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Analyzing Drivers of Tropical Moist Forest Dynamics in the Kahuzi-Biega National Park Landscape, Eastern Democratic Republic of Congo from 1990 to 2022

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Abstract: The protected areas (PA) of the Democratic Republic of the Congo serve as vital carbon reservoirs and are crucial for biodiversity conservation and climate regulation. Despite their significance, these areas face escalating rates of deforestation and degradation, often poorly understood at the local level. This study focuses on the dynamics of tropical moist forest (TMF) and the relative importance of the driving factors in the landscape of Kahuzi-Biega National Park (KBNP), one of the country's prominent PAs. Analyzing annual TMF dynamics from 1990 to 2022 using data classified by Vancutsem and his collaborators in 2021 from Landsat imagery alongside spatial datasets of deforestation and degradation drivers, we employed a comprehensive analytical approach. This included meshing, multi-scale analysis, principal component analysis, zoning, multiple linear regression, and relative importance analysis through bootstrapping. The findings indicate that the grid size considered does not significantly influence TMF dynamics in the KBNP landscape (p-value = 0.67, α = 0.05). The edge and outer zones experienced substantial dynamics, with approximately 30% forest cover loss in both areas, contrasting with the relatively stable TMF cover (~100%) in the inner zone. Fire emerged as the most influential driver, explaining TMF dynamics with a relative importance of approximately 55%, 30%, and 23% in the inner, edge, and outer zones, respectively. This study underscores KBNP's efficacy in curbing TMF loss but highlights the need for enhanced protection around its periphery. Management efforts should prioritize sustainable land use practices, livelihood improvement, and the establishment of an officially recognized buffer zone.

Keywords: tropical moist forest; deforestation; degradation; protected area; natural resource management and Kahuzi-Biega National Park

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1. Introduction

Home to more than 60% of the Congo Basin's forests [1–3], the Democratic Republic of the Congo (DRC) contains 99 million hectares of dense moist forest, with around 63 million hectares of intact forest landscapes [4,5]. These forests hold significant ecological integrity and biodiversity and play an important role in the provision of global ecosystem services, including regulation of the climate and water cycle, carbon sequestration, and biodiversity conservation [6–8]. Despite their global importance, the DRC's forests face numerous pressures, including climate change, anthropogenic pressures, and other combined factors [9,10]. Since 2001, the DRC has lost over one million hectares of forest cover annually [9], including 450,000 hectares of primary forest [2,6], mainly due to forest clearance by smallholders for agriculture and charcoal production [9,11,12]. They often move into forests to escape conflict and insecurity [13–15].

The DRC's terrestrial protected areas (PAs) cover around 324,289.7 km^2 (approximately 13.8% of the country's territory) [16,17] and are crucial for conserving tropical biodiversity and mitigating climate change by reducing deforestation and degradation [18–23]. Despite their importance, protected areas face intense anthropogenic pressures, [16,20,24] which are compounded by high population density (exceeding 100 inhabitants per km^2) in the eastern region [6,22] and widespread poverty (human development index of 0.479 [25]). The Kahuzi-Biega National Park (KBNP), one of the most important PAs for the conservation of Grauer's gorilla (*Gorilla beringei graueri*) in the DRC, faces severe threats primarily due to insecurity, which impedes the conservation and restoration of its integrity [26–28].

Straddling the Albertine Rift and the Congo Basin, the KBNP covers around 6700 km^2 of tropical forest, ranging from carbon-rich Afromontane forests to mid-altitude equatorial rainforests [26]. It is the second most important site in the Albertine Rift in terms of species richness, endemism, and threatened species [26,29–31]. The park is renowned for its extensive tracts of primary and secondary forest, with about 60% of the total area comprising intact forest landscapes with high ecological integrity [32]. These forests host a vast array of flora and fauna, with thousands of species documented [29,33,34]. Despite its importance, the KBNP is one of the DRC PAs where forest losses and degradation are severe [29,33].

The KBNP is in one of the DRC's most densely populated regions, with a population density of about 400 inhabitants per km^2, much higher than the national average [35]. The park faces significant challenges from human activities, such as bushmeat hunting, firewood collection, charcoal production, bushfires, and the establishment of villages in and around the park. Additional threats include encroachment from agriculture, mining operations, and the spread of the invasive vine *Sericostachys scandens* [28–30]. Lacking an officially recognized buffer zone, the PNKB shares its borders directly with villages where all kinds of activities take place, making it more vulnerable to anthropogenic threats [36]. Although the KBNP was inscribed on the UNESCO World Heritage List in 1980 under criterion (x), the threats have increased, particularly after the mass eviction of people from the park during its enlargement in 1975 and the civil wars of 1996–1997 and 1998–2003, leading to conflicts over land between indigenous Pygmy peoples and local communities [37,38]. Consequently, KBNP has been on the UNESCO list of World Heritage in Danger since 1997 [26,39,40].

Analyzing the impact of human activities on the park's forest dynamics and conservation status is crucial for understanding and guiding conservation efforts in this protected area, whose importance is recognized worldwide. To answer this question, we used remote sensing data and approaches. Remote sensing is recognized as an essential tool for monitoring tropical rainforest ecosystems, which are often inaccessible and large-scale [41,42]. This study uses Landsat archives, machine learning tools, and satellite image processing to analyze the KBNP landscape from 1990 to 2022. This analysis supports conservation efforts in the DRC, offering insights into deforestation and degradation (DFD) to ensure the long-term survival of Kahuzi-Biega's intact forest. Previous studies have highlighted drivers of DFD in the DRC without focusing on protected areas [11,13,43], while global studies using remote sensing have examined general threats to protected areas [44–46]. Local analyses are necessary to understand the specific issues of forest loss in the context of each protected area.

This study hypothesizes that Kahuzi-Biega National Park, a Category II protected area (as defined by the UICN and national categorization) [47], experiences a lower rate of tropical moist forest (TMF) loss compared to its unprotected surroundings. Without well-defined buffer zones [40], the park faces increasing centripetal pressures. The inner zone is less exposed to forest loss than the peripheral and outer zones, which are more vulnerable. Several studies have shown that protected areas, despite various pressures, play a significant role in mitigating DFD compared to unprotected surroundings [14,22,48]. Fire, used for agriculture, charcoal production, hunting, and savannah regeneration, is expected to be the main driver of TMF loss in the KBNP landscape [49–51]. In this study, we define a driver as any human activity that directly affects TMF cover and biomass [52–54]. As supported by Ref. [52], the term driver is more appropriate as an adjunct to discuss factors that are typical causes of land or environmental change, where there is evidence of a causal relationship, but not enough to establish causal effects and explain the causal mechanisms of a particular phenomenon. It is used here as a synonym for the direct cause of deforestation and degradation [10,53] of TMF. TMF dynamics here include any TMF disturbance that leads to TMF degradation and/or deforestation [6].

2. Materials and Methods

2.1. Study Area

Covering 6700 km^2 [29,55], KBNP is located in central Africa, eastern DRC, spanning the South Kivu, North Kivu, and Maniema provinces (Figure 1). The park stretches from the Congo River basin near Itebero-Utu to its western border northwest of Bukavu, between 1°36′–2°37′ south latitude and 27°33′–28°46′ east longitude. The KBNP comprises two distinct zones, the high-altitude and the low-altitude regions, connected by a narrow ecological corridor [26,40,56]. The high-altitude zone features an ombrophilous forest, reaching its highest point at Mount Kahuzi (3308 m), and experiences an Afroalpine climate with occasional night frosts on the peaks of Kahuzi and Biega. This region receives an average annual rainfall of up to 1900 mm, with a long dry season from June to August and a short dry season in February. In contrast, the low-altitude zone consists of the Guineo–Congolian ombrophilous forest, located between 700 and 1700 m above sea level. This region enjoys a warm climate during the day and throughout the year, with an annual average temperature of 20.5 °C and very high rainfall [26,40,57]. The park is interspersed with numerous watercourses and is traversed by National Road 2 in the highlands [40].

The KBNP landscape considered includes the park and a 15 km surrounding area, based on research suggesting that protected areas should be studied along with their surroundings for better understanding [44,48,58]. To better analyze the dynamics of TMF in the KBNP landscape, the landscape was subdivided into three main zones: the inner zone (consisting of the inner of the park minus the buffer zone), an edge zone (including an inner buffer and outer buffer with a total width of 10 km), and the outer zone (located outside the KBNP and the buffer zone. The width of the edge zone was determined based on the literature [36,59] estimating how far communities can travel in search of forest products (timber and non-timber).

