Historical and future deforestation analysis of Ribaue Mountains (Mount Ribaue and Mount M'paluwe)

Montfort Frédérique

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1_Introduction

This report presents a deforestation assessment of Ribaue Mountains based on satellite-observed land cover and vegetation change. This assessment is composed of two analysis:

- *Analysis of historical deforestation*: this section aims to map forest extent and deforestation of Ribaue Mountains over the 2000-2020 period on the basis of Landsat images.
- *Analysis of risks of future deforestation*: this section aims to map future threatened forest patches of Ribaue Mountains, based on historical deforestation and comprehension of the deforestation drivers.

Ribaue Mountains is a series of granite inselbergs in northern Mozambique near the town of Ribaue in Nampula Province (Figure 1). The Ribaue Mountains is composed of Mount Ribaue and Mount M'paluwe. The inselbergs rise from a relatively flat landscape from 500-600 m altitude up to 1675 m on Monte M'paluwe. They form part of a belt of granite rock outcrops, inselbergs and mountains, running NE-SW across Nampula and Zambezia provinces and including Mt Inago (1804 m), Mt Namuli (2419 m) and Mt Mabu (1700m) to the southwest of the Ribaue massif (Kew Botanical Garden, 2018).

This belt is considered as a center of endemism (Darbyshire et al., 2019). Overall the site supports 15 nationally endemic plant taxa (plants that only occur in Mozambique), 11 near-endemics (plants that are restricted to Mozambique and neighbouring countries) and 10 taxa that are threatened with extinction on the Global IUCN Red List (Kew Botanical Garden, 2018). Steeply sloping granite rock outcrops, mid-altitude moist forest and miombo woodland are the dominant habitat types at the Ribaue massif. The site also includes smaller areas of gallery forest, marsh, seasonal stream gullies, seepage on granite rock, and shaded granite cliffs (Kew Botanical Garden, 2018).

The expansion of subsistence agriculture on the slopes of the Ribaue Massif is a serious threat to forests and forest habitats.

Since 2019, Nitidæ with the support of the US based NGO Legado, study the Ribaue Mountains landscape dynamic through the conduction of 2 studies, this historical and future deforestation risk assessment and a detailed agrarian diagnostic still in progress to promote Mount Ribaue and Mount M'paluwe sustainable management involving local communities.

