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# Dynamics and Anthropisation of Edible Caterpillar Habitats in the Landscape of the Luki Biosphere Reserve, Democratic Republic of Congo

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## Abstract

The Luki Biosphere Reserve landscape is located in the southwest of the Democratic Republic of Congo. Illicit anthropogenic activities in this landscape have contributed to the degradation of forest massifs, which are habitats for edible caterpillars. Accordingly, based on five Landsat images covering 2004–2024 period, we analysed the dynamics of edible caterpillar habitats in the Luki Biosphere Reserve, its periphery, and the landscape. The study was complemented by the calculation of class area, number of class patches, dominance, and the disturbance index. The results show that fragmentation and attrition have caused forest areas to decline by 46.13%, 21.17%, and 23.54% in the Reserve, its periphery, and at the landscape level, respectively. The dynamics of caterpillar habitats are reflected in the replacement of forest and fallow land by savannah. The level of disturbance has thus risen from 0.3 to 1.6 in the Reserve, from 2.5 to 13.9 in the periphery, and from 2.0 to 9.2 on a landscape scale. These results are mainly attributed to the expansion of agricultural land. Our observations imply an extent of disturbance in caterpillar habitats that might cause their scarcity, and strongly indicate the need for promoting effective strategies for preserving and restoring forest ecosystems in this landscape.

**Keywords:** anthropisation; biodiversity; ecosystem; food security; Luki biosphere reserve

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Academic Editor: Shiliang Liu

Received: 17 April 2025
Revised: 29 May 2025
Accepted: 13 June 2025
Published: 1 July 2025

**Citation:** Lonpi Tipi, E.; Mpanda Mukenza, M.; Useni Sikuzani, Y.; Messina Ndzomo, J.-P.; Sambieni Kouagou, R.; Malaisse, F.; Lumande Kasali, J.; Khasa, D.; Bogaert, J. Dynamics and Anthropisation of Edible Caterpillar Habitats in the Landscape of the Luki Biosphere Reserve, Democratic Republic of Congo. *Land* **2025**, *14*, 1384. https://doi.org/10.3390/land14071384

## 1. Introduction

Human action on natural landscapes inevitably leads to spatiotemporal disturbances, the magnitude of which may compromise ecosystem health [1]. In forest landscapes in particular, such disturbances are caused by deforestation and degradation. They are frequently aggravated by sociocultural, demographic, economic, technical, and political factors [2–5]. Moreover, deforestation and degradation have caused substantial loss of biodiversity around the world [6]. Indeed, it has been estimated that, between 2015 and 2022, the annual global loss of forest cover amounted to about 25 million hectares [7]. Furthermore, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has reported that 27,000 plant and animal species are lost annually as a result of human activities [8,9]. At the regional level, particularly in the Congo Basin, deforestation and land degradation are responsible for the loss of 1.79 million hectares of forest land every year [10].

Forest cover in the Democratic Republic of the Congo (DRC) has not been spared from the effects of human activities. More than half a million hectares of primary forest are lost every year in the DRC [11,12]. Moreover, most forest losses are incurred through unsustainable agricultural practices and aggravated by population growth [7]. To mitigate these anthropogenic pressures on forest resources, almost 11% of the Congolese territory has been established as a protected areas [13]. Yet, owing to weak law enforcement and socioeconomic challenges that are faced by local populations, the conservation of forest ecosystems remains precarious in these protected areas [14]. Several studies that were conducted in protected areas in the DRC have revealed forest cover losses, with notable consequences for plant and animal habitats [13,15,16].

Similarly to other protected areas in the country, the Luki Biosphere Reserve (LBR) landscape is under great anthropogenic pressure. Indeed, landscape, forest cover is threatened by bush farming, bush fires [17,18], and the artisanal exploitation of wood for energy supplies [19]. These activities have been observed elsewhere, and are found to be responsible for changes in the spatial structure of the landscape, as manifested by the fragmentation, removal, and replacement of certain land-use categories by others [20,21]. Studies showed that different development zones within the LBR (core, buffer, and transition zones) are subject to retrogressive vegetation-cover dynamics, with negative effects on climate and carbon storage [22,23]. This disruption of natural ecosystems in the LBR landscape creates conditions that are conducive to the losses of plant and animal biodiversity [24–26].

Edible caterpillars are among the wildlife resources that are under threat in the LBR landscape. Yet, caterpillar collection and consumption practices in this area have existed only since the early 2000s [27]. Edible caterpillars in the LBR landscape are collected in forests, savannahs under protection, fallow land, and on certain tree species that are found in residential areas (villages). However, the population living in this region explains that over the years, edible caterpillars have become increasingly rare, random, and episodic in their occurrence at the times when they are expected to be available [28]. Unfortunately, few studies have analysed the problems surrounding the availability of edible caterpillars in this landscape. Elsewhere in the country, in areas where caterpillar consumption is a traditional practice, research has been conducted on the pressures affecting caterpillars, their domestication, and practices that are implemented for their sustainable management [29,30]. A recent study showed that edible caterpillar habitats in the LBR landscape had low specific diversity, with caterpillar-host trees becoming rarer, and several species being locally threatened with extinction [26]. This observation suggests the possible instability of edible caterpillar habitats in the LBR landscape, the dynamics of which need to be studied. Hence, this study focused on analysing landscape dynamics and the effects of anthropisation on edible caterpillar habitats in the LBR landscape. To this end, we have adopted an approach that allows us to consider spatial alterations inside and on the periphery of the Reserve at three spatial scale levels: LBR, LBR periphery, and landscape (LBR + LBR periphery), with the aim of highlighting spatiotemporal dynamics unfavourable to edible caterpillar habitats at the three spatial scales that were defined. The study therefore verifies the hypothesis that the anthropisation of the LBR landscape has led to the fragmentation and elimination of the main edible caterpillar habitats, i.e., forests and fallow lands, and has favoured the creation of savannahs, fields, and bare soils, which are habitats that are not conducive to the availability of edible caterpillars in the region.

## 2. Materials and Methods

### 2.1. Characteristics of the Study Area

The LBR landscape is located in Kongo Central Province, western DRC, within the geographical region of Mayombe. The designated LBR landscape includes the reserve and the surrounding area, extending approximately 20 km beyond it (Figure 1). Additionally, there are about 50 villages and 7 urban and rural centres the LBR periphery, in which the population livelihood relies mainly on the resources harvested from the forest [31,32].

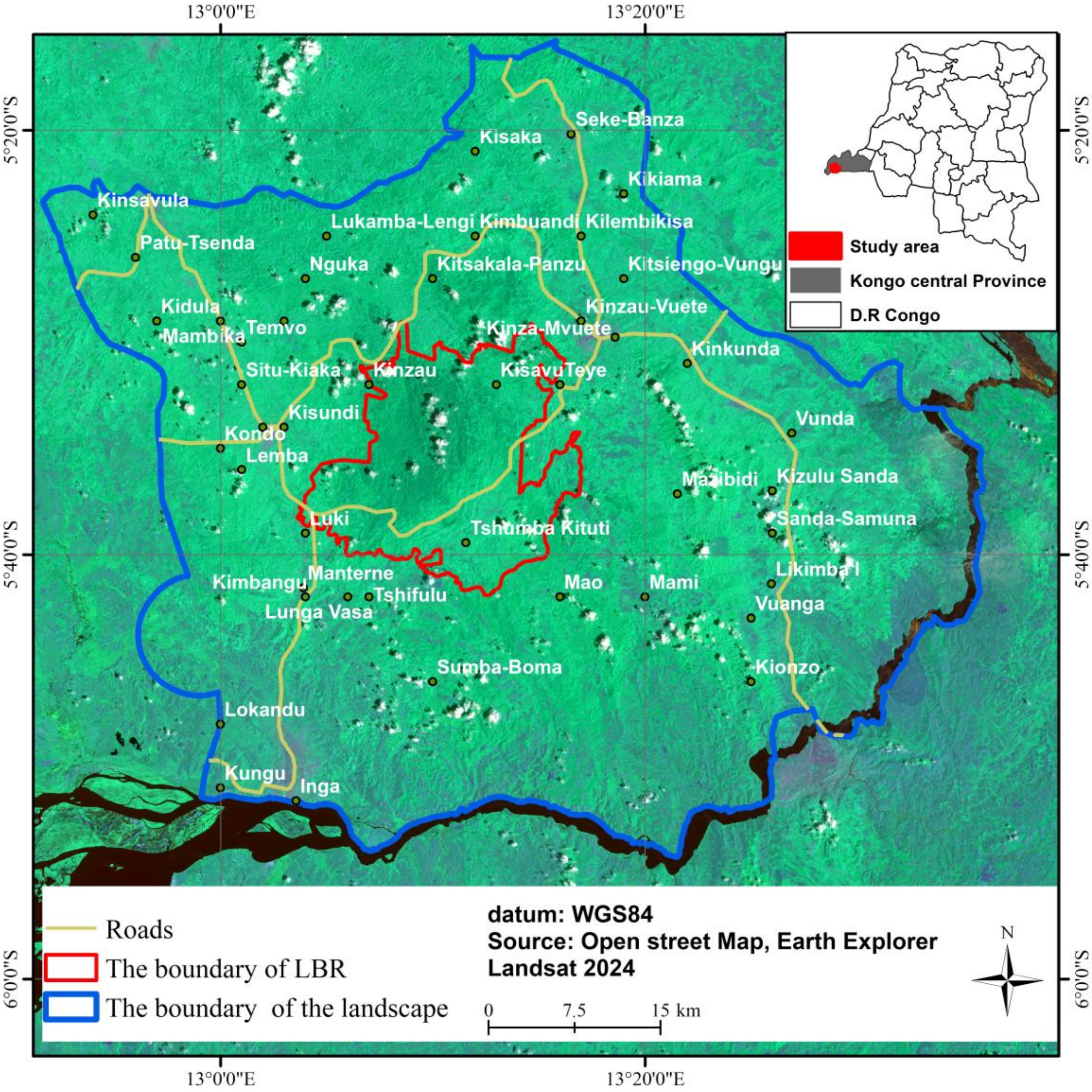

**Figure 1.** Luki Biosphere Reserve landscape. The map was produced using the datum WGS84. The red polygon represents the LBR. The periphery is the area between the LBR and the blue polygon. In the periphery, there are several villages and urban centres marked on the map by small black dots, while the names of the localities are written in white. The landscape consists of the LBR and its periphery, whose boundary of which is marked on the map by the blue polygon. This is crossed by roads that are represented by yellow lines on the map.

With an area of about 3514.20 km$^2$, the entire region encomprising by the LBR landscape lies between 5°00′00″ S and 6°00′00″ S and 12°50′00″ E and 13°40′00″ E. The climate of the region is humid tropical, (AW5), according to Köppen's classification, with a five-month dry season from mid-May to mid-October, and a seven-month rainy season from mid-October to mid-May. The vegetation in the LBR landscape is evergreen and of the semi-deciduous type [33]; it forms part of the extreme southern tip of the Mayombe Guinean forest, with the forest flora including mature and secondary forest species and non-forest flora composed of both grassy and shrubby savannahs [33]. The human population of the LBR landscape has grown from 82,000 in the early 2000s to 138,000 in 2014 and 237,000 in 2020 [28,33]. The economy of this region is based on slash-and-burn subsistence farming of cassava (*Manihot esculenta* Crantz), maize (*Zea mays* L.), and groundnuts (*Arachis hypogaea* L.) growing on clay and sandy clay soils [33]; charcoal production and trading; pit sawing [19,32]; and non-timber forest product (NTFP) collection, among which are edible caterpillars. These edible caterpillars are *Lepidoptera* of the *Saturniidae* family [28]. In this landscape, the edible caterpillars rely on 15 main plant host species (*Spondias mombin* L., *Petersianthus macrocarpus* (P.Beauv.) Liben, *Croton sylvaticus* Hochst. ex Krauss, *Hymenocardia acida* Tul., *Lannea welwitschii* (Hiern) Engl., *Macaranga spinosa* Müll.Arg., *Celtis mildbraedii* Engl., *Coelocaryon botryoïdes* Vermoesen, *Albizia gummifera* (J.F.Gmel.) C.A.Sm, *Bridelia atroviridis* Müll.Arg, *Ficus mucuso* Welw. ex Ficalho, *Funtumia elastica* (P.Preuss) Stapf, *Milicia excelsa* (Welw.) C.C. Berg. *Ricinodendron heudelotii* (Baill.) Pierre ex. Heckel, and *Terminalia superba* Engl. & Diels) [26].