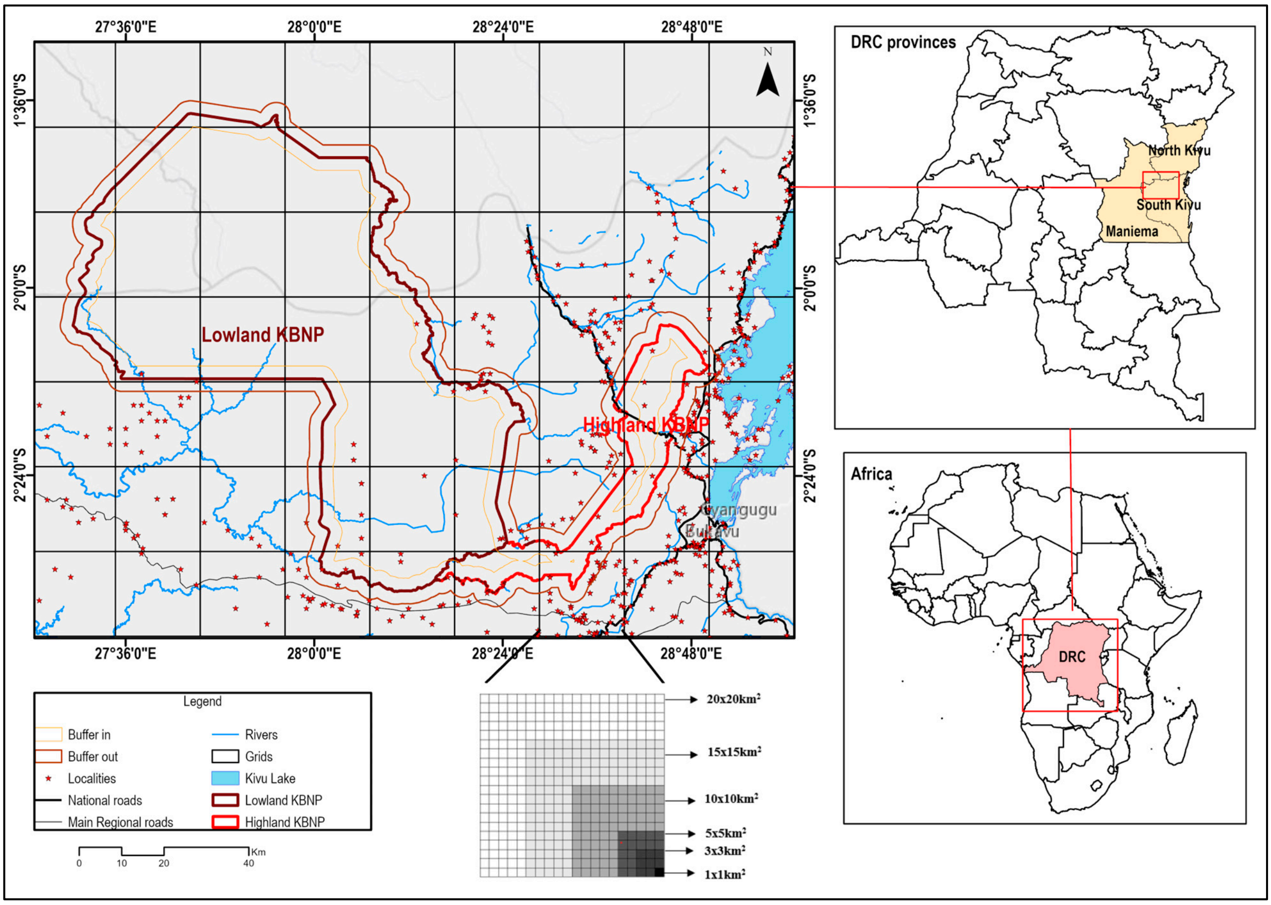

Figure 1. Study area. Landscape of the Kahuzi-Biega National Park (KBNP) with a 15 km outer zone. The park is located in central Africa, eastern Democratic Republic of Congo (DRC) between three provinces (North Kivu, South Kivu, and Maniema).

2.2. Dataset

The data analyzed were obtained from several sources (Appendix A.1). The tropical moist forest data provided by Vancutsem et al. [6] were used as the response variable and relevant deforestation/degradation factors, referred to here as drivers, as explanatory variables. The drivers considered (Appendix A.2) in the models were selected based on the literature on the main drivers of forest disturbance in the Congo Basin [11,13,60,61] and locally [29,30,62,63], but also on the availability of spatial data. The data set lacks consideration of factors such as logging activities, as well as the underlying causes of deforestation and degradation as described by Ref. [53].

2.3. Data Analysis

2.3.1. Image Quality and Adaptability Assessment

Following the acquisition, extraction, and preprocessing (Appendix A.1) of annual classified images from Ref. [6] and covering 1990 to 2022, we tested their effectiveness in analyzing TMF dynamics in Kahuzi-Biega National Park landscape. The images were chosen for their annual availability, quality (free cloud), high estimate accuracy (91.40%) [6], and high similarity rate (91.28%) with a Landsat 8 OLI/TIRS surface reflectance (2021) image classified using Google Earth Engine and the methodology proposed by Ref. [64]. Appendix A.3 shows the results of the similarity test between the two images. This test involved extracting differences between the two images and assessing their ratio to the total surface area using the Raster Calculator and Field Calculator tools in ArcMap 10.8.1.

2.3.2. Model and Variable Selection

The selection of the model and variables was carried out through the following steps:

- Deforestation quantification: To assesses the impact of spatial grain selection on TMF dynamics, we quantified deforestation in square grids of varying sizes (1 km^2, 9 km^2, 25 km^2, 100 km^2, 225 km^2, and 400 km^2) as tested by Ref. [65]. Given the study area size, we focused on the smallest grid sizes (1 km^2, 9 km^2, 25 km^2).
- Variable selection: Considering the various grid sizes retained, a selection of variables was made. The variable selection reduced the original set of variables based on Pearson correlation tests and principal component analyses (PCA) using, respectively, corrplot [66] and FactoMineR [67] packages in R 4.2.2. For the PCA analysis, eigenvalues and eigenvectors were computed to identify principal components and a correlation circle was used to visualize relationships. When two variables were highly correlated (r > 85%) and formed an acute angle on the correlation circle, the variable with the highest expression (high cos2) rate was selected.
- Model testing and scale selection: After testing models at different scales, one scale was chosen to analyze the zoning effects on our landscape. The choice was guided by Ref. [68]'s principle of fine scales for local disturbances and the model's ability to explain most variables used [69]. The analysis of variance (ANOVA) also helped to detect the differences between models and different scales.
- Analysis of zoning effects on TMF dynamics: To better understand the dynamics of TMF in the Kahuzi-Biega National Park landscape, three groups of grids were considered for the three previously defined zones: inner grids, edge grids, and outer grids. Grids located entirely within the park (excluding the buffer zone) were classified as inner grids. Grids that were entirely or predominantly within the buffer zone were classified as edge grids, while those located outside both the buffer zone and the park were classified as outer grids. At this step, the variable selection was performed again for the different zones using the same methodology described above.

2.3.3. Model Construction

The model construction involved several steps:

- Model development: At the first level, we developed TMF dynamics models across selected spatial scales using multiple linear regressions. The formula used for the multiple linear regression model is provided in Equation (1):

$$Y = \beta_0 + \beta_1 X_1 + \beta_1 X_1 + \ldots + \beta_n X_n + \epsilon \quad (1)$$

where

Y is the dependent variable (Δf),
$X_1, X_2, \ldots, X_n$ are the independent variables (predictors),
$\beta_0, \beta_1, \ldots, \beta_n$ are the coefficients,
and ϵ is the error term.

- Model validity assessment: The normality tests for residuals [70] and Durbin–Watson tests for autocorrelations [71] were used to assess the model validity. Equation (2) describes the Durbin–Watson test statistic formula:

$$DW = \frac{\sum_{t=2}^{T} (e_t - e_{t-1})^2}{\sum_{t=1}^{T} e_t^2} \quad (2)$$

where e_t is the residual at time t.

- Analysis of Variance (ANOVA): We determined scale-dependent TMF variation based on studied parameters. All variables were centered and normalized to assess their individual impacts. The results were visualized using dot–whisker plots [72]. The normalization formula used is presented in Equation (3).

$$Z = \frac{X - \mu}{\sigma} \tag{3}$$

where

X is the original value,
μ is the mean,
and σ is the standard deviation.

- Zoning and Relative important analysis: Once the optimal scale for KBNP TMF dynamics was established, we analyzed different predefined zones. Initially, we computed TMF variation statistics across all years (1990–2022) and developed multiple linear regression models for the variation of TMF (Δf) as per earlier methods. The relative importance analysis (Equation (4)) was conducted using Lindemann, Merenda, and Gold's method (lmg) with bootstrapping to estimate variability [73] by employing the relaimpo package in R 4.2.2.

$$lmg(X_j) = \sum_{S \subseteq \{X_1, \ldots, X_p\} \setminus \{X_j\}} \frac{|S|!(p-|S|-1)!}{p!} \left(R^2(S \cup \{X_J\}) - R^2(S)\right) \tag{4}$$

where

X_j is the variable of interest,
S is a subset of predictors,
R^2 is the coefficient of determination,
and p is the total number of predictors.

Figure 2 depicts the methodological workflow.