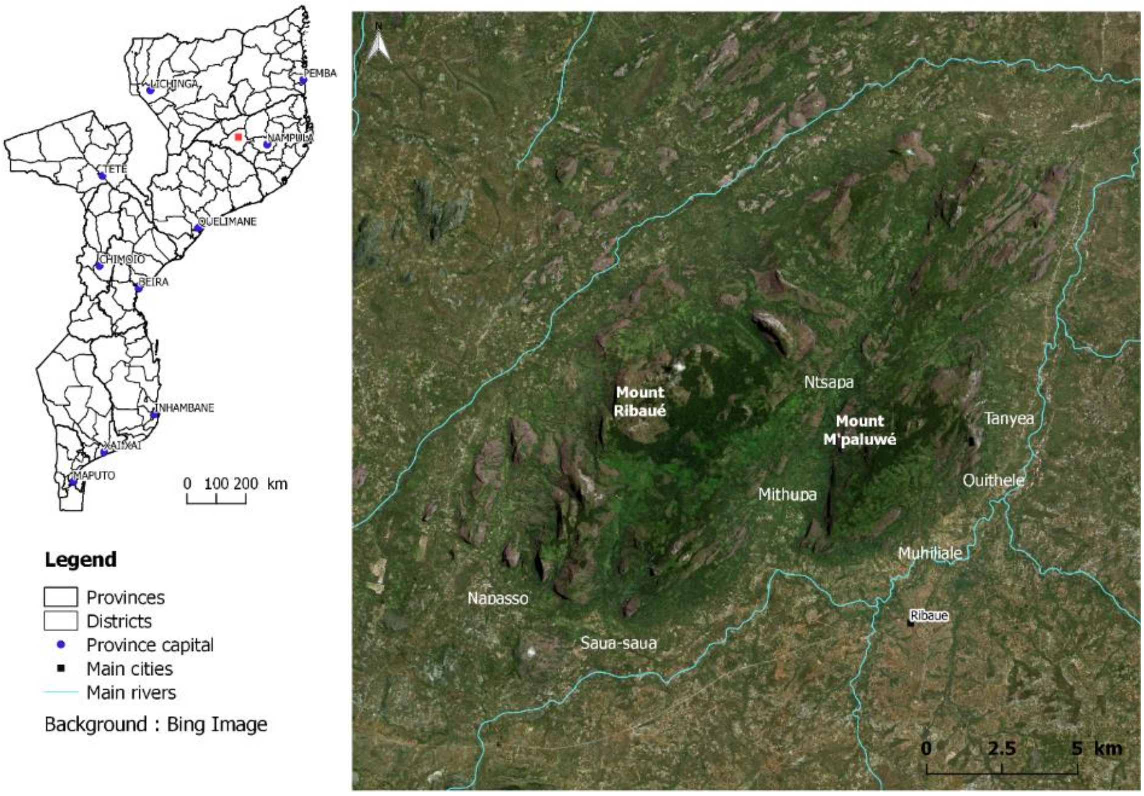

Figure 1 : Location of Ribaue Mountains

2_Analysis of historical deforestation

Historical deforestation analysis helps to better understand past dynamics and therefore provide appropriate options to reduce deforestation. The objective of this section is to map forest extent and deforestation over a 20 years period from 2000 to 2020 in the Ribaue Mountains. This section describes the various steps that have been implemented for the analysis of past deforestation, from the acquisition of satellites images to the final results.

2.1. Methodology:

The methodology used in this study is based on a classical approach of remote sensing: 1) satellite image collection, 2) data pre-processing, 3) delineation of training plots, 4) supervised classification of land use and land cover change using a statistical model and 5) post-processing. The methodology is summarized in the following figure:

