86	86.69
Marofandilia	69,670.47	65,609.39	94.17
Tsarahotana	20,692.08	1,291.54	6.24
Tsimafana	41,560.57	38,083.19	91.63

Source: Statistical processing of geographical information from BNGRC and SAPM (VIRAINA, F.F., 2023).

2.3 Data Analysis

2.3.1 Deforestation Rate in Menabe Antimena

Deforestation is defined as the permanent or temporary conversion of forest to other land-use types (FAO & JRC, 2012). Based on the methodology developed by Hansen et al. (2013), the loss in forest cover is characterised by the transition of a pixel to the "non-forest" class. In tropical forestry, the severity of this rate is generally classified according to the standardised formula by Puyravaud (2003):

TABLE 2
CATEGORISATION OF THE DEFORESTATION PRESSURE LEVEL ACCORDING TO INTENSITY

Annual Rate (%)	Deforestation Pressure Level
< 0.5%	Low (slow dynamics, diffuse or residual anthropogenic pressures)
0.5% to 1%	Medium (deforestation fronts in the process of structuring)
> 1%	High to critical (highly active clearing fronts and massive destruction of the forest cover)

2.3.2 Identification Process and Spatial Analysis of Changes to Forest Fragments in Menabe Antimena

The methodology adopted is based on a geographical and diachronic approach to the study of land use. Data are obtained through remote sensing image processing, supervised classification mapping, predictive modelling and spatial analysis (Tchibozo, 2020). These processes are determined on the basis of three main parameters considered to be fundamental elements for describing the landscape configuration, namely (i) the area of patches, (ii) the perimeter of patches and (iii) the number of patches (Collinge and Forman, 1998; Jaeger, 2000; Bogaert et al., 2004). These parameters were determined for all land-use units and for the years under study. Mapping of land-use dynamics was carried out by vectorising the results of image classification (raster). The classification of land-use patches was generated using ArcGIS 10.3.1 software to produce the various polygons from which several parameters were calculated. Thus, spatial dynamics are measured by assessing changes in land cover types, based on a comparison of the area values of the various land-use units between the study periods (Oloukoï et al., 2006).

In this study, plots represent individual forest fragments or forest blocks. The choice of metrics to be used in the analyses is based on the data available from image processing. The analyses were conducted at the landscape scale, based on the size and spatial distribution of forest block fragments.

2.3.2.1 The Number of Plots

This enables the total number of forest fragments to be counted and provides key indicators of the degree of landscape fragmentation (McGarigal and Marks, 1995):

- **Number of Patches:** This directly quantifies the level of fragmentation of the forest cover. The higher the number of fragments, the more pronounced the fragmentation.
- **Patch Density:** This measures the number of fragments per unit area. A high density characterises a highly fragmented landscape.
- **Average Fragment Size:** This provides fundamental information on the spatial structure of the forest stand. Low values indicate advanced fragmentation of the original forest stands.

Fragment size has been categorised into three classes:

- **Class 1:** Forest with an area of less than 20 ha
- **Class 2:** Forest with an area of 20 to 50 ha
- **Class 3:** Forest with an area of more than 50 ha

2.3.2.2 Spatial Fragmentation Index of the Forest Landscape (F_j)

The landscape fragmentation level was assessed by calculating the fragmentation index (F_j) for each land-use class. This approach, applied to spatial analysis, measures the degree of pixel aggregation within class j in order to express the structural complexity of the image (Bogaert & Hong, 2004; Sambiéni et al., 2015). This index is determined by the following formula:

$$Fj = \frac{(nj-1)}{(mj-1)} \quad (1)$$

Where:

- n_j represents the total number of patches for class j;
- m_j is generally, in a raster file, the number of pixels (Monmonier, 1974).

However, as the calculations in this study were carried out using a vector file, m_j was estimated as the ratio of the total area (a_{tj}) of class j to the area of the smallest patch (a_{minj}).

Therefore:

$$Fj = \frac{(nj-1)}{\frac{at_j}{aminj} - 1} \quad (2)$$

The values of this indicator are standardised and fall within a range of 0 to 1 ($0 \leq F_j \leq 1$). The structural interpretation of the landscape is based on proximity to these two limits: an F_j value close to 0 indicates a low level of fragmentation, characterising an aggregated, continuous and homogeneous spatial class (preserved forest massif). Conversely, a value close to 1 indicates pronounced fragmentation, reflecting an advanced fragmentation of the vegetation cover into a multitude of isolated patches.

2.4 Statistical Analysis

The quantitative data were processed and analysed using RStudio software (v4.3.0). Firstly, a Student's t-test for paired samples was applied to compare the average forest areas between the two ends of the study period (2017 and 2022), in order to verify whether the observed temporal variations are statistically significant or whether they are simply due to chance. Secondly, to assess the impact of migration variables on the spatial structure of the Menabe Antimena forest landscape, the data were subjected to repeated-measures correlation analyses using the rmcorr package (Marusich & Bakdash, 2021). This method estimates the common regression slope and is highly recommended for calculating correlation coefficients across multiple observations repeated over time.