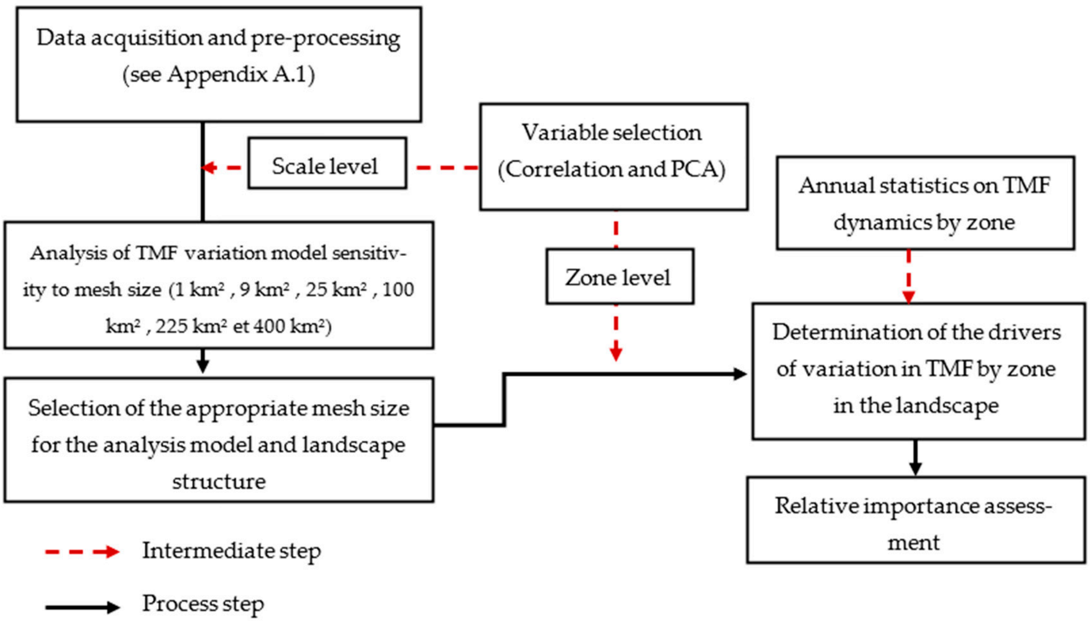

Figure 2. Methodology workflow used to assess tropical moist forest loss and quantify the contribution of factors explaining this loss in the landscape of Kahuzi-Biega National Park, eastern Democratic Republic of Congo, from 1990 to 2022.

3. Results

3.1. Analysis of Model Sensitivity to Mesh Size

Figure 3 and Appendix A.4 depict variable relationships in the model for moist forest variation in KBNP. While the first two principal components explain < 75% variance, correlation circles show relationships between original variables and components. Relationships were tested across scales (1 km^2 (a), 9 km^2 (b), 25 km^2 (c), 100 km^2 (d), 225 km^2 (e), and 400 km^2 (f)). Variables like Euclidean distance to roads and rivers are highly correlated across scales. However, rivers' Euclidean distances were not considered due to low Cos2 compared to roads. This information is assumed to be included in the latter. Other variables show scale-dependent relationships significant for model construction.

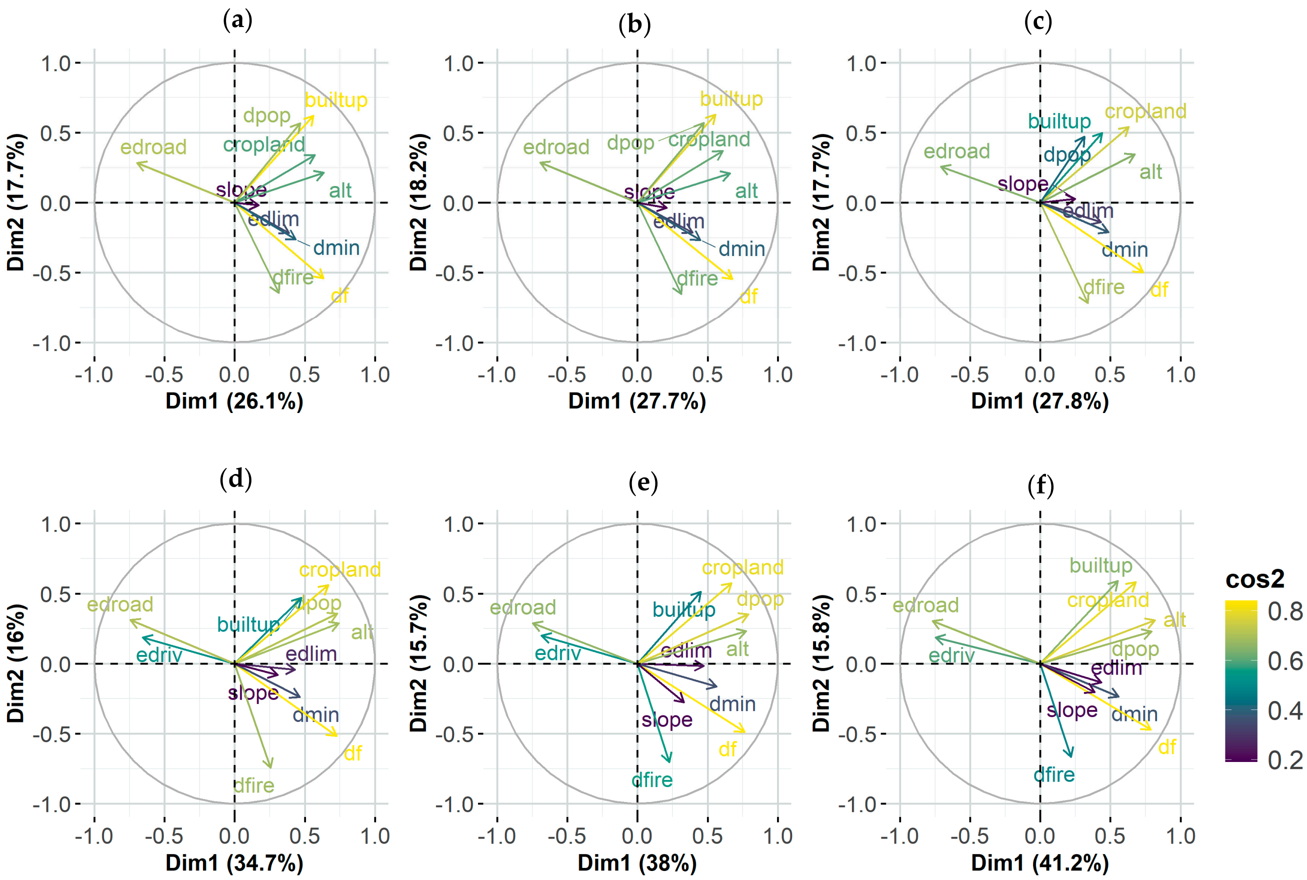

Figure 3. Correlation circles from different grid sizes (1 km^2 (**a**), 9 km^2 (**b**), 25 km^2 (**c**), 100 km^2 (**d**), 225 km^2 (**e**), and 400 km^2 (**f**)) tested for assessing tropical moist forest dynamic (df) as a function of the factors analyzed, including, edroad: Euclidean distance to roads, edriv: Euclidean distance to rivers, cropland: cropland area, builtup: built-up density, dpop: population density, edlim: Euclidean distance to limits, dmin: mining site densisty, df: TMF loss, dfire: fire.

Figure 4 displays standardized estimate coefficients (β) with standard errors on the *x*-axis and predictors (variables) on the *y*-axis. The results indicate increasing coefficient variance with grid size, and R^2 values rose across models: 0.44, 0.57, 0.62, 0.70, 0.76, and 0.87 for models 1 to 6 (see Appendices A.5 and A.6). However, variance analysis found no significant difference ($p = 0.67$, $\alpha = 0.05$) in grid size impact on TMF variation in KBNP. Therefore, the 25 km^2 grid size was deemed optimal for zoning effect analysis on the landscape.