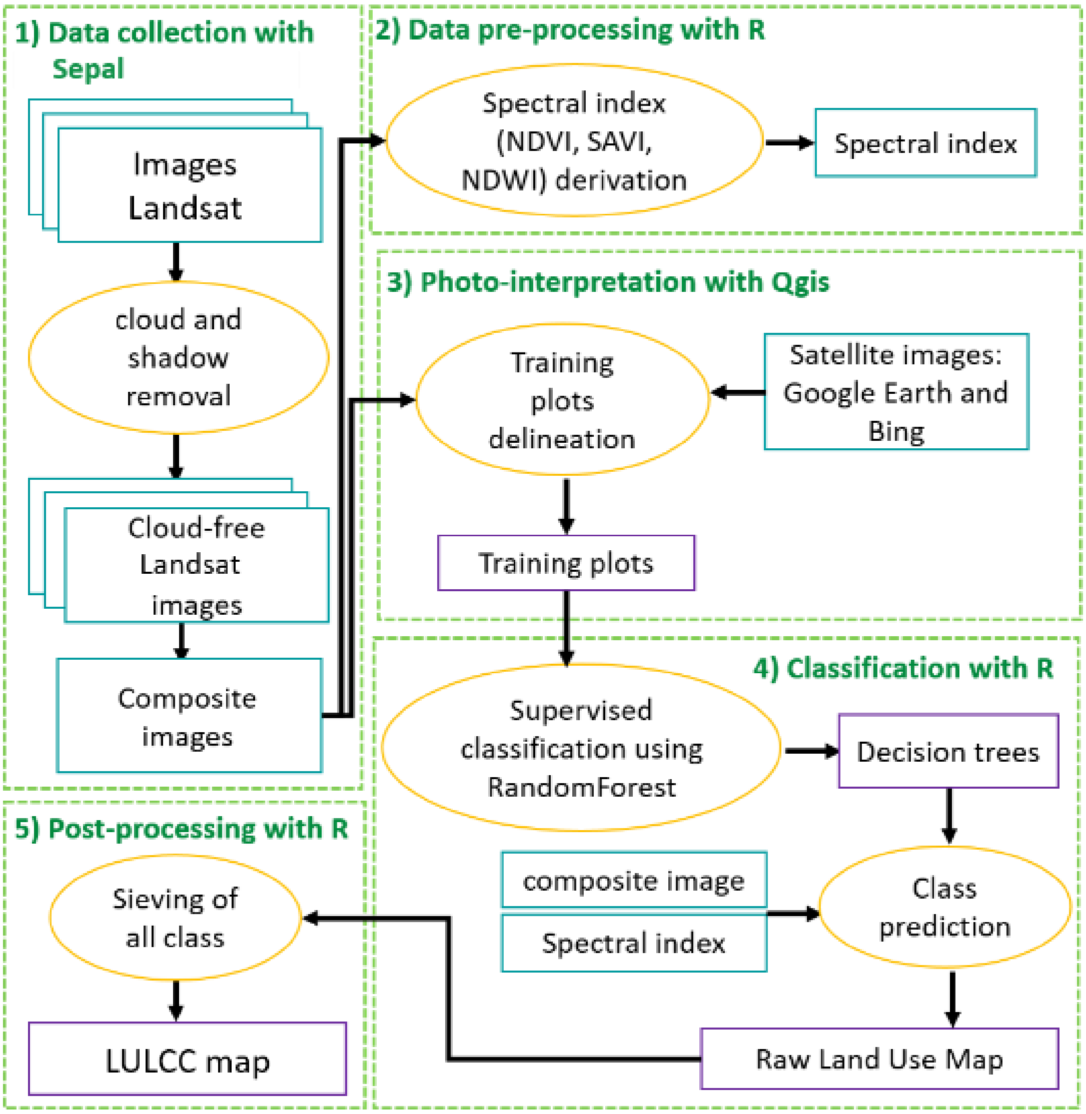

Figure 2 : Processing chain applied for the land use and land cover change mapping

2.1.1. Satellite image collection

The land use and land cover change analysis relies on Landsat imagery as it is the only consistent source of high resolution satellite data available for the period of interest. Landsat images from 2000 to 2020 were used with a spatial resolution of 30 m. Those images are available on the USGS data servers (Earth Explorer, www.earthexplorer.usgs.gov) for free. When there was no cloud-free image available we used the Sepal platform (https://sepal.io) to create a cloud-free Landsat composite. All images come from three different Landsat missions: 5, 7 and 8/OLI, which have slightly different sensors in terms of width and number of spectral bands. Images were uploaded by bands; therefore it was primarily necessary to combine these single bands into multispectral images (stacking) to be comparable from one date to another.

The study is covered by one Landsat scene, presenting the following identifiers: 165/70 (path/row). The selected Landsat scenes are presented in the following tables.

Table 1 : Date of selected LANDSAT image

Year	Satellite	Sensor	Date of acquisition	Spatial resolution (m)	Scene cloud cover (%)
2000	Landsat 5	TM	11/09/2000	30	9
2005	Landsat 5	TM	03/10/2005	30	0
2010	Landsat 5	TM	30/08/2010	30	22
2013	Landsat 8	OLI/TIRS	03/06/2013	30	0.11
2017	Landsat 8	OLI/TIRS	18/09/2017	30	2
2020	Landsat 8	OLI/TIRS	25/08/2020	30	0.21

To ensure good geometrical quality images, Landsat Global Land Survey products (GLS) and Level-1T (L1T) were used. These data have sufficient radiometric and geometric qualities to perform land use change analysis. Additionally, we performed a visual inspection of each scene to check their geometric consistencies. No additional geo-rectification was performed.