In order to overcome Simpson's paradox which tends to reverse or mask actual correlations when aggregating panel data, a Linear Mixed Model (LMM) was employed to incorporate inter-municipal variability as a random effect. For all these models, the threshold for statistical significance was set at 0.05; any probability value below this threshold ($p < 0.05$) is considered significant (Payne, 2020).

III. RESULTS

3.1 Migration Intensity Index in Menabe Antimena

The number of migrants arriving from southern Madagascar recorded across the five rural municipalities of the Menabe Antimena Protected Area increased by a factor of 3.2 between 2018 and 2022. Relative to the total population, migrants from the south accounted for between 45.39% and 51.16% of the population within Menabe Antimena, with the highest proportions being recorded in the rural municipalities of Beroboka Nord (38.24%), Marofandilia (35.25%) and Antsoha (12.90%) over the period 2018–2022. This proportion reached its maximum in 2020 before declining by 50.9% in 2022. Migration intensity increased linearly, following a constant annual growth rate of 1.4%. Accordingly, 75.66% of the variation in the migration intensity index is explained by temporal change. Consequently, migrants now occupy a substantial proportion of the area, and an increasing process of permanent settlement has become established within the protected area (Figure 2).

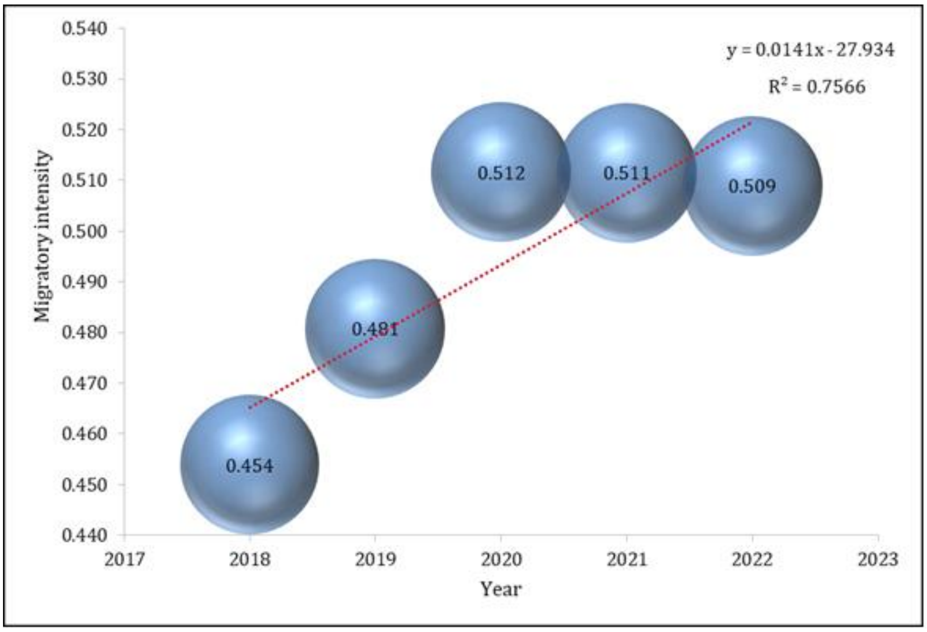


FIGURE 2: Annual migration intensity index of Menabe Antimena (2018–2022)

3.2 Assessment of the Accuracy of the Land-Cover Classification

The overall accuracy of the land-cover classification reached 89.3%, substantially exceeding the standard 85% threshold commonly accepted in remote sensing for the validation of tropical forest cover. This performance is further supported by a Kappa coefficient of 0.78, indicating excellent agreement between the model predictions and the reference observations.

3.3 Vegetation Status of Menabe Antimena in Relation to Deforestation

This study reveals a profound spatio-temporal transformation of the forest landscape across all study sites, characterised overall by a continuous decline in forest cover.

Forest area exhibited considerable annual instability throughout the 2018–2022 period. At the municipal scale, this declining trend was reflected by a minimum annual forest loss of 124.87 ha recorded in Tsimafana in 2020. Conversely, the greatest decline was identified in Marofandilia in 2018, where 3,185.19 ha of forest disappeared within a single year.

Within the Menabe Antimena Protected Area, annual deforestation ranged from a minimum loss of 1,818.80 ha in 2022 to a catastrophic peak of 22,551.90 ha of net forest loss recorded in 2019. The most extensive forest losses occurred predominantly within the boundaries of the protected area. Rural municipalities with a high degree of territorial overlap with the protected area were similarly affected, experiencing systematic forest losses.