### *2.2. Satellite Data*

In this study, we used five Landsat images that were acquired during the dry season (June–August) covering the following years: 2004, with the Landsat 5 "Thematic Mapper (TM)" sensor; 2011, with the Landsat 7 "Enhanced Thematic Mapper plus (ETM+)" sensor; 2015; 2020; and 2024, with the Landsat 8 "Operational Land Imager (OLI)" sensor. These images were obtained from the USGS website (https://glovis.usgs.gov) and represent surface reflectance data from the Level 2 Collection 2 Tier 1 dataset. The choice of these images was influenced by several parameters, such as availability and quality (absence of clouds and scratches), and the objectives of our study [21]. Thus, the need to work over a long period (20 years) to better monitor spatial dynamics and changes in socioeconomic phenomena justifies the choice of a reduced time step (five to seven years). The periods to which these images correspond were defined as follows: 2004–2011; 2011–2015; 2015–2020, and 2020–2024. The starting period (2004–2011) coincides with the period during which caterpillar collection and consumption began in the study area [27]. The 2015–2020 period corresponds to the time when people began to complain about a gradual reduction in the availability of the caterpillars that they consumed. The 2020–2024 period corresponds with the time when scarcity of edible caterpillars was reported [27,28]. Thus, there is a need to assess the evolution of caterpillar habitats from the early 2000s in order to better appreciate the decreasing potential of caterpillar availability in the LBR landscape.

### *2.3. Pre-Processing of Landsat Images*

To optimise the quality of satellite images and improve their reflectance, radiometric corrections were made using the ENVI 5.3 software [34]. These corrections eliminated biases that were associated with the spectral sensitivity of the sensors and variations in illumination, thereby ensuring greater accuracy in the analysis of the data. In addition, the imperfections specific to the 2011 images resulting from failure of the Landsat 7 satellite sensor in 2003 were corrected. This failure generated so-called "gaps" in the spectral bands. To address this problem, band-specific gap mask files ("Gap_mask") that are included in Landsat 7 data products were used to fill the gaps. This method, which is commonly recommended in the literature, has been shown to be effective in reconstructing damaged images [35,36]. Finally, the last pre-processing step involved delimiting the area of interest directly on the satellite images. Delimitation was performed using shape files that were supplied by the Observatoire Satellitaire des Forêts d'Afrique Centrale (OSFAC). These shapefiles, incorporating precise spatial information, made it possible to precisely circumscribe the study perimeter precisely, thereby, facilitating a targeted analysis of spatial dynamics in the area under consideration.

The unsupervised classification of Landsat images was performed after false-colour compositing by combining the mid-infrared (MIR), near-infrared (NIR), and red (RED) bands. This specific combination of bands was selected because given its proven effectiveness in discriminating landscape features, particularly vegetation, urban areas, and bare soil [37]. Further, NIR is particularly sensitive to NIR radiation and can be used to differentiate vegetation types, whereas MIR radiation is useful for identifying variations in soil and plant moisture contents. The red band, on the other hand, offers optimum contrast for detecting vegetation owing to its strong absorption by chlorophyll. This combination enhanced our ability to analyse the spectral characteristics of landscape features, making transitions between land-use classes more visible and distinct. This first step enabled the initial visual identification of the main land cover classes in the study area, which was a crucial step in guiding the actual classification process [21,38]. Supervised classification of the Landsat images was subsequently performed using the maximum likelihood algorithm that is described by [39].

### 2.3.1. Definition of Land-Use Classes

In order to define the relevant land-use classes for the study, we referred to the population's local knowledge of the habitats of consumed caterpillars, which are forests, protected savannahs, fallows, and inhabited areas. Furthermore, to understand the reasons for the scarcity of caterpillars as described by the population, the land-use class comprising open fields and bare soils were combined to form a single class to avoid confusion between these two classes. Population growth not only increases the need for housing but also exacerbates, the need for agricultural land. When vegetation can no longer regenerate on the land, it gives way to bare soil. As a result, six land-use classes were selected for the study (Table 1). With the help of a local guide, the study area was surveyed and the geographic coordinates of points with the characteristics described below (Table 1) for each land-use class were recorded. These geographic coordinates were supplemented by those of the high-resolution images from Google Earth in 2020 (Landsat/Copernicus image of 2024 Maxar Technologies, CNES/Airbus produced on 3 August 2020), for land use with a low probability of having changed between 2004 and 2024. These include farmland at the Institut Nationale pour l'Etude et la Recherche Agronomique station in Nguimbi, AGRIUYMBE-Luki, the forest in the core zone of the Luki reserve, and the Kinza-Vuete village. A total of 200 geographic coordinates were collected. These points were used as references from which the training polygons were selected for each image. The pixel/pixel classification method, nearest neighbour similarity, was used. In addition, the definition of land-use classes was carried out on the 2024 image, considered as the reference year, and applied to images from previous years.

**Table 1.** Land-use classes obtained by supervised classification of Landsat images using the maximum likelihood algorithm in the region of interest.

| Land-Use | Characteristics | ROI * |
|---|---|---|
| **Forests** | Forests are habitats for edible caterpillars in the study area, with a high diversity of host trees. They include primary forest, secondary forest (plantations and savannahs under protection for natural regeneration) and forest galleries. | 30 |
| **Savannahs** | Savannahs were considered to be grassy savannahs and shrub savannahs of anthropogenic origin, regularly subjected to bush fires and without fencing. The caterpillars consumed by the population in the study area are not dependent on the grasses of grassy savannahs. Also, repeated bushfires in anthropogenic savannahs do not allow the regeneration of forest forage species for the caterpillars consumed by the population. | 36 |
| **Fallow land** | Fallows are pioneer vegetation that recolonizes bare soils. Like forests, fallow lands in the study area are a preferred habitat for caterpillar feeding populations in the LBR landscape. | 39 |
| **Fields and bare soil** | These are areas where cassava, groundnuts, maize, and other crop plants are grown. According to the regional agricultural calendar, from mid-May to mid-October, there is a long dry season marked by field preparation operations (tree felling, clearing, and burning) leaving the soil devoid of plant cover. Because of their agricultural vocation and the need for charcoal, generally, the fields in the study area have no woody vegetation providing fodder for edible caterpillars, as trees are systematically felled during field preparation. | 59 |
| **Inhabited areas** | Inhabited areas are settlements that were mostly established before and during the creation of the LBR. More recent settlements have been established over the last 30 years as a result of population growth. These settlements are surrounded by tree vegetation characterised by low diversity and irregularity of edible caterpillar host species. | 36 |

* Region of interest.

### 2.3.2. Classification Validation and Construction of Confusion Matrices

To check the reliability of the classifications and construct confusion matrices, the local people's knowledge of the spatial layout of the landscape units in their terroir was sought during the focus groups. We explored the study area in order to identify exactly which land-use types were mapped. Accompanied by local guides, we explored the LBR landscape and noted each homogeneous space that could be identified on the images, i.e., with a spatial extent corresponding to or greater than the 30 m spatial resolution of the Landsat ETM+ and OLI sensor images. Two hundred geographical coordinates that were independent of those used for the supervised classification were collected in the field using Garmin St64 GPS, with an accuracy of about 5 m. The same number of samples for each class was used for supervised classification and classification validation, in order to maintain consistency and avoid deviating from the reality of the landscape. Each GPS point was then supplemented by floristic indicators of the vegetation formations in the study area [33], the history of the vegetation succession provided by the local guide and evidence of the vegetation history (generally an indicator of an ancient vegetation formation observable at the location where the geographical coordinates were taken). When the vegetation indicator did not correspond to a vegetation formation described by the local guide, reference was made to the literature by [33], and the geographical coordinate was then classified in the corresponding land-use class according to this literature.

Based on the confusion matrix, the observer and user accuracies, together with overall accuracy, were calculated to assess the reliability of the classification results, consistent with the methods used by [40,41]. The observer precision (or error of omission) measures the proportion of pixels belonging to a category that has been correctly classified. Therefore, it assesses the ability of the model not to exclude elements that should belong to a given class, such as all savannah areas that were identified herein. User accuracy (or commission error), in contrast, indicates the proportion of pixels that are classified in a given category which actually belong to that category. For example, if an area is classified as a forest, this precision estimate indicates the extent to which the classification is correct and does not include pixels from other categories (such as agriculture). Finally, overall accuracy measures the total proportion of correctly classified pixels in relation to the total number of pixels that were analysed. Our study validated the overall effectiveness of the classification model as it faithfully reproduced land-use classes present in the study area. The supervised classification of Landsat images from 2004, 2011, 2015, 2020, and 2024 covering the LBR landscape revealed overall accuracies ranging from 90.90% to 97.47%, whereas user and producer accuracies varied from 68% to 100% (Table 2). These results indicate a statistically robust differentiation between different land-use classes with a low confusion rate, thus demonstrating the effectiveness of the classification process. The high accuracy-rate observed confirms that the classification algorithm effectively distinguished between land-use types.

**Table 2.** Classification accuracy of Landsat 2004, 2011, 2015, 2020, and 2024 images based on the Maximum Likelihood Algorithm. Classification is statistically reliable. "Ua" stands for user accuracy (%) and 'Pa' for producer accuracy.

| **Image Classification Results: 2004** | | | | | | |
|---|---|---|---|---|---|---|
| | **Forests** | **Savannahs** | **Fallow Lands** | **Fields and Bare Soils** | **Inhabited Areas** | **Others** |
| Ua | 100.0 | 95.0 | 82.5 | 97.5 | 72.5 | 100.0 |
| Pa | 95.2 | 95.0 | 97.1 | 68.4 | 72.5 | 100.0 |
| Overall accuracy 2004: 90.90% | | | | | | |
| Image classification results: 2011 | | | | | | |
| Ua | 85.1 | 91.9 | 97.4 | 98.4 | 100.0 | 100.0 |
| Pa | 94.0 | 86.0 | 98.4 | 94.9 | 100.0 | 100.0 |
| Overall accuracy: 94.91% | | | | | | |
| Image classification results: 2015 | | | | | | |
| Ua | 100.0 | 100.0 | 93.5 | 91.7 | 94.9 | 100.0 |
| Pa | 100.0 | 100.0 | 100.0 | 91.7 | 89.2 | 100.0 |
| Overall accuracy: 97.47% | | | | | | |
| Image classification results: 2020 | | | | | | |
| Ua | 100.0 | 95.7 | 100.0 | 95.9 | 97.9 | 100.0 |
| Pa | 97.9 | 95.9 | 100.0 | 97.9 | 97.9 | 100.0 |
| Overall accuracy 2020: 93.89% | | | | | | |
| Image classification results: 2024 | | | | | | |
| Ua | 100.0 | 96.7 | 98.0 | 93.9 | 94.9 | 100.0 |
| Pa | 98.6 | 92.6 | 100.0 | 94.7 | 98.6 | 100.0 |
| Overall accuracy2024: 95.70% | | | | | | |

### *2.4. Assessment of Landscape Dynamics*

To assess the human impact on caterpillar habitats and consider the possible drivers of such impact as they relate to the type of predominant economic activities in the LBR region, four spatial structure indices (the total area of patches, the number of patches, the largest patch, and the disturbance indices) were calculated [42]. With these indices, we examined: (i) trends in deforestation and the extension of agricultural land and savannahs; (ii) changes in land use; (iii) spatial transformation processes that took place during the period covered by the study; and (iv) changes in the landscape matrix and the level of anthropisation of the latter.