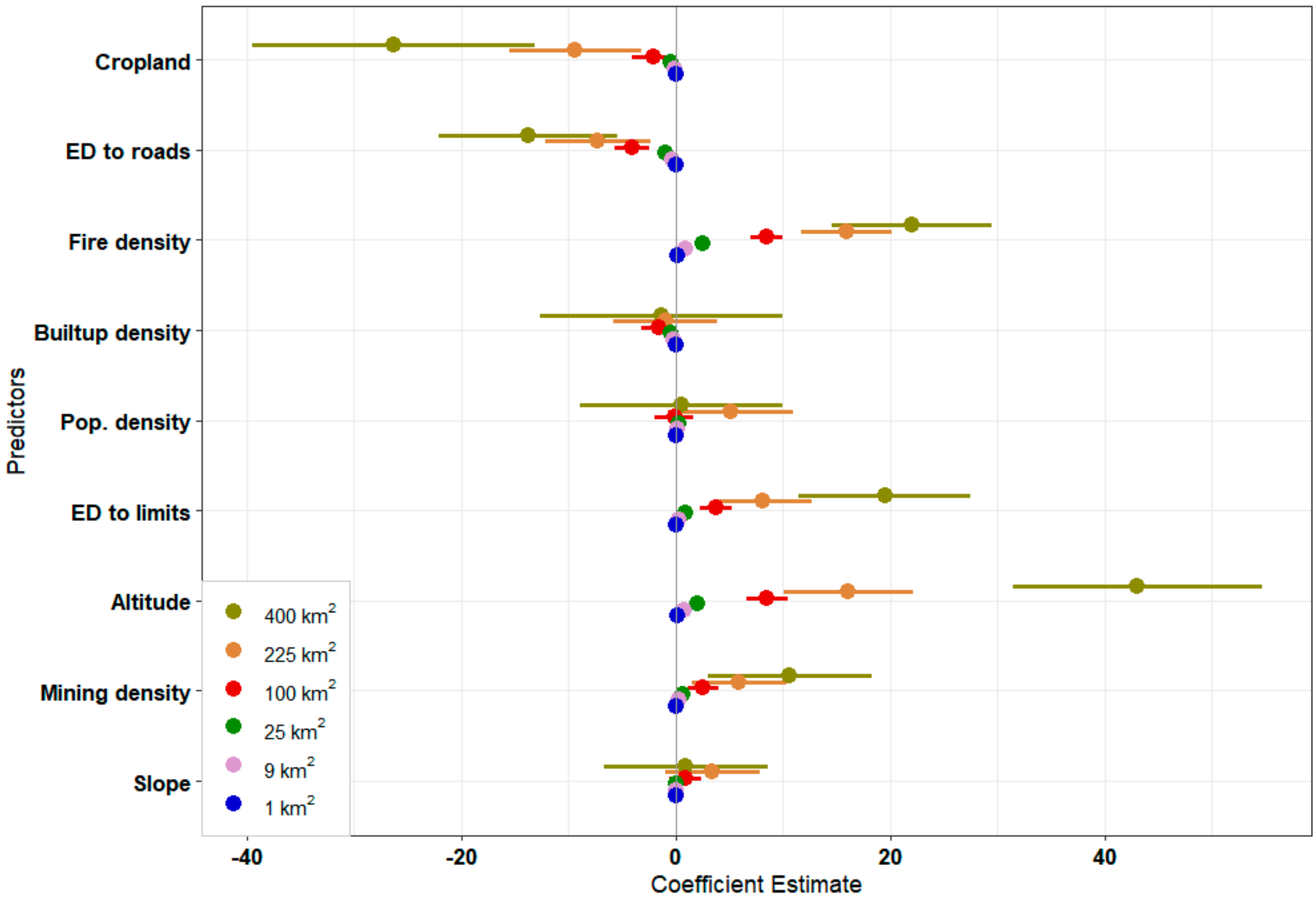

Figure 4. Influence of grid cell size on TMF dynamics. Summary results of the linear regressions carried out to analyze the contribution of the variables studied to the variation in tropical moist forest (df) in the KBNP landscape at different scales (1 km^2, 9 km^2, 25 km^2, 100 km^2, 225 km^2, and 400 km^2) and considering drivers analyzed (cropland, ED to roads: Euclidean distance to roads, fire density, built-up density, pop. density: population density, ED to limits: Euclidean distance to limits, altitude, mining site density, and slope). The points represent the median value associated to the standard error(line).

3.2. *Assessing Zoning Effect on TMF Variation*

Figures 5 and 6 depict the spatial variation of TMF (Δf) and TMF change statistics by sub-zone in KBNP from 1990 to 2022 for the 25 km^2 grid size. The results reveal significant TMF regression in the outer and edge zones compared to the less dynamic inner zone. The median proportion of dense moist forest in inner patches remained stable at around 100% from 1990 to 2022, while in the edge zone, it decreased from approximately 98% to 76%, and in the outer zone, from 98% to about 72% (Figure 6). Figure 6 highlights significant TMF variations, particularly outside the park (losses > 40%) and in the highlands.

The construction of the models was preceded by an evaluation of the relationships between the variables, as shown in Figure 7a–c and Appendix A.7. The results obtained show the existence of strong correlations between variables according to the zone of the KBNP landscape. Upon analysis of the data from each zone, it becomes evident that there is a strong correlation between the variables cultivated area and altitude, as well as the density of built-up areas and fire density, in the inner zone (Figure 7a). Similarly, in the edge zone (Figure 7b), population density is also strongly correlated with built-up density. In the outer zone (Figure 7c), there was also a strong correlation between population density and built-up density, as well as slope and elevation. In constructing the final model for each zone, one of two highly correlated variables, having high $\cos^2$, was considered. The variables excluded were cultivated land and building density for the inner zone, population density for the edge zone, and population density and slope for the outer zone.

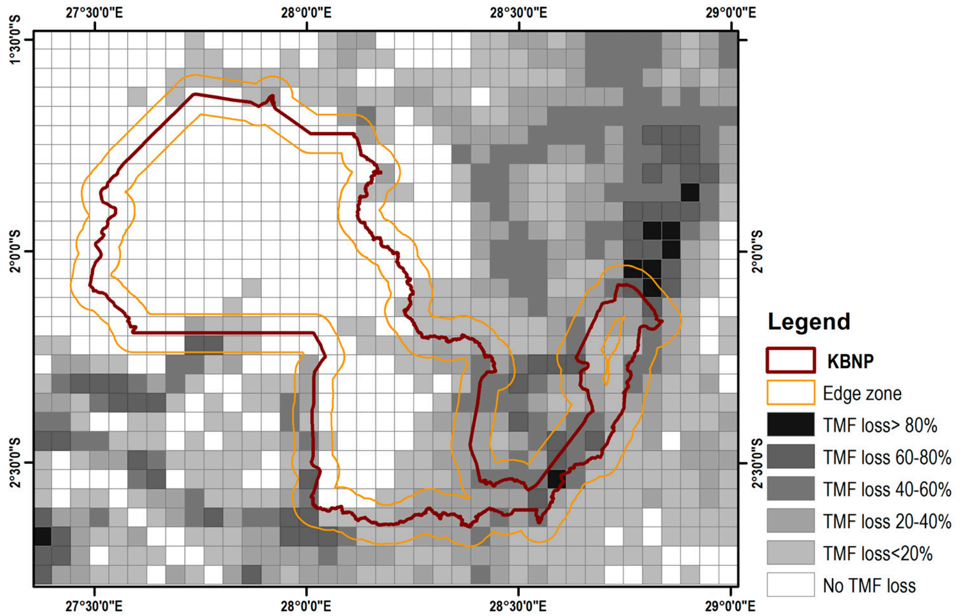

Figure 5. Change in tropical moist forest at 25 km^2 scale from 1990 to 2022 in the considered sub-zones (inner zone, edge zone, and outer zone) of the Kahuzi-Biega National Park landscape.

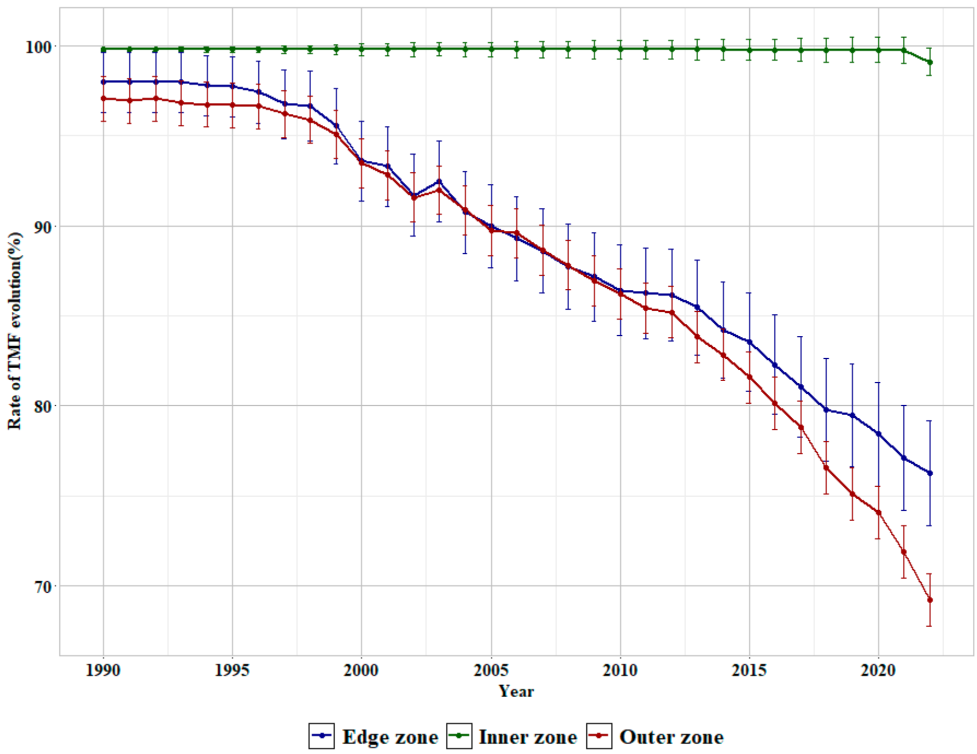

Figure 6. Rate of tropical moist forest (TMF) evolution (median associated to standard errors) from 1990 to 2022 at the scale of 25 km^2 grids in the landscape of the Kahuzi-Biega National Park.