Assessment of the annual deforestation rate highlights the intensity of local anthropogenic pressures. According to the standard thresholds used to assess deforestation in tropical environments, the rural municipalities studied exhibited moderate annual rates of forest loss ranging from 0.67% (Tsimafana, 2020) to a highly critical level of 16.94% (Antsoha, 2021), illustrating the extremely rapid disappearance of forest in these areas. In 2019 alone, forest cover within the protected area collapsed to a critical loss rate of 33.00%. By contrast, data for 2020 indicate an exceptional positive balance within the protected area, with more than 16,882.30 ha undergoing conversion and a growth rate exceeding 36.88%. This temporary increase in forest cover, which contrasts with the overall declining trend, may be explained either by a marked slowdown in human activities during the global COVID-19 pandemic or by mapping artefacts resulting from cloud cover in the original raster datasets. Despite this local fluctuation, the territory continues to lose substantial areas of forest each year because the rate of forest clearance consistently exceeds the natural regeneration capacity of the protected area (Figure 3).

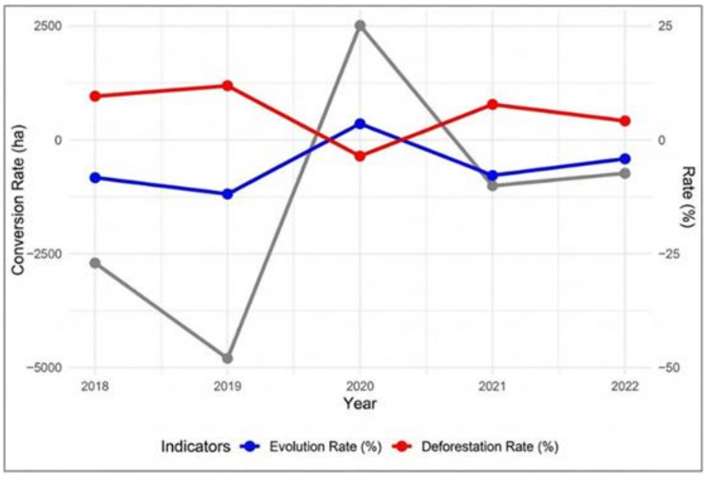


FIGURE 3: Graphical representation of the annual synthesis of the vegetation status change matrix (overall average). The grey curve represents the conversion rate (ha) of the protected area.

3.4 Analysis of the Spatio-Temporal Dynamics of Land Use and Land Cover

The analysis of forest dynamics considered the forested areas of each rural municipality, both within and outside the Menabe Antimena Protected Area. The results show that forest patch density at the different sites ranged from 0.20–0.70 patches/ha in 2017 to 0.25–1.25 patches/ha in 2022. In 2022, the protected area exhibited a markedly higher patch density of 3.92 patches/ha compared with 2.32 patches/ha in 2017. These values correspond to mean patch densities of 0.65 patches/ha in 2022 and 0.39 patches/ha in 2017, respectively. The forested areas of the rural municipalities of Tsarahotana and Antsoha displayed particularly high patch densities, although they were also highly fragmented. Using a paired Student's t-test to compare forest patch densities at time t_1 (2017) and time t_2 (2022), no statistically significant difference was detected between the patch densities recorded in 2017 and those observed in 2022 across all study sites ($t(5) = -2.36$; $p = 0.065 > 0.05$).

The forest landscape, both within and outside the protected area, exhibited a high degree of fragmentation. It was dominated by micro-fragments of forest measuring less than 20 ha, comprising 16,197 forest patches within the protected area (98.86%) and 11,607 forest patches within the protected area's buffer zone (99.08%) in 2017. This pattern of forest subdivision observed in 2017 was also detected in 2022, with an increase of 0.32% within Menabe Antimena (20,622 forest patches of less than 20 ha, representing 99.18%) and an increase of 0.22% in the municipalities located outside the protected area (12,226 forest patches of less than 20 ha, representing 99.30%).

Analysis of variance (ANOVA) revealed a highly significant difference in the number of forest fragments among fragment-size classes (one-way ANOVA: $F = 52.43$; $p = 0.00001 < 0.05$). By contrast, the analysis detected no significant effect of location (inside versus outside the protected area) on the number of fragments ($F = 0.223$; $p = 0.647 > 0.05$). Likewise, the temporal factor showed no significant difference in fragment numbers between 2017 and 2022 ($F = 0.032$; $p = 0.862 > 0.05$) (Figure 4).