Specifically, to analyse the trend towards deforestation and the expansion of savannah and farmland, the evolution of the total area (a) of patches for each land-use class was assessed. Class area refers to the relative extent of specific land-use types within a defined landscape. The category helps in understanding the landscape composition by identifying the predominant land-use matrix for a given period. In order to assess land-use transfers, the five land-use maps were crossed in pairs (2004–2011, 2011–2015, 2015–2020, 2020–2024, and 2004–2024). The various changes that occurred during the study period were highlighted using six transition matrices [43,44]. For practical reasons, only the transition matrices for the 2004–2024 crossovers are presented in the body of this work. Those for other years have been presented in the Appendix A. The study of the evolution of land-use units is generally based on three cases linked to transition matrices. These are changes within the same land-use category; conversion, i.e., the passage from one category to another, such as forests becoming cultivated areas; and the no-change situation reflecting land-use classes that have remained stable between two dates [44]. Transition matrices have thus made it possible to assess the probability of a land-use class moving from one state to another, and to see what has been lost per classes in each spatial scale under study.

Spatial transformation processes were identified using the decision tree that was proposed by [45]. This tree is based on the evolution between two dates, i.e, the initial (0) and final date (1), of the number of patches (n), their total area (a), and the total perimeter of a land-use class. The number of patches (n) plays a crucial role in assessing landscape fragmentation, given that a high number of patches indicates fragmentation and dispersed distribution. Whereas a low number suggests patch aggregation [37]. The decision tree identified the following spatial transformation processes (Figure 2): aggregation (merging of patches in a land-use class); creation (setting up new patches); enlargement (increase in the area of a class); attrition (reduction in the area of a class); dissection (subdivision of a class by lines): and fragmentation (breaking patches in a class into small fragments of varying sizes). To distinguish the process of fragmentation from that of dissection, the value of $t$, which was derived from the ratio between the total area of land use on the final date and that on the initial date, was compared using a threshold value of $t = 0.75$. Values greater than 0.75 suggest dissection, while those less than or equal to 0.75 indicate the prevalence of fragmentation. Furthermore, values greater than or equal to 1.0 indicate the prevalence of creation or aggregation [46].

Finally, the evolution of the landscape matrix was determined by calculating the Largest Patch Index (LPI), which defines the ratio between the largest area of a class and the total area of the class [47–51] while providing information on the fragmentation of land cover following its reduction. Lastly, we calculated the disturbance index, defined as the ratio between the cumulative area of anthropogenic land cover in the landscape and the total forest area [20,21], to assess the level of anthropisation of the landscape.

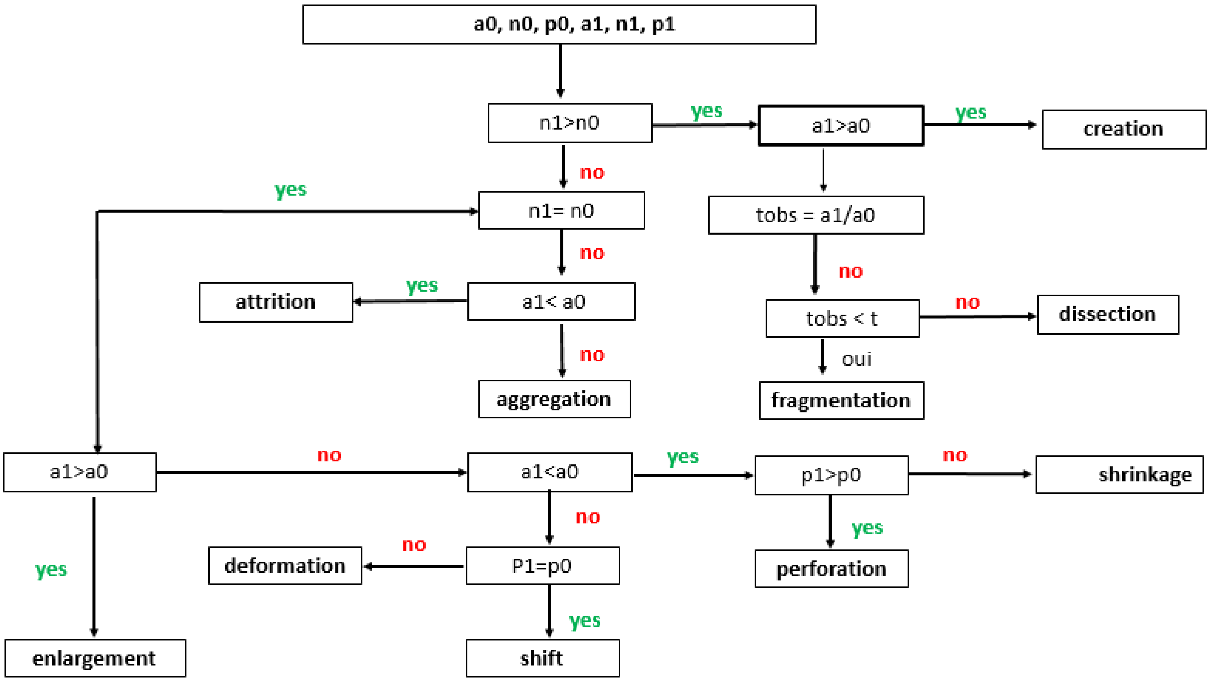

**Figure 2.** Identification of spatial transformation processes adapted from [45]. a0, n0, and p0, and a1, n1, and p1 represent the area, number, and perimeter of class patches, respectively, in the first (0) and the last year (1) of each study period. Spatial transformation processes were identified for each class in all study periods (2004–2011, 2011–2015, 2015–2020, and 2020–2024). To separate fragmentation from dissection, tobs = a1/a0 was calculated and compared with the predefined threshold of t = 0.75.

## 3. Results

### 3.1. Landscape Composition Dynamics and Land-Use Change

Visual analysis of the land cover maps (Figure 3) revealed significant changes between 2004 and 2024. Savannahs, fields and bare soils, and inhabited areas have progressively increased to the detriment of forests and fallow land, the cover area of which has steadily decreased. The analysis of the landscape composition dynamics and Land-Use Change revealed that from 2004 to 2024, forest cover at the regional level declined sharply from 33.10% to 9.52%, decreasing by 23.54%. In contrast, fields and bare soils increased from 3.50% to 24%, representing an increase of 20.5%. In turn, the savannah area also increased from 56.60% to 58.46%, while fallow lands almost disappeared (Table 3). In fact, over the 20-year period under consideration, forest area was reduced from 84.10% to 38% and from 27.70% to 6.50% in the LBR and the periphery, respectively (Table 3). Areas of fields and bare soils experienced a concomitant increased by 1.80% in the LBR and 26% in the peripheral zone over the same period, respectively. Likewise, the savannah area increased in the LBR, reaching almost 57.2%, while urbanisation remained limited. Meanwhile, in the periphery, the savannah reached 58.40% in 2024, while urbanisation expanded substantially, rising from 0.92% in 2004 to 5.90% in 2024, representing a 4.98% increase in occupied area.

In addition, the 2004–2024 cross-tabulations for each of the study areas reveal that from 2004 to 2024 (Table 3), in the LBR, 38% of the 84.1% of forest remained stable, 12% of the 15.6% of savannah area was stable and showed a gain of 45.24%. In the peripheral zone, on the other hand, 5.3% of the 27.7% of forest area remained stable between 2004 and 2024. Approximately 35.9% out of 61% of the savannah area remained stable. Therefore, In the landscape as a whole, only 8.4% of the 33.1% of forest remained stable between 2004 and 2024. No stable area was observed for fallow land. Savannahs, fields and bare soils, as well as inhabited areas, have not only remained stable, but their surface area has also increased over the period studied. Overall, these results indicate that many forests and fallow lands in the study area have been transformed into fields and bare soils, savannahs, and urbanised areas because of human activity. This loss of vegetation cover has very likely compromised the availability of edible caterpillars in the study area.

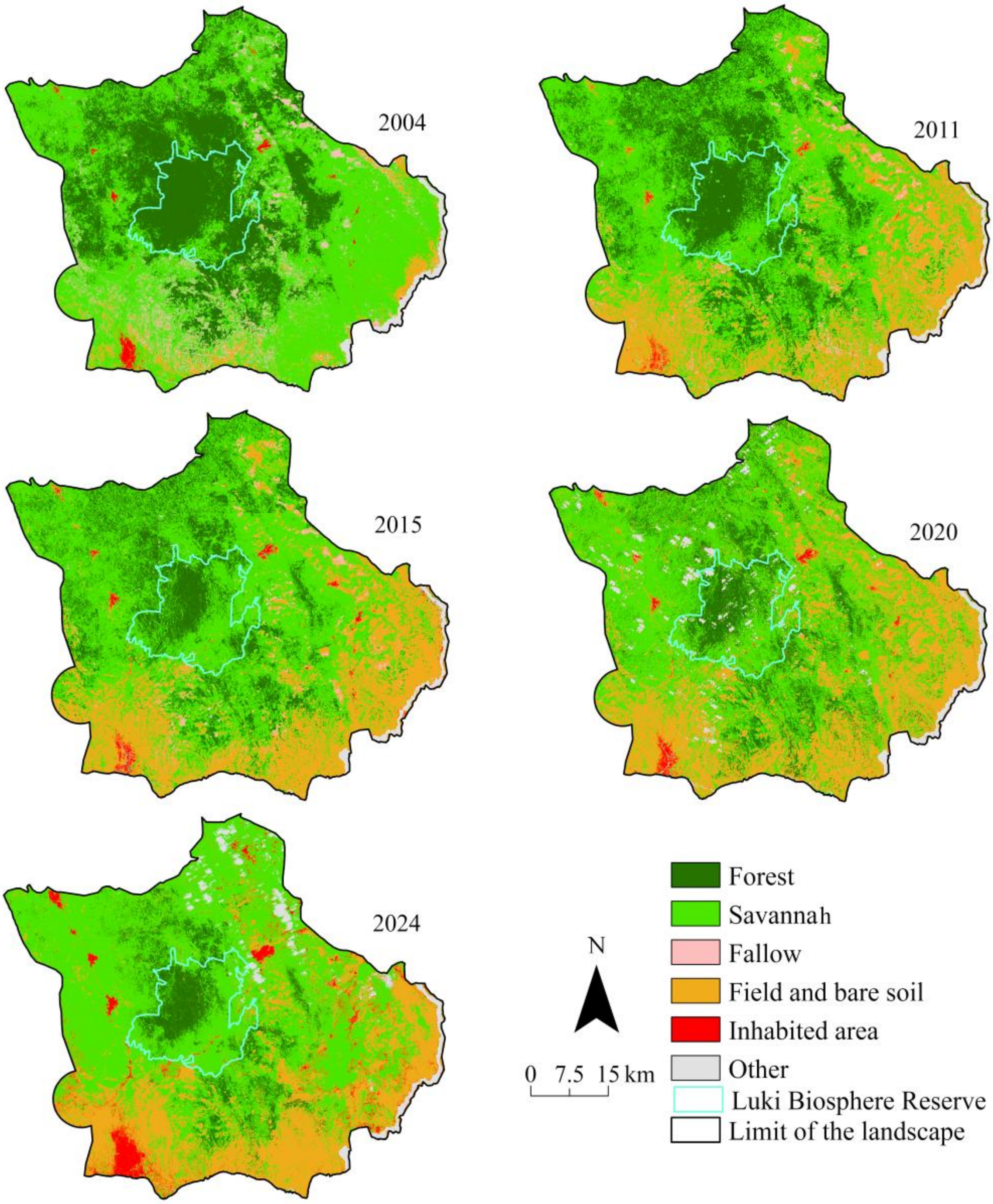

**Figure 3.** Map of land cover dynamics in the Luki Reserve landscape from 2004 to 2024, derived from supervised classification of Landsat images using the "maximum likelihood" algorithm. The 2004 map shows a preponderance of dark green (forest) versus light green (savannah) and brown (fields and bare soils). The pink colour (fallow land) was also well represented in 2004, and red dots (inhabited areas) were scarce. These different hues shifted gradually up to 2024, when light green dominated the landscape and the brown hue increased, as did the size and number of red dots. The pink hue had disappeared by 2024.