2.1.2. Data pre-processing and variables

In order to improve the classification and increase the spectral differentiation between categories, several spectral indexes were derived from the primary bands of the satellite images, as presented in the following table:

Table 2 : Spectral indexes calculated

Index	Formula	References
NDVI (Normalized Difference Vegetation Index) – Vegetation spectral enhancement	NDVI=(NIR-R)/(NIR+R)	Rouse et al., 1974
SAVI (Soil Adjusted Vegetation Index) – Soil spectral enhancement	SAVI = (NIR - R) / (NIR + R + L) * (1.0 + L)	Huete, 1988
NDWI (Normalized Difference Water Index) – Water spectral enhancement	NDWI = (NIR - SWIR) / (NIR + SWIR)	Gao, 1996

2.1.3. Delineation of training plots

After data pre-processing, the method to establish a deforestation map follows three main steps:

- Definition of land use and land cover classes;

- Delimitation of training plots;
- Classification with a specific algorithm (Random Forest).

<u>Definition of land use and land cover changes classes</u>

Land use (LU) categories that exist in the areas and are detectable with Landsat imagery and land cover change categories (LCC – 5 period of deforestation) are presented in the following table:

Table 3 : Typology of land use and land cover categories for the study

Code	Name		Description
1	Land Use and Land Cover 2020	Moist evergreen forest	Dense mature moist evergreen forest (montane forest) that have not been perturbed.
2		Miombo forest	Dense mature miombo vegetation (dominated by deciduous trees) that have not been perturbed.
3		Mosaic of culture and young fallow	This class includes land covered with temporary crops followed by harvest and a period of bare soil or fallow.
4		Grassland	Area with herbaceous plant types, but without crop cultivation
5		Secondary vegetation,woodland	Secondary vegetation is regenerated forest or other woody land that has been disturbed by human activities. It includes a wide vegetation gradient , limiting the ability for class differentiation
6		Rivers and Swampy lowland	This class includes rivers and cultivated (without specific management) and uncultivated lowlands
8		Urban area, roads	Urban area and settlement comprises all developed land, including areas of human habitation and transportation infrastructure.
9		Bare soil, rock, sands an others	This class includes bare soil, rock, and all unmanaged land areas that do not fall into any of the previous categories.
12	Land Cover Change 2000-2020	Deforestation between 2000-2005	Clearing of forest areas by cutting down the trees
13		Deforestation between 2005-2010	
14		Deforestation between 2010-2013	
15		Deforestation between 2013-2017	
16		Deforestation between 2017-2020	

<u>Delimitation of training plots</u>

Delimitation of training plots is a necessary step to calibrate the classification algorithm when applying a supervised classification. The accuracy of the classification mainly depends on the quality of the delimitation of these training plots. Polygons that represent land uses (LU) in 2020, as well as land cover changes (LCC) between each period, were delineated. Therefore, a standardized and rigorous photo-interpretation work was conducted. Photo-interpretation was carried on the basis of field knowledge, Landsat image patterns and high-resolution images from *Google Earth*. Finally, 672 plots were delineated (see table below).

Table 4 : Number of polygons and associated delineated area used as training plots

Code	Name		Number of training polygons	Cumulated area (ha)	Average size (ha)
1	Land Use and Land Cover 2020	Moist evergreen forest	84	69	0.8
2		Miombo forest	48	35	0.7
3		Mosaic of culture and young fallow	60	193	3.2
4		Grassland	36	16	0.4
5		Secondary vegetation,woodland	85	73	0.9
6		Rivers and Swampy lowland	46	16	0.3
8		Urban area, roads	40	82	2.0
9		Bare soil, rock, sands an others	89	84	0.9
12	Land Cover Change 2000-2020	Deforestation between 2000-2005	38	24	0.6
13		Deforestation between 2005-2010	40	29	0.7
14		Deforestation between 2010-2013	23	15	0.7
15		Deforestation between 2013-2017	48	28	0.6
16		Deforestation between 2017-2020	35	18	0.5
Total			672	681	1.0

First, in order to improve the localization and determination of changes, those areas were highlighted by performing a multi-dates color composite. Then, training plots were located in clusters *i.e.* by grouping several plots of different categories on a same landscape unit or small area. In order to reduce noise in training data, plots contours were verified by superposition on very high-resolution images available on *Google Earth*.