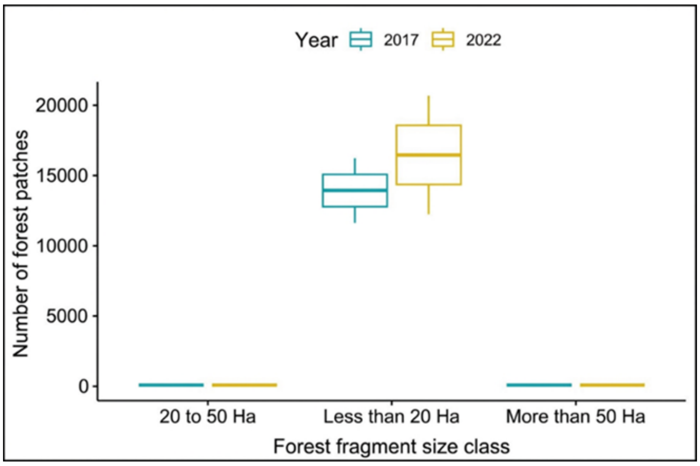


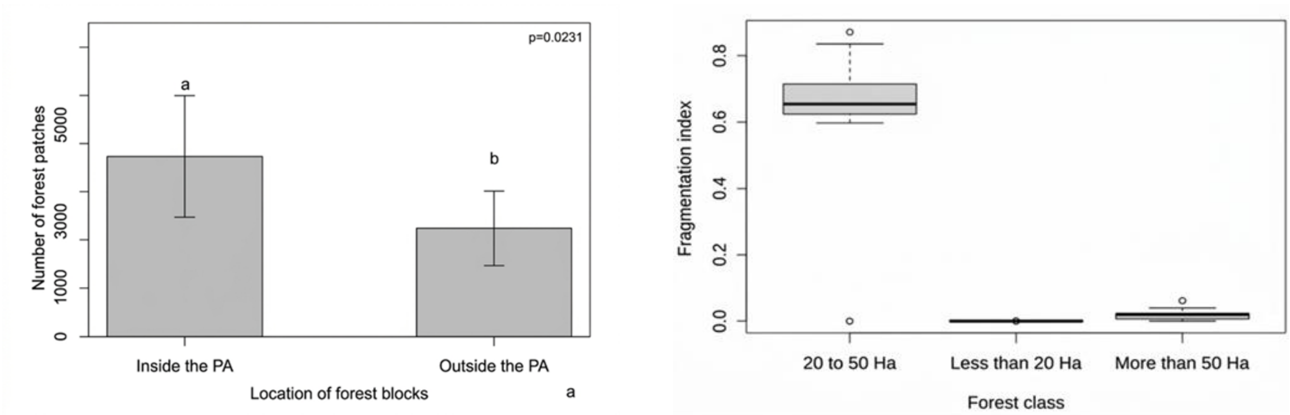
FIGURE 4: Relationship between the number of forest patches and the fragment size class in 2017 and 2022

3.5 Dynamics of Forest Landscape Fragmentation in Menabe Antimena

Forest fragmentation dynamics over the period 2017–2022 revealed a generalised increase across the study area. The results indicate that 2022 marked the highest level of landscape fragmentation throughout the study period. Within the protected area, the number of forest fragments increased by 13.94%, rising from 18,251 to 20,796 fragments. Although the surrounding areas remained overall less fragmented, the rate of increase was considerably higher, reaching 25.05%, with the number of fragments increasing from 9,943 to 12,434 (Fig. 5a).

The analysis of variance revealed significant differences in fragmentation indices among forest size classes across the entire study area (ANOVA: $F(2,57) = 148.8$; $p < 0.001$). Between 2017 and 2022, forests ranging from 20 to 50 ha exhibited the highest fragmentation index (0.60–0.87), both within and outside the protected area (Fig. 5b).

These findings demonstrate that forest fragmentation was generally more pronounced within the protected area than in the surrounding landscape. The local population, composed predominantly of migrants, increasingly expanded agricultural land into forested areas, thereby exerting considerable pressure on the protected area and accelerating the process of forest fragmentation.



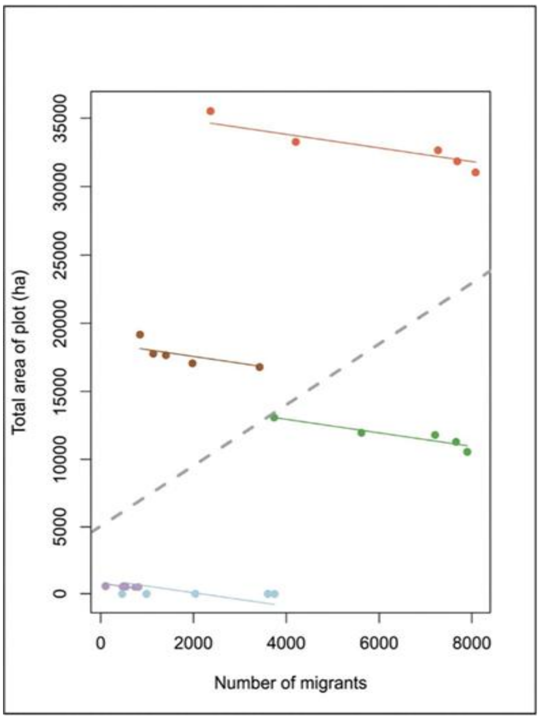
(a) **(b)**

FIGURE 5: Classification of fragmentation across the study sites. (a) According to patch location and (b) According to fragment class.