**Table 3.** Transition matrices illustrating, as a percentage of the surface area of the classes, the transformation of their area between 2004 (rows) and 2024 (columns). Each value in the table corresponds to a fraction of the landscape converted, between 2004 and 2024, from the class indicated in the row to the class at the head of the column. Values in bold indicate class permanence.

| | **Forests** | **Savannahs** | **Fallow Lands** | **Fields and Bare Soils** | **Inhabited Areas** | **Other** | **Total 2004** |
|---|---|---|---|---|---|---|---|
| | | | Luki Biosphere Reserve | | | | |
| **Forests** | **38** | 45 | 0 | 0.7 | 0.2 | 0.2 | 84.1 |
| **Savannahs** | 0.2 | **12** | 0 | 0.8 | 2.5 | 0.07 | 15.6 |
| **Fallow lands** | 0 | 0.23 | **0** | 0.3 | 0 | 0 | 0.56 |
| **Fields and Bare soils** | 0 | 0 | 0 | **0** | 0 | 0 | 0 |
| **Inhabited areas** | 0 | 0.01 | 0 | 0 | **0.1** | 0 | 0.07 |
| **Other** | 0 | 0 | 0 | 0 | 0 | **0** | 0 |
| **Total 2024** | 38 | 57.2 | 0.01 | 1.80 | 2.8 | 0.27 | **100** |
| | | | Peripheral zone | | | | |
| **Forests** | **5.3** | 20.6 | 0 | 0.8 | 0.3 | 0.63 | 27.7 |
| **Savannahs** | 1.1 | **35.9** | 0.01 | 19 | 3.9 | 0.99 | 61 |
| **Fallow lands** | 0.1 | 1.61 | **0** | 2.8 | 0.4 | 0.15 | 5.05 |
| **Fields and Bare soils** | 0 | 0.15 | 0 | **2.8** | 0.4 | 0.06 | 3.49 |
| **Inhabited areas** | 0 | 0.05 | 0 | 0 | **0.8** | 0.01 | 0.92 |
| **Other** | 0 | 0.03 | 0 | 0.2 | 0.1 | **1.22** | 1.54 |
| **Total 2024** | 6.5 | 58.4 | 0.02 | 26 | 5.9 | 3.09 | **100** |
| | | | Landscape | | | | |
| **Forests** | **8.4** | 23 | 0 | 0.8 | 0.2 | 0.6 | 33.1 |
| **Savannahs** | 1 | **33.8** | 0.01 | 17 | 3.6 | 0.9 | 56.6 |
| **Fallow lands** | 0.1 | 1.48 | **0** | 2.6 | 0.3 | 0.13 | 4.62 |
| **Fields and Bare soils** | 0 | 0.13 | 0 | **2.9** | 0.4 | 0.05 | 3.50 |
| **Inhabited areas** | 0 | 0.04 | 0 | 0 | **0.7** | 0.01 | 0.84 |
| **Other** | 0 | 0.02 | 0 | 0.2 | 0.1 | **1.14** | 1.43 |
| **Total 2024** | 9.5 | 58.46 | 0.01 | 24 | 5.4 | 2.86 | **100** |

### *3.2. Spatial Structure of Caterpillar Habitats and Anthropisation of the LBR Landscape*

Concomitant with an increase in the number of forest patches at the landscape and reserve scales, the forest area decreased in all three zones between 2004 and 2011. Consequently, the value of the spatial transformation process (STP) of the forest class during this period was determined to be greater than 0.75. This phenomenon of dissection was not observed in the peripheral zone, which instead experienced a reduction in the number of patches, indicating the attrition of the forest class in favour of other land-use classes over the same period of time (Table 4). Savannahs simultaneously increased in size in all three studied zones of the LBR, with the creation of new patches and aggregation in the LBR landscape and its periphery. Our analysis revealed a notable decreased in fallow land area and number of patches, indicating a process of attrition. Meanwhile, inhabited areas regressed in area and number of patches in the LBR perimeter, whereas in the peripheral zone and, more generally, at the landscape level, patches of this land-use class increased in overall area as a result of aggregation (Table 4).

**Table 4.** Land-use class configuration indices in 2004, 2011, 2020, and 2024, and identification of the spatial transformation process (STP) based on the decision tree of ref. [45]. Note: 'a' stands for total area (km$^2$) and 'n' for number of patch.

| Spatial Scales | Forest | | Savannah | | Fallow Land | | Inhabited Area | |
|---|---|---|---|---|---|---|---|---|
| | **a** | **n** | **a** | **n** | **a** | **n** | **a** | **n** |
| **LBR**$_{2004}$ | 283.14 | 864 | 49.45 | 2366 | 2.11 | 311 | 0.25 | 42 |
| **Peripheral zone**$_{2004}$ | 878.40 | 18,804 | 1937.58 | 19,872 | 160.40 | 32,379 | 29.51 | 2246 |
| **Landscape**$_{2004}$ | 1162.41 | 19,561 | 1987.91 | 22,107 | 162.62 | 32,730 | 29.78 | 2289 |
| **LBR**$_{2011}$ | 215.67 | 1440 | 115.88 | 3373 | 0.43 | 89 | 0.04 | 13 |
| **Peripheral zone**$_{2011}$ | 655.00 | 18,729 | 1650.95 | 17,647 | 57.28 | 8866 | 17.82 | 1770 |
| **Landcape**$_{2011}$ | 871.16 | 20,011 | 1766.7 | 20,820 | 57.74 | 8945 | 17.27 | 1781 |
| **LBR**$_{2015}$ | 151.53 | 3123 | 180.25 | 3102 | 0.33 | 74 | 0.2 | 33 |
| **Peripheral zone**$_{2015}$ | 521.55 | 26,999 | 1698.83 | 15,598 | 39.29 | 7011 | 29.25 | 1495 |
| **Landscape**$_{2015}$ | 673.36 | 29,900 | 1879.8 | 18,526 | 39.61 | 7082 | 29.44 | 1526 |
| **LBR**$_{2020}$ | 145.45 | 3601 | 158.54 | 3778 | 0.15 | 112 | 0.63 | 160 |
| **Peripheral zone**$_{2020}$ | 398.00 | 39,268 | 1666.70 | 15,834 | 8.72 | 7353 | 33.73 | 3057 |
| **Landscape**$_{2020}$ | 543.56 | 42,631 | 1826.00 | 19,427 | 8.87 | 7466 | 34.37 | 3213 |
| **LBR**$_{2024}$ | 128.56 | 3022 | 196.59 | 3844 | 0.04 | 49 | 2.17 | 725 |
| **Peripheral zone**$_{2024}$ | 206.1 | 18,248 | 1856.00 | 20,386 | 0.7 | 569 | 188.00 | 29,870 |
| **Landscape**$_{2024}$ | 334.7 | 21,125 | 2053.77 | 24,103 | 0.75 | 618 | 189.92 | 30,631 |

From 2011 to 2015, the forest area continued to decrease in all three zones, accompanied by an increase in the number of patches, reflecting fragmentation in the LBR (ratio < 0.75) and dissection at the peripheral and landscape scales (ratio > 0.75). Savannah area simultaneously increased, but the number of patches decreased in all zones, indicating aggregation. Fallow land continued to decrease in area and number of patches (Table 4). Yet, inhabited areas increased in all zones, suggesting spot creation followed by aggregation in the peripheral zone and at the landscape scale.

Between 2015 and 2020, the forest, savannah, and fallow areas decreased in turn, concomitant with an increase in the number of patches, thereby signalling a dissection of the latter in all zones (ratio > 0.75). Inhabited areas likewise continued to increase, a trend that was marked by a simultaneous increase in area that was covered and the number of patches.

Finally, between 2020 and 2024, forests had experienced attrition process across all zones, with a simultaneous reduction in area and number of patches. In contrast, savannahs had undergone an increase in both area and number of patches, indicating a process of creation. At the same time, fallow land has continued to be suppressed, whereas new patches of inhabited area were created in all three zones under study, with a simultaneous increase in the area and the number of patches (Table 4).

Overall, it appears that from 2004 to 2024, forests and fallow land have been severely affected by human activities, with the dominant STPs being fragmentation and removal. Fields and bare soil, as well as savannah and inhabited area classes have all experienced an increase in their corresponding numbers of patches and total area over time. These responses were not simple linear progressions in terms of area or number of patches. For example, inhabited land-use area could be ordered (from lowest to highest) as 2011 < 2015 < 2004 < 2020 < 2024 (almost perfect agreement across spatial scales: W = 0.956, Chi-square = 11.47, df = 4, $P = 0.0218$). Likewise, the decrease in fallow patch number was not a linear progression, where it was ordered from largest to smallest as 2004 > 2011 $\geq$ 2020 $\geq$ 2015 > 2024 (almost perfect agreement: W = 0.960, Chi-square = 11.47, df = 4, $P = 0.0218$).These findings suggests a conversion of caterpillar-collecting ecosystems into habitats that do not favour caterpillar population growth. Overall, edible caterpillar-collecting habitats in the LBR landscape as a whole have been severely disturbed during the study period.

Between 2004 and 2024, the dominance index (D) indicated significant changes in land use within the LBR, in the peripheral zone, and at the regional scale (Table 5). In particular, in the LBR, the forest dominance index dropped from 80.68% in 2004 to 32.65% in 2024, indicating substantial fragmentation of forest areas. Simultaneously, the savannah dominance index rose sharply from 6.77% to 50.47%, marking a notable expansion of the savannah. Fallow land has maintained a very low index (not exceeding 0.048%), while inhabited areas, although marginal, show a slight increase from 0.0083% to 0.0683%, signalling the slow but steady growth of urbanised areas.

**Table 5.** Evolution of the dominance index among land-use classes between 2004 and 2024 within the Luki Biosphere Reserve, its periphery, and the LBR Landscape. For each spatial scale, savannah dominated. Until 2015, the landscape matrix within the LBR was forest. Subsequently, from 2015 to 2024, the opposite situation was subsequently observed, with forests increasingly giving way to savannah.

| Luki Biosphere Reserve | | | | | |
|---|---|---|---|---|---|
| | **2004** | **2011** | **2015** | **2020** | **2024** |
| Forest | 80.68 | 54.96 | 32.43 | 30.41 | 32.65 |
| Fallow | 0.05 | 0.01 | 0.03 | 0.00 | 0.00 |
| Savanna | 6.77 | 18.14 | 38.88 | 30.95 | 50.47 |
| Inhabited area | 0.01 | 0.01 | 0.02 | 0.03 | 0.07 |
| Peripheral zone | | | | | |
| Forest | 11.74 | 8.16 | 2.61 | 0.91 | 0.70 |
| Fallow | 0.10 | 0.03 | 0.06 | 0.00 | 0.00 |
| Savanna | 55.45 | 43.30 | 47.34 | 44.58 | 52.61 |
| Inhabited area | 0.40 | 0.15 | 0.25 | 0.39 | 1.28 |
| Landscape | | | | | |
| Forest | 22.99 | 7.74 | 3.92 | 2.48 | 4.24 |
| Fallow | 0.09 | 0.02 | 0.03 | 0.00 | 0.00 |
| Savanna | 51.13 | 25.28 | 28.67 | 26.63 | 52.77 |
| Inhabited area | 0.36 | 0.08 | 0.14 | 0.21 | 1.16 |

This situation is even more pronounced in the peripheral zone, where the forest dominance index has decreased drastically, from 11.74% in 2004 to 0.70% in 2024, indicating a severe loss of the forest continuity. In contrast, the savannah dominance index remains high, fluctuating slightly before reaching 52.61% by 2024, and indicating stabilisation (Table 5). The dominance index for fallow land remains very low (less than 0.10%), whereas that of inhabited areas has increased from 0.40% to 1.28%, reflecting marked urban growth.