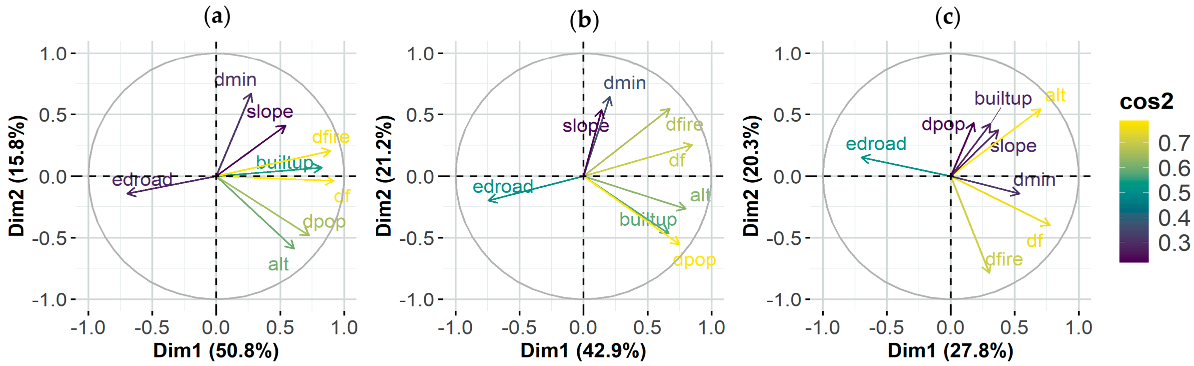

Figure 7. Correlation circles for different sub-zones. (**a**) Inner zone, (**b**) edge zone, and (**c**) outer zone. Legend: edroad: Euclidean distance to roads, cropland: cropland area, builtup: built-up density, dpop: population density, edlim: Euclidean distance to limits, dmin: mining site density, df: TMF loss, dfire: fire density.

The results in Table 1 show the main drivers (predictors) that act differently in the inner, edge, and outer zones. Population density, fire density, and the density of mining sites are the main drivers of forest degradation whether inside, on the edge, or outside the boundaries of the KBNP (p-value < 0.0001). DFD in the edge zone is in turn more influenced by fire density, altitude, and distance from roads (p-value < 0.0001). The expansion of agricultural areas and the density of mining sites also have a significant effect (p-value < 0.05). In the outer zones, the loss of tropical moist forest was strongly influenced by all the drivers analyzed in this study (p-value < 0.0001 for all the drivers analyzed). The different correlation coefficients obtained in the model show a strong correlation between degradation and deforestation and the drivers analyzed in the inner zone (R^2 = 0.87) compared to the other zones, including the edge zone and the outer zone (R^2 of 0.73 and 0.56, respectively), where other drivers not analyzed here may also have a significant impact on the DFD of the tropical moist forest in the KBNP.

Table 1. Multiple linear regression between tropical moist forest loss and the drivers analyzed as a function of the zones making up the landscape of Kahuzi-Biega National Park. Legend: β: Coefficient estimate, t = t value, Pr = p-value, ED: Euclidean distance.

Predictors	**Inner Zone (R^2 = 0.87) (p-Value: <2 × 10^{-16})**			**Edge Zone (R^2 = 0.73) (p-Value: <2 × 10^{-16})**			**Outer Zone (R^2 = 0.56) (p-Value: <2 × 10^{-16})**		
	β	**t**	**Pr (>|t|) (*)**	**β**	**t**	**Pr (>|t|) (*)**	**β**	**t**	**Pr (>|t|) (*)**
Built-up density	-	-	-	−1.38	−1.10	0.27	−0.52	−4.07	**0.00 *****
Cropland area	-	-	-	1.98	2.24	**0.03 ***	−0.56	−3.83	**0.00 *****
ED to roads	0.02	0.27	0.79	−1.10	−3.40	**0.00 *****	−1.24	−7.04	**0.00 *****
Altitude	0.30	1.79	**0.07.**	1.63	5.26	**0.00 *****	2.24	14.14	**<2 × 10^{-16} *****
Fire Density	4.87	24.24	**<2 × 10^{16} *****	2.82	8.15	**0.00 *****	2.46	18.39	**<2 × 10^{-16} *****
Population density	6.72	4.69	**0.00 *****	-	-	-	-	-	
Mining density	−4.90	−3.82	**0.00 *****	1.11	2.05	0.04 *	0.56	4.74	**0.00 *****
Slope	−0.10	−0.65	0.52	−0.69	−1.71	**0.09.**	-	-	-
ED to park limits	-	-	-	5.25	1.19	0.24	0.80	5.49	**0.00 *****

(*) The probability values (Pr) obtained do not consider the existence of spatial autocorrelations. Consequently, they should be treated with caution when interpreting trends. The values in bold showed significant difference. Significance Index (p value≤): «***» 0.001 «**» 0.01 «*» 0.05 «.» 0.1 « » 1.

The assessment of the relative importance of the drivers studied on the variation of tropical moist forest in the KBNP landscape shown in Figure 8a–c indicates that fire is the main driver of deforestation and degradation whether inside, on the fringe, or outside the protected area with a relative importance (RI) of about 55%, 30%, and 23% for the three zones, respectively. In the inner zone, it is followed by population density (~15%), road ED (~9%), and altitude (~7%). The density of mining sites in turn contributes less. In the edge zone, fire density is followed by altitude (~17%), road ED (~15%), and built-up density (~10%). In the outer zone, it is altitude (~12%), road ED (~11%), and mining density (~7%). As one moves away from the protected area, the density of mining sites has an increasing influence on the variation of tropical moist forest in the KBNP landscape.

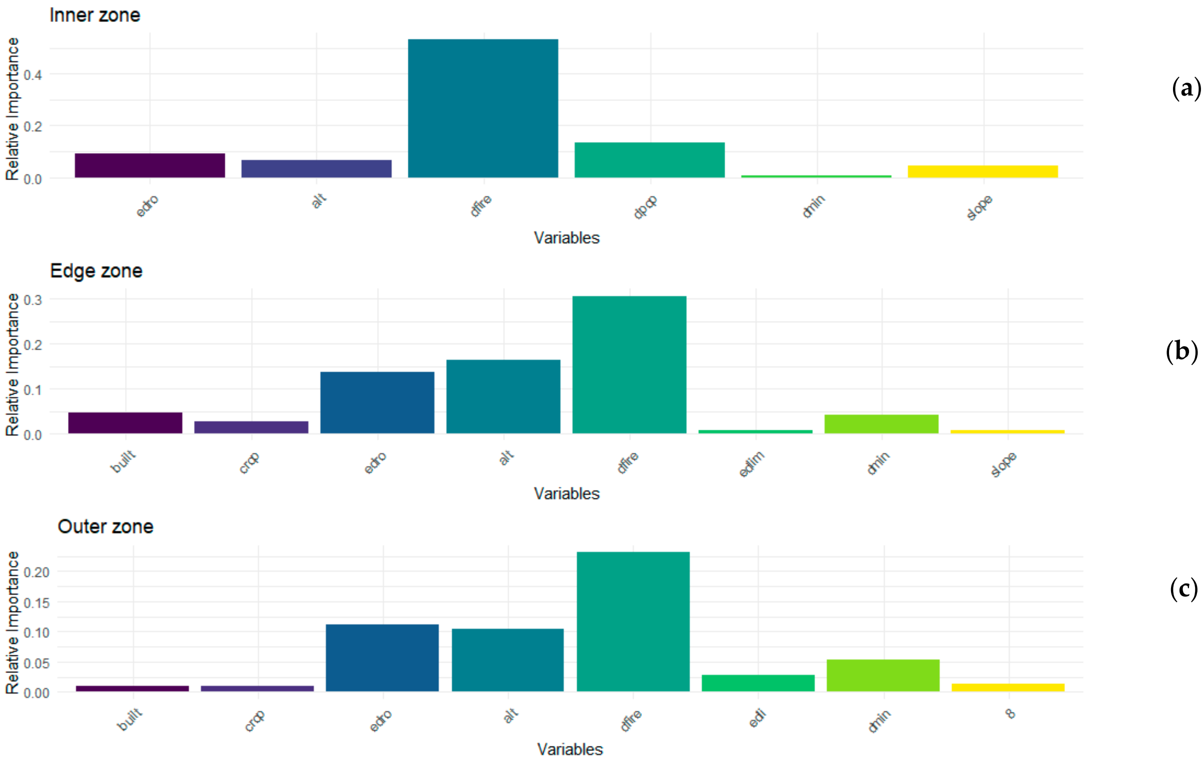

Figure 8. Drivers' relative importance assessment for forest variation with 95% bootstrap confidence intervals with LMG (Lindemann, Merenda, and Gold) method in the Kahuzi-Biega Landscape from 1990 to 2022. (**a**) Inner zone, (**b**) edge zone, and (**c**) outer zone. Legend: built: built-up density, crop: cropland area, edro: Euclidean distance to roads, alt: altitude(elevation), dpop: population density, dfir: fire density, edli: distance to park limits, dmin: mining site density.

4. Discussion

4.1. Data, Methods, and Limits of the Study

Human-induced habitat change profoundly impacts biodiversity, including forest degradation and loss [74]. This study examines tropical moist forest dynamics in the Kahuzi-Biega National Park from 1990 to 2022. The typological methodology used assesses the relative importance of contributing drivers. The IUCN mission in 2017, evaluating the park's UNESCO World Heritage status, noted gaps in forest dynamics and deforestation submissions. This observation prompted further reflection. Indeed, the intact forest block represents the third conservation objective of the park [40], but monitoring has been hindered by persistent cloud cover, especially from 1980 to 2000. Leveraging advancements in remote sensing and machine learning [15,42,64], we sourced global tropical moist forest dynamics data [6]. This dataset distinguishes disturbances over three decades, revealing the extent of undisturbed primary and secondary forests [6]. A 15 km outer zone around KBNP enhances the assessment of park effectiveness in mitigating disturbances, as highlighted by other studies [20,44,75]. The drivers analyzed include global, regional [11,22,60,61,76], and local-scale literature [30,35,38]. We could not use the global data on the human footprint on biodiversity conservation by Venter et al. [61] due to its low spatial resolution (1 km^2), lack of updates, and numerous gaps in the study area. Our analysis includes a broader range of drivers than those considered in Venter et al.'s study, which focused solely on infrastructure, land cover, and human access to natural areas.