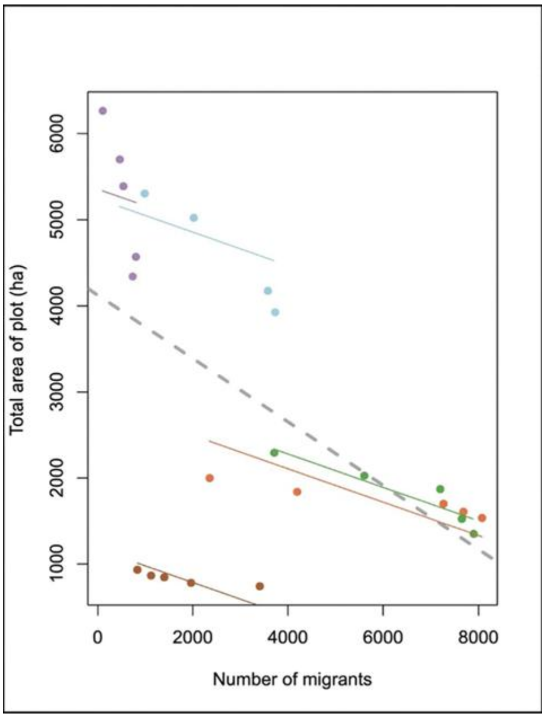
When expressed relative to the area of each municipality, the rural municipality of Marofandilia, located within the protected area, exhibited the highest fragmentation rate, with 8,968 forest fragments distributed across 65,765.53 ha in 2022. It was followed by the rural municipality of Beroboka Nord, which recorded 6,143 forest fragments over an area of 55,374.13 ha during the same year. Across all study sites, forest patch subdivision intensified steadily between 2017 and 2022. Analysis of this temporal trend indicates that the rate of fragmentation remained relatively homogeneous among the different study sites.

3.6 Effects of Migration on Forest Fragment Configuration

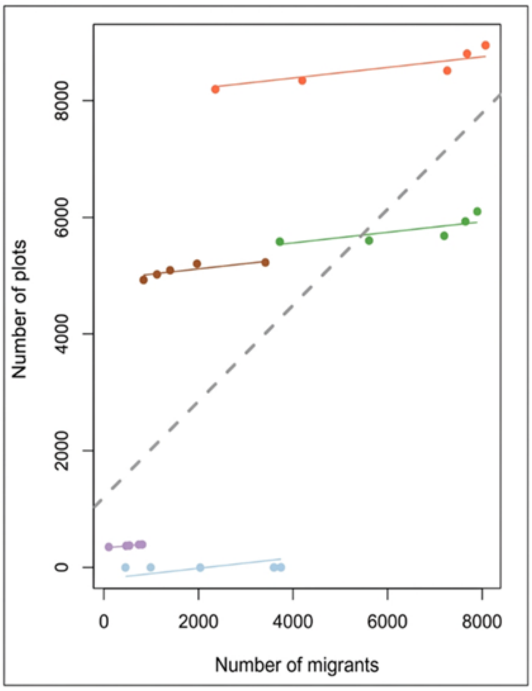
The overall trend reveals a direct relationship between demographic dynamics and the quantitative and spatial configuration of forest cover. The increase in the number of migrants across the rural municipalities of Menabe Antimena was accompanied by a substantial increase in the number of forest fragments and a concomitant reduction in forest area. For forest patches located within the protected area, repeated-measures correlation analysis between the number of migrants and the number of forest patches over the period 2018–2022 revealed a strong, positive and statistically significant relationship ($r = 0.79$; 95% CI: 0.55–0.91; $p < 0.001$) (Fig. 6c). A moderate but statistically significant positive correlation was also observed for the portions of the study area located outside the protected area ($r = 0.53$; 95% CI: 0.12–0.78; $p = 0.014$) (Fig. 6d). By contrast, a strong and statistically significant negative correlation was observed between forest area and the number of migrants in the municipalities located within the protected area ($r = -0.83$; 95% CI: −0.93 to −0.61; $p < 0.001$) (Fig. 6a). For municipalities located outside the protected area, a moderate inverse correlation was likewise found between forest area and migrant influx, and this relationship was statistically significant ($r = -0.59$; 95% CI: −0.81 to −0.21; $p = 0.005$) (Fig. 6b). Overall, these results indicate a significant inverse relationship whereby the increase in the number of forest fragments is associated with a reduction in forest area across the municipalities of the protected area. This process promotes the expansion of forest clearings and increases the prevalence of edge effects within Menabe Antimena. Consequently, land cover within the protected area is now dominated by non-forest formations, including those locally referred to as "Monkas".