The trends that were observed in and around the LBR were mirrored at the regional level. Within the entire region, the forest dominance index decreased from 22.99% in 2004 to 4.24% in 2024, indicating an increase in fragmentation. In turn, after an initial decline, by 2024 savannah had experienced a rise in dominance index to 52.77%. Similarly, fallow areas maintained a low dominance index (not exceeding 0.09%), whereas inhabited areas recorded a slight increase from 0.36% to 1.16% during the same period.

Between 2004 and 2024, the evolution of the anthropisation index showed a gradual increase in the three zones that were studied: the LBR, peripheral zone, and LBR Landscape (Figure 4). In 2004, the index was low for the LBR (0.3), it was 2.5 in the peripheral zone, and 2.0 in for the region. By 2011, these values had then increased to 0.6, 3.8, and 3.0, respectively, reflecting moderate anthropisation in the LBR and are greater elsewhere. In 2015, the index had doubled in the LBR (1.2) and continued to increase in the peripheral zone (5.0) and at the landscape scale (4.1). In 2020, the trend had stabilised in the LBR (1.2), but increased in the peripheral zone (6.7) and at the landscape scale (5.1). In 2024, a recovery was observed in the LBR (1.6), while the peripheral area (13.9) and the landscape scale (9.2) values indicated strong intensification of human activities. Overall, anthropisation has clearly increased in the peripheral zone and more globally at the landscape scale, whereas the LBR remains the zone that was least affected by human activities. Thus, the disturbance levels were much higher for all three zones during the periods 2015–2020 and 2020–2024. These results provide ample evidence that edible caterpillar habitats in the LBR landscape are characterised by instability due to disruptive anthropogenic activities that are aggravated by population growth.

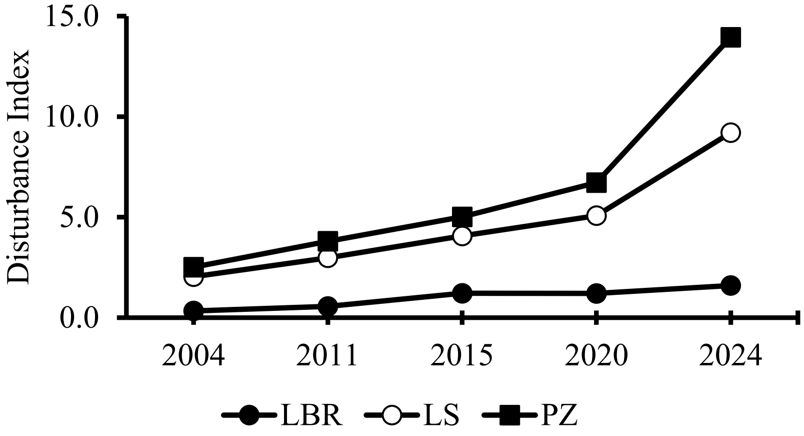

**Figure 4.** Evolution of the anthropisation index in the LBR, at its periphery and, across the entire landscape. The LBR remains the least anthropized area, unlike its periphery. The scarcity of forest resources in the peripheral zone will undoubtedly put greater pressure on the LBR. Note: LBR, Luki Biosphere Reserve; PZ, peripheral; LS, Landscape.

## 4. Discussion

Generally, studies on the spatiotemporal dynamics of protected areas give very little consideration to their peripheries. Yet, the anthropogenic pressures on protected areas most often come from their surrounding areas. The source of these anthropogenic pressures are populations in search of means of subsistence. If conservation is to be achieved while meeting the primary needs of the local population, solutions must be considered in their entirety. Hence this study, which assessed the spatiotemporal dynamics affecting the availability of edible caterpillars in the LBR landscape, considering the LBR, its periphery and the landscape as a whole. The results revealed that the landscape dynamics at the spatial scales that were studied was marked by the loss of vegetation cover in the edible caterpillar habitats. This loss of vegetation cover gives way to the development of savannahs, fields and bare soils, and inhabited areas, all of which are unfavourable habitats for edible caterpillars [26]. The degradation of vegetation cover can largely be explained by the expansion of anthropogenic activities, most notably agriculture and wood-energy exploitation [19,32]. These factors are at the root of deforestation and forest cover degradation in our study area, and are not only aggravated by unchecked population growth, but also by the lack of avenues for decision-making process regarding natural resource management [31], whereas an assessment of land uses and the factors underlying their dynamics in both LBR and its periphery area could provide these avenues. In addition, the approach to implementing development projects in the study area since 2004 has made little room for community participation and socioeconomic development, which has not led to any real sense of ownership by the people living in the surrounding of the LBR [52].

The results of our study on landscape composition dynamics in the area do not contradict those of previous studies conducted in the same landscape by [18] and on the LBR [22], which suggest deforestation in the study area as a major challenge. The same result was demonstrated in the Yangambi Biosphere Reserve landscape [53] and the Kundelungu Reserve landscapes [36], where retrogressive forest-cover dynamics were clearly demonstrated. In Africa, several authors have observed severe deforestation in forest ecosystems [54], indicating significant anthropogenic pressure on plant resources. The extension of savannahs in the study area was considered by [18], as the establishment of secondary forests, probably because their study considered as the savannah class, only those savannahs that were put under protection for the natural regeneration of forest species. However, the protected savannahs in our study was included in the forest class to limit confusion between the two classes. This decision was made because it was difficult to differentiate between the forest and regenerated savannah [22], demonstrated evidence of savannisation in the LBR. This was confirmed by our results regarding the evolution of vegetation in the LBR, within its periphery, and at the landscape level.

Structural dynamics revealed that fragmentation (caused by the fragmentation of forest patches into small fragments) and attrition (caused by the reduction in area and eradication of vegetation patches) were the main STPs underlying the disturbances imposed on edible caterpillar habitats in our study. The first STP was caused by the fragmentation of forest patches into small fragments. The second STP was caused by the reduction in area and eradication of vegetation patches. Previously, several studies had reported the detrimental effects of fragmentation and attrition on forest ecosystems [55,56]. These two processes are often responsible for the absence of certain diameter classes in plant species, resulting in significant reduction rates in the specific diversity and density of woody species in a given population [57,58]. This is likely the case in the study area. Indeed, in the absence of individuals of forest species that host edible caterpillars in several diameter classes, there is an irregularity in the distribution of these species in different habitats, as well as low specific diversity [26]. In their study of the management zones of the LBR (core, buffer, and transition zones) in relation to forest species diversity [24], demonstrated that the core zone, which is the conservation zone in which all human activities are restricted, was less disturbed and had a higher index of species diversity than the transition zone, which had been heavily disturbed. Furthermore, no economic (road building) or natural phenomena occurring in our study area would explain the dissection that was observed in the forests. These dissections are, therefore, fragmentations with regard to the types of socioeconomic activities (slash-and-burn agriculture, wood-energy, and logging) that prevail in the landscape. This observation reflects the difficulty in distinguishing between fragmentation and dissection when studying forest disturbances in tropical Africa [39,51].

Moreover, fallow land has been eliminated because of land pressure for agricultural purposes [59]. Indeed, owing to population growth, fallow periods have decreased. The hope for the regeneration of vegetation cover in edible caterpillar-collecting habitats lies in the restoration of degraded habitats but the fact that, between 2015–2020 and 2020–2024, fragmentation/dissection and an increase in the disturbance index were observed in the three areas under study might soon dash this hope. This period corresponds to the slackening of conservation projects in the LBR, when many households and young people were receiving remuneration for their involvement in reforestation activities. The increase in the areas that were occupied by fields and bare soils in the reserve after several years of conservation project implementation highlights the issues of ownership of development projects and rural employment in relation to the conservation of natural resources.

Overall, this study revealed the instability of edible caterpillar habitats in the LBR, its periphery, and the entire landscape in general. This instability was evidenced by the increase in the disturbance index over the years of the study period, the growing dominance of savannahs, the increase in the area of fields and bare soils, and inhabited areas, and the reduction in the areas of forests and fallow lands. However, it has been shown that, as edible caterpillar habitats, forests, and fallow lands are richer and more diverse than inhabited areas, where several caterpillar-host species have become rare or even locally threatened with extinction [26]. This may explain the complaints of caterpillar collectors regarding the scarcity of caterpillars. Thus, for example, in their study on the status of terrestrial mammal populations in the LBR, ref. [25] showed that, following the disturbance of the LBR, the mammalian community consisted of only a small relict population of chimpanzees (*Pan troglodytes*) that were located in the least anthropized habitats of the reserve. Consequently, it appears that the least anthropized habitats have healthy biodiversity, unlike habitats where human impact is high [60–62].

This study can be applied in the decision-making process on the integration of ecosystem goods and services in protected area management and local development community plans of communities living in their surrounding areas. For the practical application of this study, it should first be noted that the LBR landscape has a total area of 3514 km$^2$, of which 3177 km$^2$ is the periphery and 335 km$^2$ is the LBR itself. The study revealed that, despite human impact, anthropisation remains moderate in the LBR. On the other hand, in the periphery, savannahs and fields and bare soils have expanded over the past 20 years, and caterpillar habitats have been considerably affected. Inhabited areas are also habitats for edible caterpillars, which are expanding rapidly in this landscape. In view of population growth, and considering the expansion of savannahs and fields and bare soils on the peripheral zone, edible caterpillars' domestication strategies by enriching these spatial units with degradation would favour the availability of this animal protein in this landscape as recommend by [63,64] for non-timber forest products. In addition, the promotion of soil fertility improvement techniques on village lands in the peripheral zone and the development of income-generating activities will make it possible to contain the agricultural pioneer front currently directed towards the LBR [64]. This study can also be replicated in other landscape of protected area in other to assess changes on forest ecosystems and the availability of livelihood on which depend rural communities in the context of population growth and poverty.

## 5. Conclusions

Changes to natural ecosystems have both positive and negative effects on the livelihoods of people who derive most of their sustenance from nature. By using landscape ecology methods in combination with remote sensing and a Geographic Information System, this study highlighted the spatiotemporal dynamics affecting edible caterpillar-habitats. The study covered an area that was subdivided into three spatial scales: the Luki Biosphere Reserve, its periphery, and the entire landscape encomprising the LBR and its periphery. The results showed that, over the years, edible caterpillar habitats, in particular forests and fallow lands, have been converted to savannahs and fields and bare soils, which are not favourable habitats for the development of caterpillars consumed by the population in this part of the Democratic Republic of Congo. Disturbance of the edible caterpillar habitats are mainly due to fragmentation and attrition of forests and fallow land. Drivers of this transformation include the expansion of agriculture and human settlements driven by population growth. On the basis of these results, we can confirm that the hypothesis put forward at the outset has been verified. Although the research hypothesis has been verified, this study is far from complete, which leads to the formulation of further research perspectives with a view to its completion. Therefore, it would be important to study the effects of fragmentation on the phenology and reproductive capacity of edible caterpillar host plants. Similarly, it is important to analyse the impact of the fragmentation of the Luki Biosphere Reserve landscape on the local climate and its implications on the availability of edible caterpillars.

**Author Contributions:** Conceptualization, E.L.T., R.S.K., J.L.K., D.K. and J.B.; Data curation, E.L.T.; Formal analysis, E.L.T. and M.M.M.; Investigation, E.L.T.; Methodology, E.L.T., M.M.M., Y.U.S. and J.B.; Project administration, E.L.T.; Resources, E.L.T. and M.M.M.; Software, E.L.T. and M.M.M.; Supervision, Y.U.S., F.M., J.L.K., D.K. and J.B.; Validation, Y.U.S., J.-P.M.N., F.M., D.K. and J.B.; Visualisation, E.L.T.; Writing—original draft, E.L.T.; Writing—review and editing, E.L.T., M.M.M., Y.U.S., J.-P.M.N., R.S.K., F.M., D.K. and J.B. All authors have read and agreed to the published version of the manuscript.