The study's primary limitation is the sparse and uneven spatial distribution of available data on the variables analyzed (e.g., population data limited to health zone scales), preventing a comprehensive multi-temporal analysis. To mitigate this challenge, a mesh method for multi-spatial analysis aggregated variables spatially within the landscape [77]. This approach facilitated assessing each variable's contribution and constructing analytical models by statistically comparing values across cells. Adopting a zoning approach, uncommon in such studies, addressed dynamics near boundaries by isolating and treating them separately as an 'edge zone'. This isolation may introduce biases beyond control but likely does not alter overall trends. Variable selection combined PCA with Pearson correlation tests, focusing on variables explaining less than 70% variance [67]. Linear regression models commonly used for spatial phenomena face spatial autocorrelation in residuals, indicating specification errors [78]. Thus, the conclusions relied on relative importance analysis over probability values, employing bootstrap resampling to address these challenges [73].

4.2. TMF Dynamics and the Influence of Deforestation and Degradation Drivers

Given that ecological processes operate across diverse spatial and temporal scales [79], we tested how aggregation scale affects moist forest dynamics in the KBNP landscape. The analysis found no significant differences across scales (p = 0.67, α = 0.05), aligning with Ref. [80] on biomass scale independence. Regression coefficients rose from 0.44 to 0.87 from 1 km^2 to 400 km^2, reflecting reduced unit variation and increased within-unit variance at larger scales [79]. Yet, this scale increase does not guarantee better modeling, as finer scales better capture local disturbances [68]. Among the 1 km^2, 9 km^2, and 25 km^2 scales tested, 25 km^2 was optimal (R^2 = 0.62), with seven of nine variables being significant. At 25 km^2, a detailed sub-zone analysis from 1990 to 2022 showed varying TMF reductions across the inner, edge, and outer zones.

Among the three zones analyzed, the inner zone showed less tropical moist forest (TMF) loss from 1990 to 2022. However, fire use, human presence, distance from roads, and altitude influenced its dynamics. Consistent with other studies [11,15,48,49,81–84], forest loss correlated positively with higher fire and population densities and greater accessibility (distance to roads and slope). It is generally perceived that the exploitation of fragmented forests and forest edges is a more straightforward process than that of dense tropical forests [85]. Interestingly, TMF loss in the inner zone contrasts with larger-scale analyses, possibly due to limited, artisanal mining activities in remote park areas, mainly exploiting gold and coltan on non-forested sites like rocks [86]. Historical factors, including park boundary expansions in 1975 without community consultation [35,39], followed by armed conflicts from 1996 to 2004 [14,39], exacerbated cultural conflicts and led to widespread illegal activities like logging, fires, and mining, significantly impacting TMF regression in this once-intact landscape [35–37,40]. By analyzing the dynamics of TMF in the edge zone and the outer zone, it can be observed that the greatest losses occurred during the periods in which wars were reported to have begun and during which there were major civil invasions in and around the KBNP [26,37,39,40]. This confirms the results already found by other authors [14,87], who have reported the significant impacts of population movements on forest conservation, notably the increased need for agricultural land, firewood, and building materials. The impact of altitude noted for both zones can be attributed to the fact that the high-altitude zones of the park are more susceptible to human influence due to their high population density [35,40]. Conversely, the low-lying areas are less dynamic, largely due to their isolation and limited accessibility.

Compared to the inner zone, both the edge zone and outer zones have experienced greater dynamics due to various deforestation and degradation drivers, making them more vulnerable to external pressures. In these zones, TMF loss rates are almost identical, reflecting the vulnerability of areas close to the park boundaries. Although Article 33 of Law No. 14/003 on nature conservation in the DRC [88] stipulates that buffer zones may be created and delimited by a decree for protected areas declared to be of national interest (as in the case of Lomami NP [89]), the situation in the KBNP is different. To date, no buffer zone has been officially established, which increases the vulnerability of peripheral areas. Studies conducted in protected areas [46,75,90] highlight the role of buffer zones in alleviating pressure on inner forests. For example, Ref. [48] observed significantly higher forest losses (up to four times higher) in buffer zones surrounding protected areas in the DRC compared to the inner zones, where losses were well below the national average.

The edge zone of Kahuzi-Biega National Park is particularly affected by fire use, altitude, and distance from roads, as well as built-up density, mining density, and agriculture. These relationships align with findings from previous studies mentioned above. Furthermore, the study conducted by Ref. [91] in the eastern DRC revealed that agriculture and urban expansion contribute significantly (25 times greater) to deforestation than artisanal mining. Interestingly, built-up density shows a negative correlation with TMF loss, indicating that deforestation occurs farther away from urban areas characterized by densification rather than expansion. As population density rises, so does the demand for forest resources, leading communities to penetrate deeper into the forest for survival needs. The study conducted by Ref. [59] in Falgore Game Reserve (Nigeria) revealed that communities are willing to travel up to 10.25 km from their villages to the forest in search of forest products. The edge zone, covering significant highlands of the park, faces intense human pressure exacerbated by local poverty, driving activities such as logging, charcoal production, non-timber forest product collection, slash-and-burn agriculture, and small-scale livestock farming [29,40,86]. Proximity to National Road No. 2 within the park's internal boundaries further amplifies these effects. In the outer zone of Kahuzi-Biega National Park, TMF variation is influenced by analyzed drivers, particularly fire, altitude, distance from roads, mining density, and proximity to the park boundary. These trends echo findings from previous studies [11,92,93], highlighting them as primary drivers of deforestation and degradation in the DRC, albeit at varying rates compared to this study. For instance, small-scale agriculture, driven by population growth and recent conflicts, is a major factor according to Ref. [11]. Comparing the contributions of factors between the outer and edge zones reveals distinct patterns; mining site density plays a more significant role in the outer zone, while built-up areas and agricultural land have a lesser impact. These observations underscore how despite similarities, these regions face differing pressures.

5. Conclusions and Implications for Conservation

The use of novel remote sensing approaches and multi-scale analysis enabled us to analyze the drivers of deforestation and degradation (DFD) influencing tropical moist forest (TMF) dynamics in KBNP. These methods mitigated data scarcity, enhancing our understanding of TMF dynamics in this understudied landscape. The results confirmed that fire significantly affects TMF loss, with varying impacts across zones. Fire's relative importance was highest in the inner zone (55%), followed by the edge (30%) and outer zones

(23%). Population density, altitude, and distance from roads also emerged as significant factors, with their impacts varying by zone.

Overall, KBNP mitigates DFD compared to surrounding areas, which face substantial anthropogenic pressures. Centripetal pressures threaten park integrity, necessitating strategies to promote sustainable land use practices like agroforestry and restoration. Sustainable conflict management and livelihood diversification are crucial, given historical injustices and ongoing land conflicts exacerbated by population growth and poverty. Establishing and recognizing a buffer zone around KBNP could safeguard its resources and surrounding areas.

Future research should focus on characterizing fires and their uses. Identified as a major driver of TMF loss in the landscape, deeply analyzing fire dynamics is critical for understanding TMF loss dynamics. Assessing the ecological implications of TMF loss will guide conservation efforts in KBNP, informing management decisions crucial for this unique forest landscape.

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Data Availability Statement: The data used for this study is available from the corresponding author on reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Appendix A.1

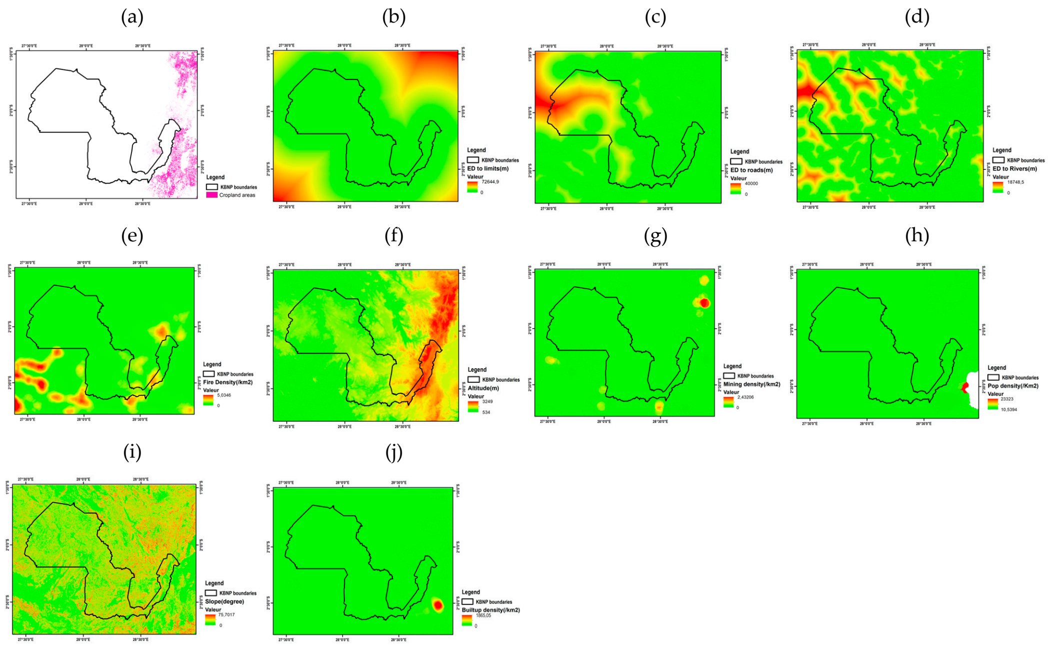
A1. Description, source, and pre-processing steps applied to data used for explaining variation of TMF loss in the KBNP landscape from 1990 to 2022.