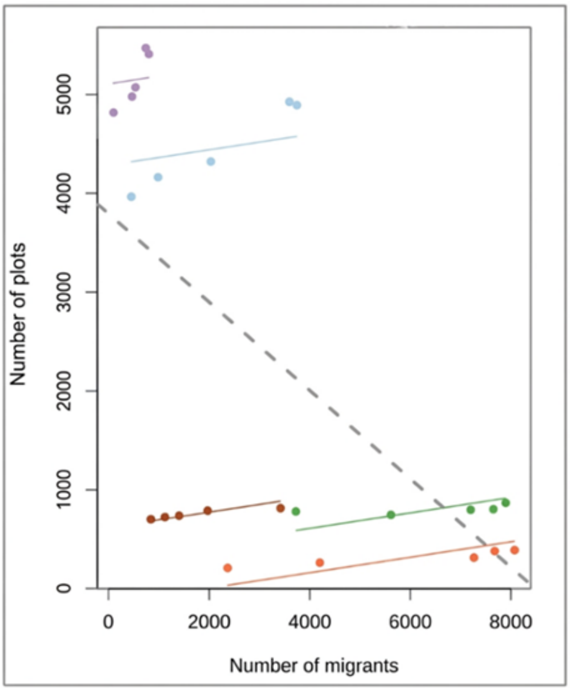
(a)



(b)



(c)



(d)

FIGURE 6: (a-b) Repeated measures correlation between plot area (ha) and the number of migrants from 2018–2022. (c-d) Repeated measures correlation between the number of plots and the number of migrants from 2018–2022. (a) and (c): inside the protected area; (b) and (d): outside the protected area. In colour: the study sites for each year; dashed grey line: overall correlation trend.

The model outputs (Figs. 6a and 6d) reveal a marked reversal in the observed trend when comparing the global and site-specific scales, thereby providing a clear illustration of Simpson's paradox (Bakdash & Marusich, 2017; Kievit et al., 2013; Levick & Rogers, 2011). A combined correlation analysis (grey regression line) misleadingly suggests a negative relationship between forest configuration and increasing migrant numbers ($r = -0.83$ in Fig. 6a and $r = -0.59$ in Fig. 6d). In contrast, the coloured regression lines highlight the dynamics specific to each municipality (site-level scale), demonstrating that both forest fragmentation and changes in forest area consistently progress with increasing migrant settlement. This graphical representation illustrates a typical case of "Simpson's paradox", whereby the initial structural heterogeneity among study sites (site effect) obscures the underlying temporal dynamics. To eliminate this ecological bias, account for inter-municipality variability and accurately estimate the temporal trajectory, a linear mixed-effects model (LMM) was fitted, with study sites included as a random effect to control for spatial heterogeneity. The mixed-effects model confirmed, at the local scale, a positive and highly significant relationship between migrant numbers and the number of forest fragments ($\beta = 0.075$; $z = 2.61$; $p = 0.009$), together with a highly significant negative relationship between migrant numbers and forest area ($\beta = -0.58$; $z = 0.12$; $p < 0.01$).

These estimates therefore confirm a consistent acceleration of forest fragmentation within each municipality, supporting the hypothesis that migrant populations have expanded agricultural activities throughout the study area.

Taken together, these two dynamics reveal a severe process of forest fragmentation and degradation within the Menabe Antimena Protected Area. The reduction in forest area ($\beta = -0.58$), combined with the increasing number of forest fragments ($\beta = 0.075$), results in the disruption of ecological connectivity.

IV. DISCUSSION

4.1 Alarming and Widespread Fragmentation of Menabe Antimena

The results of this study demonstrate a worrying acceleration in the dynamics of forest fragmentation in Menabe Antimena between 2017 and 2022. The annual increase in the number of forest fragments provides direct evidence of an ongoing process of forest subdivision, resulting in a critical loss of the protected area's ecological connectivity (Zou et al., 2025; Rafanoharana et al., 2024). Furthermore, within the protected area itself, this trend is reflected in the emergence of 2,545 new forest patches (representing 14%) over a five-year period. It has been demonstrated that more than 50% of the world's protected areas experienced an intensification of internal anthropogenic pressure between 2000 and 2020, characterised by increased housing construction and the expansion of agricultural land. This phenomenon is strongly correlated with increased internal fragmentation of protected areas (Zhang et al., 2026). This observation confirms, at the local scale, the macro-temporal analyses reported by Andrianambinina et al. (2025) at the scale of Madagascar, highlighting the acceleration of deforestation within the national protected area network itself. In tropical forest regions, these findings are often explained by increasing internal anthropogenic pressures, such as subsistence logging and slash-and-burn agriculture. These observations are consistent with the conclusions of Hending et al. (2023) regarding the dynamics of forest degradation in Madagascar, as well as with the work of Fitz et al. (2022). The latter demonstrate that protected area status does not preclude internal anthropogenic pressures; under the combined effects of population growth and the lack of socio-economic alternatives, local communities continue to engage in agricultural activities and illegal logging, thereby intensifying internal forest fragmentation.

The analysis of fragmentation indices by forest size class reveals that forest blocks ranging from 20 to 50 ha exhibit the highest level of degradation (0.60 to 0.87). This finding indicates that this forest class is undergoing severe landscape fragmentation because, geographically, it is more accessible to neighbouring communities and provides sufficient area to make the establishment of an agricultural frontier economically viable. These forest edges are subject to severe microclimatic changes, which accelerate the mortality of mature trees and promote the encroachment of peripheral bushfires (Hansen et al., 2020).