**Funding:** The internship: which strengthened our capacity in analyzing spatial dynamics using satellite images, GIS and landscape ecology at the Ecology, Ecological Restoration and Landscape Unit of the Faculty of Agricultural Sciences at the University of Lubumbashi, was funded by the European Union in June 2021. This internship was carried out as part of the project 'Strengthening Climate Change Resilience of Local Communities in Luki and Mai-Ndombe, Democratic Republic of Congo', which was implemented by the Regional Postgraduate School for Integrated Management of Forests and Tropical Territories (ERAIFT) and the World Wide Fund for Nature.

**Data Availability Statement:** The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

**Acknowledgments:** Support for the NSERC Discovery Grant is gratefully acknowledged. We also extend our gratitude to the local communities living in and around the Luki Biosphere Reserve.

**Conflicts of Interest:** The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work that is reported in this paper.

## Appendix A

**Table A1.** Transition matrices resulting from cross-referencing 2004–2011, 2011–2015, 2015–2020, 2020–2024, and 2004–2024. These illustrate the transformations within the Luki Biosphere Reserve, the periphery and the landscape at the different periods studied.

| **Luki Biosphere Reserve** | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Forest** | **Savannah** | **Fallow** | **Field and Bare Soil** | **Inhabited Area** | **Other** | **Total 2004** |
| Forest | **63.1** | 21.21 | 0.01 | 0.04 | 0.00 | 0.14 | 84.51 |
| Savanna | 1.26 | **12.93** | 0.06 | 0.48 | 0.00 | 0.01 | 14.75 |
| Fallow | 0.01 | 0.4 | **0.05** | 0.15 | 0 | 0.00 | 0.63 |
| Field and Bare soil | 0 | 0.4 | 0.00 | **0.00** | 0 | 0 | 0.41 |
| Inhabited area | 0 | 0.02 | 0 | 0.03 | **0.00** | 0.00 | 0.07 |
| Other | 0 | 0 | 0 | 0 | 0 | **0** | 0 |
| **Total 2011** | 64.37 | 34.99 | 0.12 | 0.72 | 0.01 | 0.16 | **100** |
| | | | | | | | **Total 2011** |

**Table A1.** *Cont.*

| Luki Biosphere Reserve | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Forest** | **Savannah** | **Fallow** | **Field and Bare Soil** | **Inhabited Area** | **Other** | **Total 2004** |
| Forest | **42.55** | 21.70 | 0 | 0.00 | 0 | 0.08 | 64.34 |
| Savanna | 2.55 | **31.57** | 0.07 | 0.38 | 0.00 | 0.02 | 34.61 |
| Fallow | 0 | 0.09 | **0.00** | 0.02 | 0 | 0 | 0.13 |
| Field and Bare soil | 0.00 | 0.33 | 0.01 | **0.33** | 0.04 | 0.00 | 0.72 |
| Inhabited area | 0 | 0.00 | 0 | 0.00 | **0.01** | 0 | 0.01 |
| Other | 0.08 | 0.07 | 0 | 0.00 | 0 | **0.00** | 0.16 |
| **Total 2015** | 45.20 | 53.77 | 0.09 | 0.75 | 0.05 | 0.11 | **100** |
| | | | | | | | **Total 2015** |
| Forest | **32.16** | 9.53 | 0.00 | 0.76 | 0.01 | 2.71 | 45.20 |
| Savanna | 11.15 | **37.59** | 0.02 | 3.03 | 0.05 | 1.90 | 53.77 |
| Fallow | 0.00 | 0.00 | **0.00** | 0.08 | 0 | 0.00 | 0.09 |
| Field and Bare soil | 0.01 | 0.11 | 0.01 | **0.52** | 0.06 | 0.01 | 0.75 |
| Inhabited area | 0 | 0.00 | 0 | 0.00 | **0.04** | 0.00 | 0.05 |
| Other | 0.05 | 0.03 | 0 | 0.00 | 0.00 | **0.01** | 0.11 |
| **Total 2020** | 43.39 | 47.29 | 0.04 | 4.42 | 0.18 | 4.65 | **100** |
| | | | | | | | **Total 2020** |
| Forest | **28.40** | 14.44 | 0.00 | 0.35 | 0.06 | 0.12 | 43.40 |
| Savanna | 7.03 | **39.23** | 0.00 | 0.59 | 0.23 | 0.18 | 47.29 |
| Fallow | 0 | 0.01 | **0** | 0.02 | 0.00 | 0.00 | 0.04 |
| Field and Bare soil | 0.44 | 2.86 | 0.00 | **0.85** | 0.20 | 0.04 | 4.42 |
| Inhabited area | 0.01 | 0.04 | 0.00 | 0.01 | **0.11** | 0.00 | 0.19 |
| Other | 2.47 | 2.07 | 0.00 | 0.05 | 0.02 | **0.02** | 4.65 |
| **Total 2024** | 38.37 | 58.68 | 0.01 | 1.88 | 0.64 | 0.38 | **100** |
| | | | | | | | **Total 2004** |
| Forest | **38** | 45 | 0 | 0.7 | 0.18 | 0.2 | 84.08 |
| Savanna | 0.2 | **12** | 0 | 0.8 | 2.53 | 0.07 | 15.6 |
| Fallow | 0 | 0.23 | **0** | 0.3 | 0.03 | 0 | 0.56 |
| Field and Bare soil | 0 | 0 | 0 | **0** | 0 | 0 | 0 |
| Inhabited area | 0 | 0.01 | 0 | 0 | **0.06** | 0 | 0.07 |
| Other | 0 | 0 | 0 | 0 | 0 | **0** | 0 |
| **Total 2024** | 38.2 | 57.24 | 0.01 | 1.8 | 2.8 | 0.27 | **100** |
| **Peripheral zone** | | | | | | | |
| | **Forest** | **Savanna** | **Fallow** | **Field and Bare soil** | **Inhabited area** | **Other** | **Total 2004** |
| Forest | **15.52** | 12.02 | 0.01 | 0.07 | 0 | 0.01 | 27.66 |
| Savanna | 4.87 | **37.28** | 1.25 | 17.38 | 0.13 | 0.06 | 61 |
| Fallow | 0.21 | 2.24 | **0.42** | 2.15 | 0 | 0 | 5.04 |

**Table A1.** *Cont.*

| **Peripheral zone** | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Forest** | **Savanna** | **Fallow** | **Field and Bare soil** | **Inhabited area** | **Other** | **Total 2004** |
| Field and Bare soil | 0 | 0.24 | 0.09 | **3.46** | 0.02 | 0 | 3.82 |
| Inhabited area | 0 | 0.06 | 0 | 0.49 | **0.35** | 0 | 0.92 |
| Other | 0 | 0.07 | 0.01 | 0.47 | 0.02 | **0.95** | 1.53 |
| **Total 2011** | 20.61 | 51.93 | 1.8 | 24.05 | 0.54 | 1.04 | **100** |
| | | | | | | | **Total 2011** |
| Forest | **13.28** | 7.27 | 0 | 0.02 | 0 | 0.02 | 20.61 |
| Savanna | 3.08 | **43.35** | 0.32 | 5.02 | 0.03 | 0.11 | 51.94 |
| Fallow | 0 | 0.23 | **0.33** | 1.23 | 0 | 0 | 1.8 |
| Field and Bare soil | 0.02 | 2.56 | 0.58 | **20.17** | 0.5 | 0.19 | 24.1 |
| Inhabited area | 0 | 0 | 0 | 0.15 | **0.37** | 0.01 | 0.54 |
| Other | 0.01 | 0.03 | 0 | 0.05 | 0 | **0.94** | 1.05 |
| **Total 2015** | 16.41 | 53.47 | 1.23 | 26.66 | 0.92 | 1.29 | **100** |
| | | | | | | | **Total 2015** |
| Forest | **6.56** | 8.71 | 0 | 0.51 | 0 | 0.61 | 16.41 |
| Savanna | 5.55 | **39.52** | 0.05 | 7.12 | 0.05 | 1.15 | 53.47 |
| Fallow | 0.02 | 0.17 | **0.02** | 0.96 | 0 | 0.03 | 1.23 |
| Field and Bare soil | 0.36 | 3.94 | 0.18 | **21.36** | 0.38 | 0.41 | 26.66 |
| Inhabited area | 0 | 0.01 | 0 | 0.24 | **0.58** | 0.07 | 0.92 |
| Other | 0.02 | 0.08 | 0 | 0.07 | 0.02 | **1.08** | 1.29 |
| **Total 2020** | 12.52 | 52.46 | 0.27 | 30.29 | 1.06 | 3.38 | **100** |
| | | | | | | | **Total 2020** |
| Forest | **3.54** | 7.49 | 0 | 1.14 | 0.12 | 0.2 | 12.52 |
| Savanna | 2.61 | **42.05** | 0 | 5.24 | 1.5 | 1.04 | 52.46 |
| Fallow | 0 | 0.05 | **0** | 0.19 | 0.02 | 0 | 0.27 |
| Field and Bare soil | 0.11 | 7.39 | 0.01 | **19.08** | 3.17 | 0.51 | 30.29 |
| Inhabited area | 0 | 0.05 | 0 | 0.07 | **0.9** | 0.01 | 1.06 |
| Other | 0.2 | 1.37 | 0 | 0.33 | 0.15 | **1.3** | 3.37 |
| **Total 2024** | 6.48 | 58.42 | 0.01 | 26.08 | 5.86 | 3.06 | **100** |
| | | | | | | | **Total 2004** |
| Forest | **5.32** | 20.64 | 0 | 0.78 | 0.25 | 0.63 | 27.65 |
| Savannah | 1.05 | **35.92** | 0.01 | 19.05 | 3.94 | 0.99 | 61 |
| Fallow | 0.09 | 1.61 | **0** | 2.83 | 0.35 | 0.15 | 5.05 |
| Field and Bare soil | 0 | 0.15 | 0 | **2.83** | 0.44 | 0.06 | 3.49 |
| Inhabited area | 0 | 0.05 | 0 | 0.04 | **0.81** | 0.01 | 0.92 |
| Other | 0 | 0.03 | 0 | 0.18 | 0.1 | **1.22** | 1.54 |
| **Total 2024** | 6.48 | 58.42 | 0.01 | 25.74 | 5.9 | 3.09 | **100** |