2.1.4. Supervised classification

Afterward, the training plot spatial database was correlated with the multi-date stacked image database using a statistical algorithm. The RandomForest algorithm, developed by Breiman (2002) and available in R software was used. It is a data-mining algorithm that combines bugging techniques and decision trees. It was successfully applied in land cover change studies in humid forests of Madagascar (Grinand et al., 2013) and in the Miombo forest biome (Kamusoko et al., 2014). First, the RandomForest algorithm must be calibrated to predict the different land-use categories to be classified. The calibration of the model is done from the database regrouping the previously delimited training plots.

2.1.5. Post-classification treatments

After classification, some isolated pixels were found, giving a noisy appearance to the map. Those isolated pixels were removed with the GDAL sieve filter (pixel connections: 4) in Qgis and replaced with the classification of the majority class that surrounds it, during post-classification processing. Remove only isolated pixels makes it possible to keep information on deforestation over small areas that would be removed with a stronger filter.

2.1.6. Deforestation rate calculation

In a first approach, an annual deforestation rate is a ratio between the deforestation area over a period and the number of years between the two dates of the same period (Menon and Bawa 1997). However, several publications explained that this simple ratio could not be used as deforestation rate dynamics followed a compound interests rule because the ratio changed with forest area during the period of interest as deforestation continued (Puyravaud 2003). Hence, an adaptation of this law was done to calculate annual deforestation rate. The following standardized equation proposed by Puyravaud (2003) was used in the present study:

$$\theta = -\frac{1}{t2 - t1}\, ln\frac{A2}{A1}$$

Where A_i is the forest area during the year t_i.

This calculation approach requires knowing exactly the interval between the two dates (t1 and t2) of the considered period. Therefore, a table summarizing the exact interval between images was established (Table 5).

Table 5 : Time interval between reference year

Period		Time interval (decimal year)	
		Day	Year
11/09/2000	03/10/2005	1848	5.06
03/10/2005	30/08/2010	1792	4.91
30/08/2010	03/06/2013	1008	2.76
03/06/2013	18/09/2017	1568	4.30
18/09/2017	25/08/2020	1072	2.94

2.2. Results

2.2.1. Forest cover and historical deforestation maps

Deforestation map and forest cover maps for each date of analysis are presented in Figure 3 and 4. Forests in Ribaue moutains have been lost progressively since 2000. In 2020, Miombo forests are significantly fragmented. Some large patches of moist evergreen forest are still present mainly at high altitude.