Consequently, the temporal dynamics of fragmentation observed between 2017 and 2022 demonstrate the current inability of the protected area to maintain the integrity of its ecological functions, thereby posing a direct threat to the water, food, and economic security of neighbouring communities (Jaroensutasinee et al., 2024).

4.2 Diffuse Anthropogenic Transformation of the Forest Landscape

A clear trend towards widespread forest fragmentation has been demonstrated across the study sites. This is reflected in the increasing density of forest patches. This increase indicates that the forest landscape is being divided into smaller and more numerous units throughout the protected area in a spatially homogeneous and temporally consistent manner. An analysis of the current fragmentation trend reveals that the forest is undergoing a rapid forest transition phase, with the landscape now being almost entirely dominated by small forest blocks of less than 20 ha, both inside and outside the protected area. Human activities lead to the anthropogenic transformation of the landscape, in which artificial features become dominant and natural patch types are frequently reduced to a dispersed pattern (Bogaert and Mahamane, 2005). The drivers of fragmentation are therefore associated with population pressure and demographic growth, land subdivision, a low land-to-labour ratio, and traditional agricultural practices (Aslam and Fazal, 2025). This study therefore highlights the statistical significance of the migration variable. The positive association between migration and forest fragmentation indicates that an increase in one is accompanied by an increase in the other.

Such a predominance of small fragments increases edge effects, making the forest more vulnerable to anthropogenic pressures. Furthermore, the fact that the advanced degree of forest fragmentation is observed both inside and outside the protected area, with no significant difference between them, demonstrates that the current protection status is struggling to curb fragmentation despite the various management actions already undertaken. The Category V protected area designation does not alleviate demographic pressure because local populations remain dependent on agricultural activities for their livelihoods.

4.3 Towards an Irreversible Tipping Point in the Intentional Transformation of Forests under Migratory Pressure

Protected status generally reduces forest fragmentation by 82% following designation as a protected area (Zou et al., 2025). Despite its conservation status as an IUCN Category V protected area, Menabe Antimena has experienced intense and continuous fragmentation, reaching its highest level in 2022 with more than 20,000 forest fragments recorded both within the protected area and throughout its surrounding green belt. Category V permits interaction between people and nature within a protected landscape. In the case of Menabe Antimena, this designation has been interpreted as providing an opportunity for agricultural expansion. The implementation of non-participatory conservation policies, characterised by the absence of local community involvement, creates significant imbalances between the local population and its ecosystem. This model generates a sense of exclusion among local communities, fuelling land-use conflicts that are manifested through the excessive and illegal exploitation of natural resources. This finding has been confirmed by Bwalya Umar and Kapembwa (2020) and Aubert et al. (2013), who argued that when local communities are denied access to the resources essential for their livelihoods, they resort to illegal resource exploitation and disregard the boundaries of protected areas as a strategy for economic survival.

A study by Zou et al. (2025) reported that between 58% and 80% of tropical forests became more fragmented between 2000 and 2020. Given the high level of fragmentation within the protected area, the present study indicates that populations with a strong migratory component specifically target forest blocks located inside the protected area for agricultural activities. Consequently, this fragmentation is not a natural process but an anthropogenic one. Accordingly, Brown and Pearce (2023) stated that forest cover and forest structure were negatively correlated with population size. The continuous increase in the number of forest patches between 2017 and 2022 reflects growing pressure on land resources. During the interviews, migrant respondents emphasised that the principal ecosystem service provided by Menabe Antimena is the provisioning service, namely the availability of fertile agricultural land. However, the organisations involved in managing this protected area recognise only supporting, regulating, and socio-cultural ecosystem services (MEDD, 2022), despite their essential contribution to human well-being (Kalinauskas et al., 2024). For communities living adjacent to classified forests, the immediate priority is access to fertile land and soil nutrient reserves, enhanced by the ash resulting from deforestation, in order to ensure food security. This perception directly contradicts policies aimed at conserving the natural heritage (Levers et al., 2021; Rives, 2006).

This phenomenon is particularly evident in sub-Saharan Africa, where high population densities and the scarcity of agricultural land drive communities to seek new areas for cultivation (Hlovor et al., 2021).

Finally, the rate of fragmentation, considered to be homogeneous across all study sites, particularly in the rural communes of Marofandilia and Beroboka Nord, suggests that the landscape has already moved beyond the stage of isolated forest clearings and has entered an irreversible phase of degradation. The protected area has become largely devoid of forest cover, and extensive closed-canopy forest blocks are now rarely observed. What remains are isolated tree trunks or baobabs that have survived repeated fires, together with forest patches characterised by a highly open canopy. Vast degraded areas, locally known as Monkas, have been converted primarily to groundnut cultivation, while cash crops such as cassava have replaced the emblematic forests of the region. After several production cycles, these lands lose their productivity and are subsequently abandoned by local populations.