Id	Data	Description	Source	Pre-Processing
1	Collection of annual changes in land use (1990–2022)	- Landsat images classified into seven classes (undisturbed TMF, degraded TMF, TMF regrowth, deforested land, ongoing deforestation and degradation, water, other landcover including afforestation) - Spatial resolution (29.90 m) - Acquisition: Google Earth Engine on 17 October 2023 - Asset ID: projects/JRC/TMF/v1_2022/AnnualChanges	Forest Observations (europa.eu) [6]	- Reclassification (two classes: TMF and other classes) - Calculation of the annual proportion of forest for each grid - Calculation of the change in the TMF (Δf) from the reference year (1990) to the final year (2022) at all scales
2	Landsat image (2021)	Landsat 8 OLI/TIRS surface reflectance: USGS Landsat 8 Level 2, Collection 2, Tier 1, cloud cover < 1%	Google Earth Engine (GEE): https://code.earthengine.google.com/	Supervised classification via GEE using the Random Forest algorithm (two classes: TMF and other classes) [64]
3	Built-up areas	Buildings provided by Open Street Map	Geofabrik Download Server	Calculation of the density of buildings/km^2 for each grid at different scales

Id	Data	Description	Source	Pre-Processing
4	Roads	Road and waterway data provided by Open Street Map	Geofabrik Download Server	Calculation of the average Euclidean distance to roads in km for each grid at different scales
5	Rivers	Watercourse data provided by Open Street Map	Geofabrik Download Server	Calculation of the average Euclidean distance to rivers in km for each grid at different scales
6	Altitude and Slope	Digital terrain model with 30 m resolution	OpenTopography—Shuttle Radar Topography Mission (SRTM GL1)	Calculation of the average altitude (m) of each grid at different scales
7	Population data	Population at health zone level	Humanitarian Data Exchange (humdata.org)	Calculation of population density/km^2 for each grid at different scales
8	Agricultural areas	Land cover map for 2021 at 10 m resolution based on Sentinel-1 and Sentinel-2 data	https://esa-worldcover.org/en [94]	Determination of the agricultural area (km^2) in each grid at different scales
9	Lights	Active fires and hot spots derived from the MODIS collection 6.1	https://firms.modaps.eosdis.nasa.gov/	Calculation of the average density of fires/km^2 for each grid at different scales
10	Mining areas	Small-scale artisanal mining sites	IPIS—Opendata (shinyapps.io)	Calculation of the average density of mining sites/km^2 for each grid at different scales
11	Distance from park boundaries	Euclidean distance of the boundaries of the KBNP in the study landscape	Analyses in Arc Map 10.8.1	Determination of the Euclidean distance of the park boundaries in km

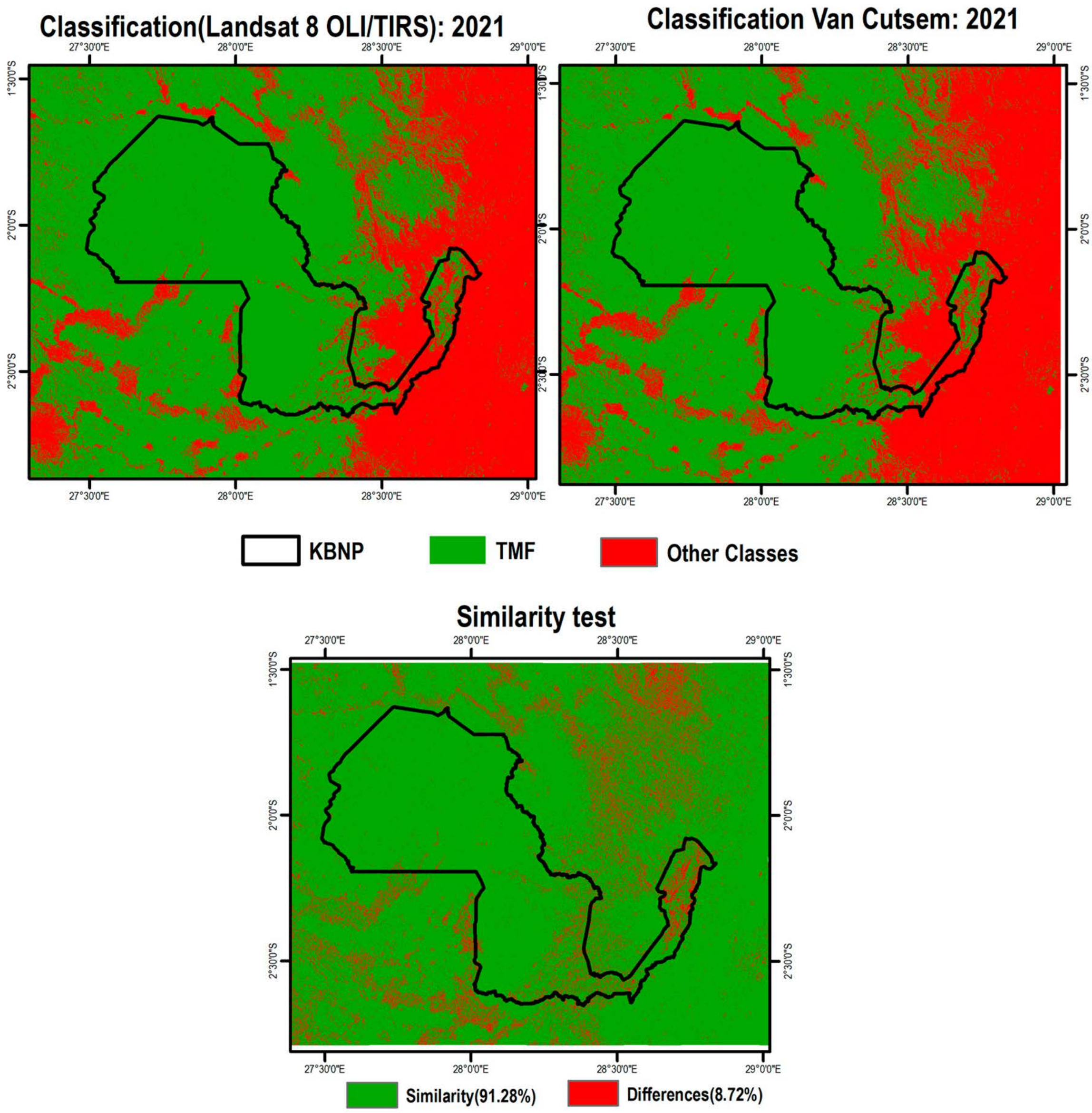
Appendix A.2

A2: Drivers considered for explaining tropical moist forest loss in Kahuzi-Biega National Park, eastern Democratic Republic of Congo from 1990 to 2022 (see also attached figures).(a): cropland areas,(b): ED to limits,(c): Ed to roads,(d): ED to rivers,(e): fire density,(f)altitude,(g)mining density,(h): population density,(i): slope and (j): built up density.