**Table A1.** *Cont.*

| | **Landscape** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Forest** | **Savannah** | **Fallow** | **Field and Bare soil** | **Inhabited area** | **Other** | **Total 2004** |
| Forest | **20.06** | 12.9 | 0.01 | 0.07 | 0 | 0.02 | 33.08 |
| Savanna | 4.52 | **34.95** | 1.14 | 15.76 | 0.11 | 0.05 | 56.57 |
| Fallow | 0.19 | 2.06 | **0.39** | 1.96 | 0 | 0 | 4.62 |
| Field and Bare soil | 0 | 0.22 | 0.08 | **3.13** | 0.01 | 0 | 3.46 |
| Inhabited area | 0 | 0.06 | 0 | 0.45 | **0.32** | 0 | 0.84 |
| Other | 0 | 0.06 | 0 | 0.43 | 0.02 | **0.86** | 1.4 |
| **Total 2011** | 24.8 | 50.3 | 1.62 | 21.82 | 0.5 | 0.93 | **100** |
| | | | | | | | **Total 2011** |
| Forest | **16.08** | 8.65 | 0.00 | 0.00 | 0.00 | 0.03 | 24.77 |
| Savanna | 3.03 | **42.22** | 0.30 | 4.60 | 0.03 | 0.10 | 50.28 |
| Fallow | 0.00 | 0.22 | **0.29** | 1.11 | 0.00 | 0.00 | 1.64 |
| Field and Bare soil | 0.02 | 2.35 | 0.52 | **18.27** | 0.46 | 0.17 | 21.82 |
| Inhabited area | 0.00 | 0.00 | 00.00 | 0.14 | **0.33** | 0.00 | 0.49 |
| Other | 0.02 | 0.03 | 00.00 | 0.04 | 0.00 | **0.85** | 0.96 |
| **Total 2015** | 19.16 | 53.50 | 1.13 | 24.16 | 0.83 | 1.18 | **100** |
| | | | | | | | **Total 2015** |
| Forest | **9** | 8.79 | 0 | 0.53 | 0 | 0.81 | 19.16 |
| Savanna | 6.08 | **39.34** | 0.05 | 6.73 | 0.05 | 1.22 | 53.5 |
| Fallow | 0.02 | 0.16 | **0.02** | 0.88 | 0 | 0.03 | 1.12 |
| Field and Bare soil | 0.32 | 3.58 | 0.17 | **19.37** | 0.35 | 0.37 | 24.18 |
| Inhabited area | 0 | 0.01 | 0 | 0.22 | **0.53** | 0.06 | 0.83 |
| Other | 0.02 | 0.07 | 0 | 0.06 | 0.01 | **0.98** | 1.18 |
| **Total 2020** | 15.47 | 51.96 | 0.25 | 27.82 | 0.97 | 3.5 | **100** |
| | | | | | | | **Total 2020** |
| Forest | **5.92** | 8.16 | 0 | 1.07 | 0.12 | 0.2 | 15.47 |
| Savanna | 3.03 | **41.78** | 0 | 4.79 | 1.38 | 1 | 51.98 |
| Fallow | 0 | 0.05 | **0** | 0.17 | 0.01 | 0 | 0.23 |
| Field and Bare soil | 0.14 | 6.96 | 0 | **17.34** | 2.89 | 0.46 | 27.82 |
| Inhabited area | 0.00 | 0.05 | 0 | 0.06 | **0.83** | 0.01 | 0.97 |
| Other | 0.42 | 1.43 | 0 | 0.3 | 0.14 | **1.2** | 3.5 |
| **Total 2024** | 9.52 | 58.44 | 0 | 24 | 5.3 | 2.87 | **100** |
| | | | | | | | **Total 2004** |
| Forest | **8.44** | 22.97 | 0 | 0.77 | 0.24 | 0.6 | 33.05 |
| Savanna | 0.97 | **33.75** | 0.01 | 17.3 | 3.6 | 0.9 | 56.56 |
| Fallow | 0.08 | 1.48 | **0** | 2.59 | 0.32 | 0.13 | 4.62 |
| Field and Bare soil | 0 | 0.13 | 0 | **2.87** | 0.4 | 0.05 | 3.47 |

**Table A1.** *Cont.*

| | Landscape | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Forest** | **Savannah** | **Fallow** | **Field and Bare soil** | **Inhabited area** | **Other** | **Total 2004** |
| Inhabited area | 0 | 0.04 | 0 | 0.04 | **0.73** | 0.01 | 0.84 |
| Other | 0 | 0.02 | 0 | 0.16 | 0.09 | **1.14** | 1.43 |
| **Total 2024** | 9.51 | 58.43 | 0.01 | 23.75 | 5.41 | 2.86 | **100** |

## References

1. Giradoux, P. La santé des écosystèmes: Quelle définition? *Bull. Acad. Vet.* **2022**, *175*, 120–139.
2. Amar, R. Impact de l'anthropisation sur la biodiversité et le fonctionnement des écosystèmes marins. Exemple de la Manche-mer du nord. *Vertigo* **2010**, *8*, 1–13.
3. Teyssèdre, A. Les Services Écosystémiques, Notion clé Pour Explorer et Préserver le Fonctionnement des (Socio)Écosystèmes. Regard R4 SFE2 2010. sfecologie.org. Available online: https://sfecologie.org/wp-content/uploads/2010/10/R4-Teyssedre-2010.pdf (accessed on 2 January 2025).
4. Bitamba, F.J.; Bazirukize, K.E.; Zikama, N.L.; Ntahondi, H.A. Impact des activités humaines sur les écosystèmes forestiers du groupement Kamuronza en territoire de Massisi, Nord-Kivu. *Bull. Inf. Tour. Environ.* **2012**, 122–132. Available online: https://www.istougoma.ac.cd/pdf/publication/640f295d51fd2.pdf (accessed on 20 September 2024).
5. Brun, L.E.; Sinasson, G.; Azihou, A.F.; Gibigaye, M.; Tente, B.A.H. Perceptions des facteurs déterminants de dégradation de la flore des zones humides dans la commune d'Allada, Sud—Bénin. *Afri. Sci.* **2020**, *16*, 52–67.
6. FAO; PNUD. La Situation des Forêts Dans le Monde 2020. Forêts, Biodiversité et Activités Humaines. Rome 2020. Fao.org. Available online: https://openknowledge.fao.org/handle/20.500.14283/ca8642fr (accessed on 2 January 2025).
7. Global Forest Watch. Global Annual Tree Cover Loss. Global Forest Watch. 2023. Available online: https://www.globalforestwatch.org/dashboards/global/ (accessed on 2 January 2025).
8. Bongaarts, J. IPBES, 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. *Popul. Dev. Rev.* **2019**, *45*, 680–681. [CrossRef]
9. Vancutsem, C.; Achard, F.; Pekel, J.-F.; Vieilledent, G.; Carboni, S.; Simonetti, D.; Gallego, J.; Aragão, L.E.O.C.; Nasi, R. Long-term (1990–2019) monitoring of forest cover changes in the humid tropics. *Sci. Adv.* **2021**, *7*, 21. [CrossRef]
10. Dalimier, J.; Achard, F.; Delhez, B.; Desclée, D.; Bourgoin, C.; Eva, H.; Gourlet, S.-F.; Hansen, M.; Kibambe, J.P.; Mortier, M.; et al. Répartition des Types de Forêts et Évolution Selon Leur Affectation. In *ETAT des Forêts de L'AFRIQUE Centrale*; UC-Louvain-Geomatics: Louvain, Belgium, 2022; pp. 3–36. Available online: https://www.cifor-icraf.org/publications/pdf_files/Books/Etat-des-forets-2021.pdf (accessed on 2 January 2025).
11. Molinaro, G.; Hansen, M.C.; Patapov, P. Forest cover dynamics of shifting cultivation in the Democratic Republic of Congo: Remote sensing-based assessment for 2000–2010. *Environ. Res. Lett.* **2015**, *10*, 094009. [CrossRef]
12. Molinaro, G.; Hansen, M.C.; Patapov, P.; Tyukavina, A.; Stehman, S. Contextualizing landscape-scale forest cover loss in the Democratic Republic of Congo (DRC) between 2000 and 2015. *Land* **2020**, *9*, 23. [CrossRef]
13. Kyale, K.J.; Wardell, D.A.; Mikwa, J.-F.; Kabuanga, J.M.; Monga, N.A.M.; Oszwald, J.; Doumenge, C. Dynamique de la déforestation dans la Réserve de biosphère de Yangambi (République démocratique du Congo): Variabilité spatiale et temporelle au cours des 30 dernières années. *Bois Forêts Trop.* **2019**, *341*, 15–28. [CrossRef]
14. Tingu, C.; Mathunabo, A. Analyse de la situation socio- économique et alimentaire des ménages des provinces du Nord et Sud Ubangi en RDC. *Rev. Mar. Sci. Agron. Vét.* **2019**, *7*, 203–211.
15. Semeki, N.J.; Linchant, J.; Quevauvillers, S.; Kahindo, M.J.-M.; Lejeune, P.; Vermeulen, C. Cartographie de la dynamique de terroirs villageois à l'aide d'un drone dans les aires protégées de la République démocratique du Congo. *Bois Forêts Trop.* **2016**, *330*, 70–83.
16. Nyembo, F.; Mertens, B.; Cherif, M.; Inza, K. Menaces d'origine anthropique et Habitat de *Pan Paniscus* dans La reserve naturelle de Sankuru, en République démocratique du Congo. *Eur. Sci. J.* **2021**, *16*, 290–309.
17. Cirezi, C.N.; Tshibasu, E.; Lutete, E.; Mushagalusa, A.; Mugumaarhahama, Y.; Ganza, D.; Karume, K.; Michel, B.; Lumbuenamo, R.; Bogaert, J. Fire risk assessment, spatiotemporal clustering and hotspot analysis in the Luki biosphere reserve region, Western DR Congo. *Trees For. People* **2021**, *5*, 22. [CrossRef]