At the current rate of fragmentation, the forest within the protected area is increasingly approaching complete conversion into agricultural land and degraded areas. Reversing this trend will require a revision of the zoning scheme together with the strict enforcement of legislation, particularly regarding forest clearance and forest fires, in order to conserve and effectively manage the remaining forest.

4.4 The Hidden Dimension of Forest Degradation

This study highlights a pattern of forest fragmentation that is closely associated with migratory movements, particularly within the protected area. Its protected status has proved insufficient to curb forest landscape fragmentation in the face of increasing migratory pressure.

Despite its protected status, the area is subject to more intense migratory pressure, while its highly fertile soils are more sought after than those in the surrounding peripheral zones. Population influx into the rural communes within the protected area, driven by the search for agricultural land, accelerates the structural fragmentation of large forest blocks. This phenomenon demonstrates the strong positive correlation between direct human pressure and the proliferation of small forest patches. The attractiveness of natural resources may explain the increased migratory pressure (Wittemyer et al., 2008). In both the Amazon and tropical Africa, migratory pressure is likewise concentrated in areas where forests remain best preserved, creating a frontier effect (Hänggli et al., 2023). This process reduces the overall forest area and increases the extent of forest edges, progressively transforming the forest landscape into an anthropogenic environment. This observation appears to be supported by Yuan et al. (2024) and Geldmann et al. (2019), who reported that fragmentation is a far more severe issue, affecting 34% of the world's protected areas, and is often regarded as the earliest sign of degradation in tropical ecosystems, even before the complete loss of forest cover. The profound deterioration in habitat quality and the dominance of non-forest areas within the protected area call into question the actual effectiveness of its protection status in the face of persistent anthropogenic pressure.

In light of these findings, the strict conservation model currently applied to the management of the protected area demonstrates its limitations. Strengthening local governance and transferring management responsibilities to local stakeholders, with a view to promoting local economic development, are therefore essential. In this respect, Berenger and Morrissey (2022) demonstrated that, in the Maya Biosphere Reserve in Guatemala, the allocation of sustainable forest concessions to local communities enabled deforestation rates to be reduced to almost zero. Following this model, the development of ecotourism or sustainable forestry value chains in Menabe Antimena could transform local communities, and potentially migrants who have settled permanently in the rural communes of the protected area, into active participants in forest monitoring, by making the forest more economically valuable than slash-and-burn agriculture (tavy or hatsake). Despite the major operational constraints faced by the community-based management organisations already established in Menabe Antimena and throughout Madagascar, scientific studies (Zapata et al., 2026; Kyaw et al., 2024; Laudari et al., 2024) confirm the long-term effectiveness of this decentralised approach in sustainably reversing the trend of structural fragmentation and ensuring the long-term conservation of this landscape, which is characteristic of western Madagascar.

V. CONCLUSION

This study has demonstrated that the anthropogenic footprint associated with migration is a key driver of the regressive spatial and temporal evolution of forest cover within the Menabe Antimena Protected Area. Assessing forest quality represents an essential complement to the quantitative analysis of forest cover. As highly sensitive ecosystems, tropical dry forests respond to anthropogenic pressures through irreversible landscape transformation. This qualitative approach makes it possible to map and quantify the degree of forest degradation while anticipating their trajectories of conversion into non-forest landscapes. Furthermore, it enhances landscape transition modelling in Madagascar by incorporating national demographic drivers. By integrating spatial analysis with demographic data, this study proposes a reproducible methodological framework for quantifying and mapping the vulnerability of other protected areas across Madagascar that are exposed to similar pressures, such as the Ankarafantsika National Park (Muttenzer, 2012; Brou, 2018). This assessment provides a significant contribution to the redesign of national conservation strategies by demonstrating the necessity of integrating internal demographic dynamics into protected area management plans.

The strong correlation between the large-scale arrival of migrants, the proliferation of forest patches resulting from the expansion of anthropogenic landscapes, and land speculation provides compelling evidence of profound changes in both land use and the forest structure of Menabe Antimena. Reversing this trend and stabilising forest cover represent both a humanitarian and an ecological challenge for policymakers and protected area managers alike. It is crucial to address the underlying drivers of migration by reconciling climate resilience with the development of economic opportunities in migrants' areas of origin. Further research should be undertaken to improve the predictive modelling of these landscape dynamics in order, on the one hand, to provide decision-makers with early warning tools and, on the other hand, to integrate socio-demographic data into protected area planning and management strategies. Incorporating these internal migratory dynamics into environmental governance constitutes an essential strategic lever for addressing the biodiversity crisis, while placing Madagascar on a trajectory towards achieving the equity and ecological performance objectives established under the Kunming–Montreal Global Biodiversity Framework by 2030.

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CONFLICT OF INTEREST

The authors of this manuscript declare that they have no conflicts of interest.

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