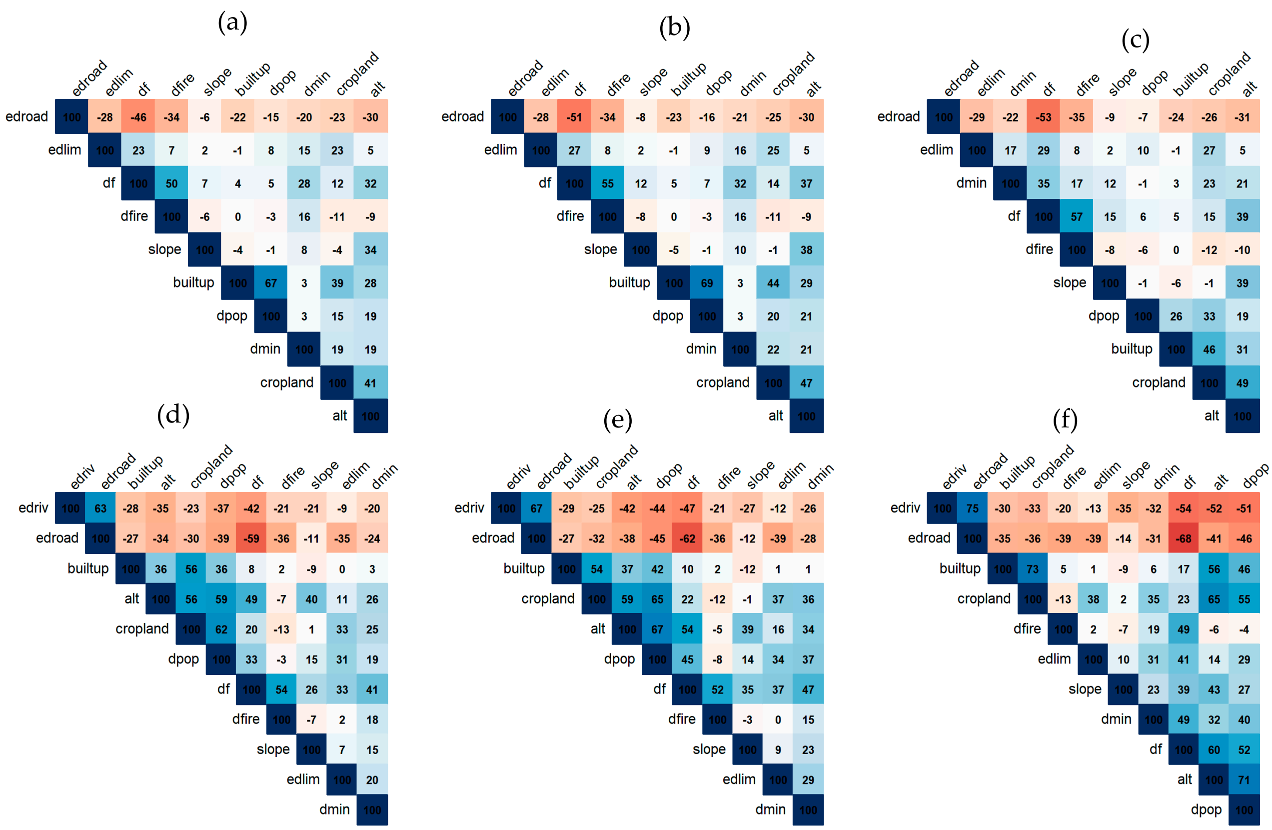
Appendix A.3

A3: Test of the adaptability of images used to analyze tropical moist forest (TMF) dynamic: Comparison of [6] classification from Landsat image and our own classification using Landsat image (2021), collected training points from Google Earth and supervised classification using a Random Forest algorithm in the landscape of Kahuzi-Biega National Park. The classification considers two classes, including the undisturbed TMF and the other landcover types (Other LC), which include deforestation and degradation.



Appendix A.4

A4: Plots of correlations at different grid sizes ((1 km^2 (a), 9 km^2 (b), 25 km^2 (c), 100 km^2 (d), 225 km^2 (e), and 400 km^2 (f)) tested for analysis of variation in tropical moist forest in the Kahuzi-Biega National Park landscape from 1990 to 2022. The blue color indicates a positive correlation and the red color indicates a negative correlation. Dark colours indicate a strong correlation and light colours a weak correlation.



Appendix A.5

A5: Multiple linear regression between the loss of tropical rainforest and the drivers analyzed at scales of 400 km^2, 225 km^2, and 100 km^2 in the Kahuzi-Biega National Park landscape.

Predictors	**Grid Size: 400 km^2 (R^2 = 0.87) (*p*-Value: <2 × 10^{-16})**				**Grid Size: 225 km^2 (R^2 = 0.76) (*p*-Value: <2 × 10^{-16})**				**Grid Size: 100 km^2 (R^2 = 0.70) (*p*-Value: <2 × 10^{-16})**			
	β	**t**	**Pr (>|t|) (*)**		**β**	**t**	**Pr (>|t|) (*)**		**β**	**t**	**Pr (>|t|) (*)**	
Built-up density	−26.33	−4.02	0.00	***	−9.38	−3.03	0.00	**	−2.07	−1.96	0.05	
Cropland area	−13.74	−3.31	0.00	**	−7.27	−2.94	0.00	**	−4.07	−4.92	1.60 × 10^{-6}	***
Distance to roads	43.04	7.46	8.20 × 10^{-10}	***	16.04	5.28	7.70 × 10^{-7}	***	8.51	8.72	4.50 × 10^{-16}	***
Distance to rivers	21.99	5.94	2.30 × 10^{-7}	***	15.91	7.38	5.10 × 10^{-11}	***	8.46	11.5	<2 × 10^{-16}	***
Altitude	−1.37	−0.24	0.81		−1.04	−0.43	0.67		−1.59	−1.9	0.06	
Fire density	0.49	0.1	0.92		5.08	1.73	0.09		−0.14	−0.15	0.88	
Population Density	19.51	4.88	1.00 × 10^{-5}	***	8.12	3.57	0.00	***	3.74	4.91	1.60 × 10^{-6}	***
Ext. distance to limits	10.60	2.79	0.01	**	5.9	2.67	0.01	**	2.55	3.59	0.00	***
Mining site density	0.93	0.24	0.81		3.42	1.54	0.13		0.84	1.13	0.26	

(*) The probability values (Pr) obtained do not consider the existence of spatial autocorrelations. Consequently, they should be treated with caution when interpreting trends. Significance Index (*p* value≤): «***» 0.001 «**» 0.01 «*» 0.05 «.» 0.1 « » 1.

Appendix A.6

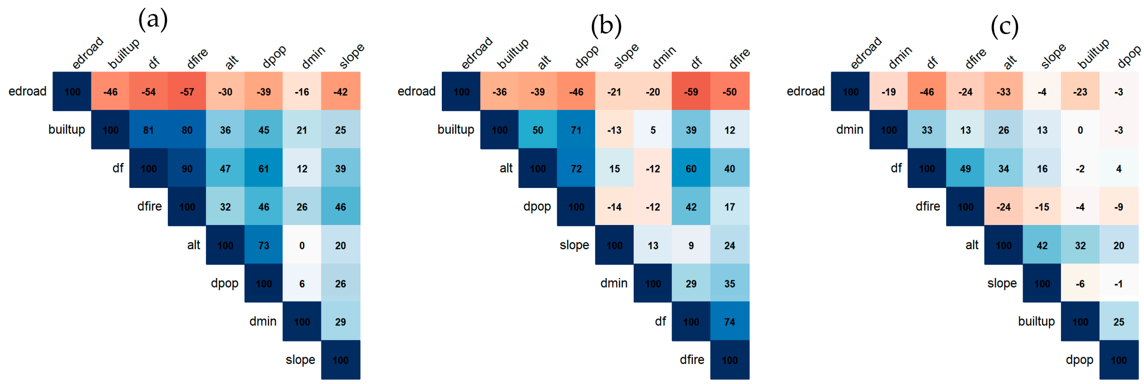
A6: Multiple linear regression between the loss of tropical rainforest and the drivers analyzed at scales of 25 km^2, 9 km^2, and 1 km^2 in the Kahuzi-Biega National Park landscape.

Predictors	**Grid Size: 25 km^2 (R^2 = 0.62) (p-Value: <2 × 10^{-16})**				**Grid Size: 9 km^2 (R^2 = 0.57) (p-Value: <2 × 10^{-16})**				**Grid Size: 1 km^2 (R^2 = 0.44) (p-Value: <2 × 10^{-16})**			
	β	**t**	**Pr (>∣t∣) (*)**		**β**	**t**	**Pr (>∣t∣) (*)**		**β**	**t**	**Pr (>∣t∣) (*)**	
Built-up density	−0.45	−3.31	0.00	***	−0.45	−3.31	0.00	***	−0.01	−4.2	2.70 × 10^{-5}	***
Cropland area	−1.03	−8.85	<2 × 10^{-16}	***	−1.03	−8.85	<2 × 10^{-16}	***	−0.04	−32.64	<2 × 10^{-16}	***
Distance to roads	2.06	15.83	<2 × 10^{-16}	***	2.06	15.83	<2 × 10^{-16}	***	0.08	56.06	<2 × 10^{-16}	***
Distance to rivers	2.53	23.33	<2 × 10^{-16}	***	2.53	23.33	<2 × 10^{-16}	***	0.10	87.76	<2 × 10^{-16}	***
Altitude	−0.48	−4.24	2.40 × 10^{-5}	***	−0.48	−4.24	2.40 × 10^{-5}	***	−0.03	−16.87	<2 × 10^{-16}	***
Fire density	0.23	2.22	0.02647	*	0.23	2.22	0.03	*	0.01	6.57	5.20 × 10^{-11}	***
Population Density	0.87	8.12	1.30 × 10^{-15}	***	0.87	8.12	1.30 × 10^{-15}	***	0.03	23.18	<2 × 10^{-16}	***
Exterior distance to limits	0.65	6.31	4.20 × 10^{-10}	***	0.65	6.31	4.20 × 10^{-10}	***	0.03	22.82	<2 × 10^{-16}	***
Mining site density	−0.03	−0.31	0.76		−0.03	−0.31	0.76		−0.01	−8.21	2.30 × 10^{-16}	***

(*) The probability values (Pr) obtained do not consider the existence of spatial autocorrelations. Consequently, they should be treated with caution when interpreting trends. Significance Index (p value≤): «***» 0.001 «**» 0.01 «*» 0.05 «.» 0.1 « » 1.

Appendix A.7

A7: Plots of correlations between different variables at the scale of zones (inner (a), edge (b), and outer (c)) within the KBNP landscape from 1990 to 2022.The blue color indicates a positive correlation and the red color indicates a negative correlation. Dark colours indicate a strong correlation and light colours a weak correlation.



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