18. Cirezi, C.N.; Bastin, J.F.; Tsibasu, E.; Lonpi, T.E.; Chuma, G.B.; Mugumaarhahama, Y.; Sambieni, K.R.; Karume, K.-C.; Lumbuenamo, S.R.; Bogaert, J. Contribution of human induced fires to forest and savannah land conversion dynamics in the Luki biosphere reserve landscape, western Democratic Republic of Congo. *Int. J. Remote Sens.* **2022**, *43*, 6406–6429. [CrossRef]
19. Semeki, N.J.; Tongo, Y.M. Livelihoods Means and Local Populations Strategies of the Luki's Biosphere Reserve in Democratic Republic of Congo. *Int. J. Nat. Resour. Ecol. Manage* **2019**, *4*, 42–49.
20. Kaleba, C.S.; Sikuzani, U.Y.; Sambieni, K.R.; Bogaert, J.; Munyemba, K.F. Dynamique des écosystèmes forestiers de l'arc cuprifère katangais en République Démocratique du Congo. Causes, transformations spatiales et ampleur. *Tropicultura* **2017**, *35*, 192–202.
21. Sikuzani, U.Y.; Malaisse, F.; Kaleba, C.S.; Munyemba, K.F.; Bogaert, J. Rayon de déforestation autour de la ville de Lubumbashi (Haut-Katanga, RD. Congo), Synthèse. *Tropicultura* **2017**, *35*, 215–221. [CrossRef]
22. Opelele, O.M.; Ying, Y.; Wengi, F.; Chen, C.; Kachaka, S.K. Examining land use/land cover and its prediction based on a multilayer perception Markov Approach in the Luki biosphere reserve, Democratic Republic of Congo. *Sustainability* **2021**, *13*, 6898. [CrossRef]
23. Opelele, O.M.; Ying, Y.; Wenyi, F.; Lubalega, T.; Chen, C.; Kachaka, S.K. Analysis of the impact of land-use/land-cover change on land-surface temperature in the villages withing the Luki biosphere reserve. *Sustainability* **2021**, *13*, 11242.
24. Opelele, O.M.; Ying, Y.; Wenyi, F.; Lubalega, T.; Chen, C.; Kachaka, S.K.C. Impact of land use change on tree diversity and aboveground carbon storage in the Mayumbe Tropival forest of the Democratic Republic Congo. *Land* **2022**, *11*, 787.
25. Kwidja, D.Y.; Fonteyn, D.; Semeki, N.J.; Mvuezolo, N.M.; Poulain, P.; Lonpi, T.E.; Vermeulen, C. État des populations des mammifères terrestres dans la Réserve de Biosphère de Luki (République démocratique du Congo). *Biotechnol. Agron. Soc. Environ.* **2023**, *27*, 13.
26. Lonpi, T.E.; Sambieni, K.R.; Messina, N.J.-P.; Nsevolo, M.P.; Boyombe, L.L.; Kasali, J.L.; Khasa, D.; Malaisse, F.; Bogaert, J. Diversity and availability of edible caterpillar host plants in the Luki biosphere reserve landscape in the Democratic Republic of the Congo. *Trees For. People* **2024**, *18*, 100719. [CrossRef]
27. Lonpi, T.E. RDC: Comment les atteintes à la biodiversité affectent les habitudes alimentaires. *The Conversation*, 2022. Available online: https://theconversation.com/en-rdc-comment-les-atteintes-a-la-biodiversite-affectent-les-habitudes-alimentaires-174092 (accessed on 30 June 2022).
28. Lonpi, T.E.; Sambieni, K.R.; Khasa, D.; Bogaert, J.; Kasali, J.L.; Huart, A.; Konda, K.M.A.; Malaisse, F. Les chenilles consommées dans la région de la réserve de biosphère de Luki en République démocratique du Congo: Acteurs, connaissances locales et pressions. *BOIS For. DES Trop.* **2023**, *355*, 21–34. [CrossRef]
29. Bomolo, O.; Niassy, S.; Chocha, A.; Longanza, B.; Bugeme, D.M.; Ekesi, S.; Tanga, C.M. Ecological diversity of edible insects and their potential contribution to household food security in Haut-Katanga Province, Democratic Republic of Congo. *Afri. J. Ecol.* **2017**, *55*, 640–653. [CrossRef]
30. Looli, B.L.; Dowiga, B.; Bosela, O.; Salamu, P.; Manzenga, J.C.; Posho, B.; Mabossy-Mobouna, G.; Latham, P.; Malaisse, F. Techniques de récolte et exploitation durable des chenilles comestibles dans la région de Yangambi, R.D. Congo. *Geo-Eco-Trop* **2021**, *45*, 113–129.
31. Nyangue, N.M. Participation des communautés locales et gestion durable de forêts: Cas de la réserve de la biosphère de Luki en République Démocratique du Congo. *Thèse Dr. Sci. For.* **2014**, 205. Available online: https://www.google.com.hk/url?sa=t&source=web&rct=j&opi=89978449&url=https://dam-oclc.bac-lac.gc.ca/download?id=8996c639-1979-4e54-b42a-a75dc98c6a7f&fileName=30892.pdf&ved=2ahUKEwiN3oCh_O2NAxWTslYBHVTQJJUQFnoECBYQAQ&usg=AOvVaw15kxElraX0Krs2-BZxk56b (accessed on 15 September 2024).
32. Desclee, D.; Michel, B.; Trefon, T. Enquête et étude de diagnostic des capitaux et stratégies d'existence des ménages dépendant de ressources de la Réserve de Biosphère de Luki en République Démocratique du Congo. *Tropicultura* **2018**, *36*, 492–505.
33. Lubini, A. La végétation de la réserve de biosphère de Luki au Mayombe (Zaïre). *Opera Bot. Belg.* **1997**, *10*, 155.
34. Kergomard, C. Pratique des corrections atmosphériques en télédétection: Utilisation du logiciel 5S-PC. *Cybergio Eur. J. Geogr.* **1996**, *181*. [CrossRef]
35. Nkwunonwo, U.C. Land use/Land cover mapping of the Lagos Metropolis of Nigeria using 2012 SLC-off Landsat ETM+ Satellite Images. *Int. J. Sci. Eng. Res.* **2013**, *4*, 1217–1223.
36. Sikuzani, U.Y.; Mukenza, M.M.; Malaisse, F.; Kazaba, K.P.; Bogaert, J. The spatiotemporal changing dynamics of Miombo deforestation and illegal human activities for forest fire in Kundelungu National park, Democratic Republic of the Congo. *Fire* **2023**, *6*, 174. Available online: https://www.mdpi.com/2571-6255/6/5/174 (accessed on 25 February 2025). [CrossRef]
37. Barima, Y.S.S.; Barbier, N.; Bamba, I.; Traore, D.; Lejoly, J.; Bogaert, J. Dynamique paysagère en milieu de transition forêt-savane ivoirienne. *BOIS For. DES Trop.* **2009**, *299*, 15–25.
38. Mama, A.; Sinsin, B.; De Cannière, C.; Bogaert, J. Anthropisation et dynamique des paysages en zone soudanienne au Nord du Bénin. *Tropicultura* **2013**, *31*, 78–88.
39. Kabuanga, M.J.; Guguya, B.A.; Okito, N.E.; Maestripieri, N.; Saqalli, M.; Rossi, V.; Iyongo, W.M.L. Suivi de l'anthropisation du paysage dans la région forestière de Babagulu, République Démocratique du Congo. *Vertigo* **2020**, *20*, 28.

40. Skupinski, G.; Tran, D.B.; Weber, C. Les images satellites Spot multi-dates et la métrique spatiale dans l'étude du changement urbain et suburbain: Le cas de la basse vallée de la Bruche (Bas-Rhin, France). *Eur. J. Geogr.* **2009**, *439*, 22.
41. Mukenza, M.M.; Muteya, K.H.; Nghonda, N.D.; Sambieni, K.R.; Malaisse, F.; Kaleba, C.S.; Bogaert, J.; Sikuzani, U.Y. Uncontrolled Exploitation of Pterocarpus tinctorius Welw. and Associated Landscape Dynamics in the Kasenga Territory: Case of the Rural Area of Kasomeno (DR Congo). *Land* **2022**, *11*, 1541. [CrossRef]
42. O'Neill, R.V.; Krumme, J.R.; Gardner, R.H.; Sugihara, G.; Jackson, B.; DeAngelist, D.L. Indices of landscape pattern. *J. Landsc. Ecol.* **1988**, *1*, 153–162.
43. Schlaepfer, R. Analyse de la dynamique du paysage. *Fiche d'enseignement 4.2, Laboratoire de Gestion des Ecosystèmes, Ecole Polytechnique de Lausanne, Switzerland*. 2002. Available online: https://www.scirp.org/reference/referencespapers?referenceid=2987497 (accessed on 25 February 2021).
44. Mama, A.; Bamba, I.; Sinsin, B.; Bogaert, J.; De Cannière, C. Déforestation, savanisation et développement agricole des paysages de savanes-forêts dans la zone soudano-guinéenne du Bénin. *BOIS For. DES Trop.* **2014**, *322*, 65–75.
45. Bogaert, J.; Ceulemans, R.; Salvador-Van, E.D. Decision Tree Algorythm in landscape transformation. *JEM* **2004**, *33*, 62–73.
46. De Haulleville, T.; Rakotondrasoa, O.L.; Rakoto, R.H.; Bastin, J.F.; Brostaux, Y.; Verheggen, F.J.; Rajoelison, L.G.; Malaisse, F.; Bogaert, J.; Poncelet, M.; et al. Fourteen years of anthropization dynamics in the Uapaca bojeri Baill. forest of Madagascar. *Landsc. Ecol. Eng.* **2018**, *14*, 135–146.
47. Kabulu, D.J.; Bamba, I.; Munyemba, K.F.; Defourny, P.; Vancutsem, C.; Nyembwe, N.S.; Ngongo, L.M.; Bogaert, J. Analyse de la structure spatiale des forêts du Katanga. *Ann. Fac. Sci. Agro.* **2008**, *1*, 12–18.
48. Mohamed, M.E.; Abdelghani, H.; Mohamed, E.F. Apport de la télédétection et du SIG au suivi de la dynamique spatiotemporelle des forêts des massifs numidien de Jbel Outka (Rift central, Maroc). *Rev. Geogr. Ordenam. Territ.* **2017**, *1*, 171–187. [CrossRef]
49. Mcgarigal, K. *FRAGSTATS Help*; University of Massachusetts: Amherst, MA, USA, 2015.
50. Mama, A.; Oumorou, M.; Sinsin, B.; De Canniere, C.; Bogaert, J. Anthropisation des paysages naturels des aires protégées au Bénin: Cas de la forêt classée de l'Alibori Supérieur (FC-AS). *Am. J. Innov. Res. Appl. Sci.* **2020**, *11*, 117–125.
51. Kilensele, M.T. Limites des Stratégies de Conservation Forestière en République Démocratique du Congo. Cas de la Réserve de Biosphère de Luki. Doctoral Thesis, Faculté des Sciences Institut de Gestion de L'environnement et D'aménagement du Territoire, Université Libre de Bruxelles, Bruxelles, Belgique, 2015. Available online: https://www.academia.edu/85872793/Limites (accessed on 15 September 2024).
52. Bwazani, B.J.; Meniko To Hulu, J.P.P.; Bogaert, J. Anthropisation et Modélisation Prospective des Paysages Forestiers Dans la Province de la Tshopo, RD Congo « Cas de la Réserve de Biosphère de Yangambi et de la Réserve Forestière de Masako. Master's Thesis, de l'Université de Kinshasa, Kinshasa, Democratic Republic of the Congo, 2023. Available online: https://www.researchgate.net/publication/375756179 (accessed on 15 September 2024).
53. Abdou, K.I.; Abasse, T.A.; Massaoudou, M.; Rabiou, H.; Soumana, I.; Bogaert, J. Influence des pressions anthropiques sur la dynamique paysagère de la réserve partielle de faune de Dosso (Niger). *Int. J. Biol. Chem. Sci.* **2016**, *13*, 1094.
54. Inoussa, M.M.; Mahamane, A.; Mbow, C.; Saadou, M.; Yvonne, B. Dynamique spatio-temporelle des forêts claires dans le Parc national du W du Niger (Afrique de l'Ouest). *JLE* **2011**, *22*, 108–116. [CrossRef]
55. Toyi, M.S.S.; Andre, M.; Sikuzani, Y.U.I.; Bogaert, J.; Sinsin, B. Trente ans d'anthropisation des paysages forestiers au sud du Bénin (Afrique de l'Ouest). *Afr. J. OnLine* **2019**, *23*, 183–197.
56. Razafimahefa, A.L. Impact de la Fragmentation D'habitat Chez Adansonia rubrostipa Dans la Région Menabe. *Master's Thesis*; Université d'Antananarivo: Antananarivo, Madagascar, 2016. Available online: https://protectedareas.mg/ (accessed on 15 September 2024).
57. Bouko, B.S.; Dossous, P.J.; Amadou, B.; Sinsin, B. Exploitation des ressources biologiques et dynamique de la forêt classée de la Mekrou au Benin. *Eur. Sci. J.* **2016**, *12*, 228–244. [CrossRef]
58. Dejace, D. Perspectives de Mise en Place de la Régénération Naturelle Assistée Pour L'amélioration de Jachères Apicoles, en périphérie de la Réserve de Biosphère de Luki (RDC). Master's Thesis, Université de Liège, Gembloux, Belgique, 2019.
59. Boissier, O. *Impact des Pressions Anthropiques Sur les Communautés de Frugivores et la Dispersion des Graines en Forêt Guyanaise*; Museum National D'histoire Naturelle: Paris, France, 2012.
60. Cateau, E. Reponse des Coleopteres Saproxyliques Apteres aux Perturbations Anthropiques des Forets et des Paysages. *Doctoral Thesis*; Université de Toulouse: Toulouse, France, 2016. Available online: https://hal.inrae.fr/tel-02796092v2/file/Cateau_Eugenie.pdf (accessed on 15 September 2024).
61. Alongo, S.; Kombele, F.; Bogaert, J. Etude des relations sol-plante après la fragmentation de la forêt par l'agriculture itinérante sur abattis brûlis dans la région de Yangambi, R.D. Congo. *J. Agroecol. Environ. Res.* **2022**, *1*, 74–83.
62. Doumenge, C.; Palla, F.; Itsoua Madzous, G.-L. (Eds.) *Aires Protégées D'afrique Centrale—État 2020*; OFAC-COMIFAC, Yaoundé, Cameroun & UICN: Gland, Switzerland, 2021; pp. 132–173. Available online: https://agritrop.cirad.fr/598758/1/EDAP_2020.pdf (accessed on 19 May 2025).

63. Molnar, A.; Sara, J.; Khare, S.; Khare, A. Qui Conserve Les Forêts Du Monde? Stratégies Communautaires de Protection des Forêts et de Respect des Droits. 2021, p. 32. Available online: https://rightsandresources.org/wp-content/uploads/Who-Owns-the-Worlds-Land-French.pdf (accessed on 19 May 2025).
64. Angu, K.; Pélissier, C.; Tchamou, N. La Gestion des Aires Protégées Dans Les Paysages du Pfbc: Un État des Lieux. 2021, pp. 185–206. Available online: https://www.researchgate.net/publication/326804788_La_Gestion_des_Aires_Protegees_dans_les_Paysages_du_PFBC_Un_Etat_des_Lieux (accessed on 19 May 2025).