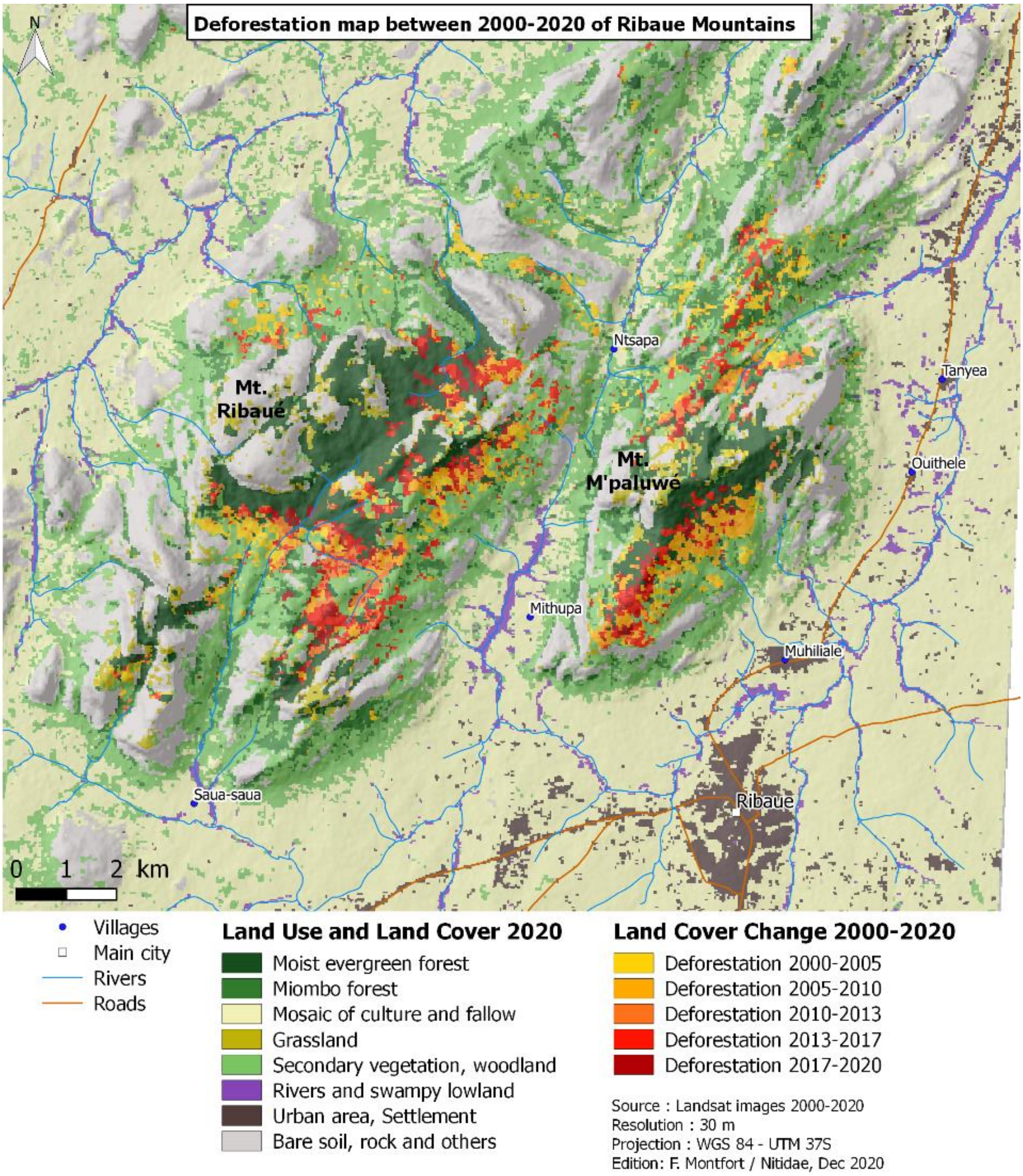

Figure 3 : Deforestation map between 2000 and 2020 of Ribaue Mountains

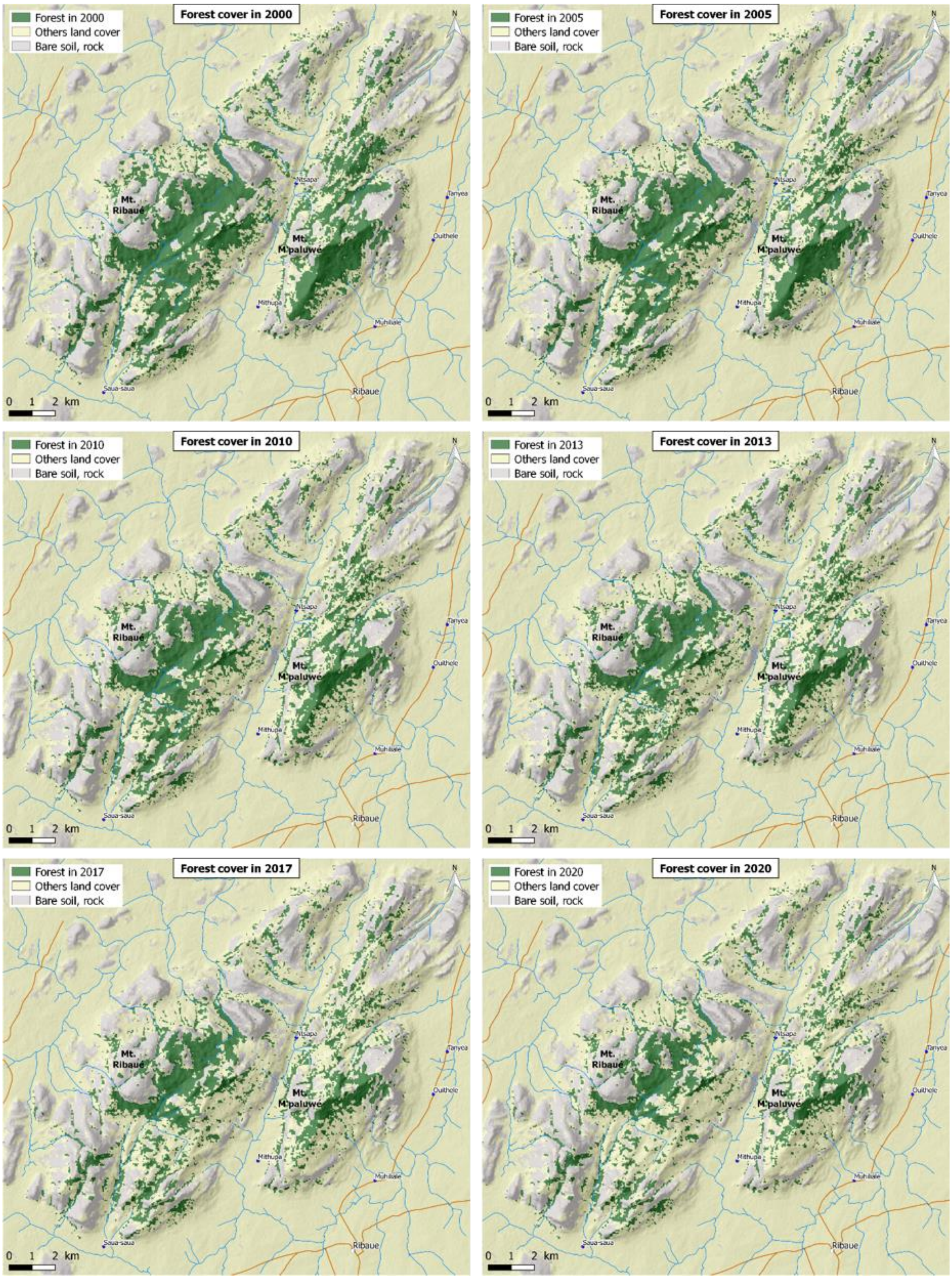

Figure 4 : Forest cover in 2005, 2010, 2013, 2017 and 2020 of Ribaue Mountains

2.2.2. Forest and deforestation statistics

Forest and deforestation statistics extracted from the deforestation map are presented in the tables 6 and 7 and Figure 5 and 6. **More than 37% (i.e. 1707 ha) of forested areas (Moist evergreen forest and Miombo forest) in Ribaue Mountains was lost between 2000 and 2020**. Indeed, forest cover in 2000 was estimated at 4555 ha and, in 2020 remaining forest patches are estimated at 2848 ha (Table 6). **Ribaue Mountains had suffered important deforestation, losing on average 85 ha of forest per year, between 2000 and 2020 – this is an average annual deforestation rate of 2.4 %** (Table 7). The deforestation rate has been steadily increasing since 2000. At the present rate of loss the remaining forest can be expected to be exhausted within 35 years.

Table 6 : Forest statistics

Years	Forest area (ha)
2000	4555
2005	4089
2009	3715
2013	3491
2017	3091
2020	2848

Table 7 : Historical deforestation between 2000 and 2020

Period	Cumulative deforestation from 2000 (ha)	% forest lost compared to 2000	Annual forest loss (ha/an)	Annual deforestation rate (%)
2000 - 2005	466	10.2	92.1	2.1
2005 - 2010	840	18.4	76.2	2.0
2010 - 2013	1064	23.3	80.9	2.2
2013 - 2017	1464	32.1	93.2	2.8
2017 - 2020	1707	37.5	82.9	2.8
2000 - 2020	1707	37.5	85.0	2.4

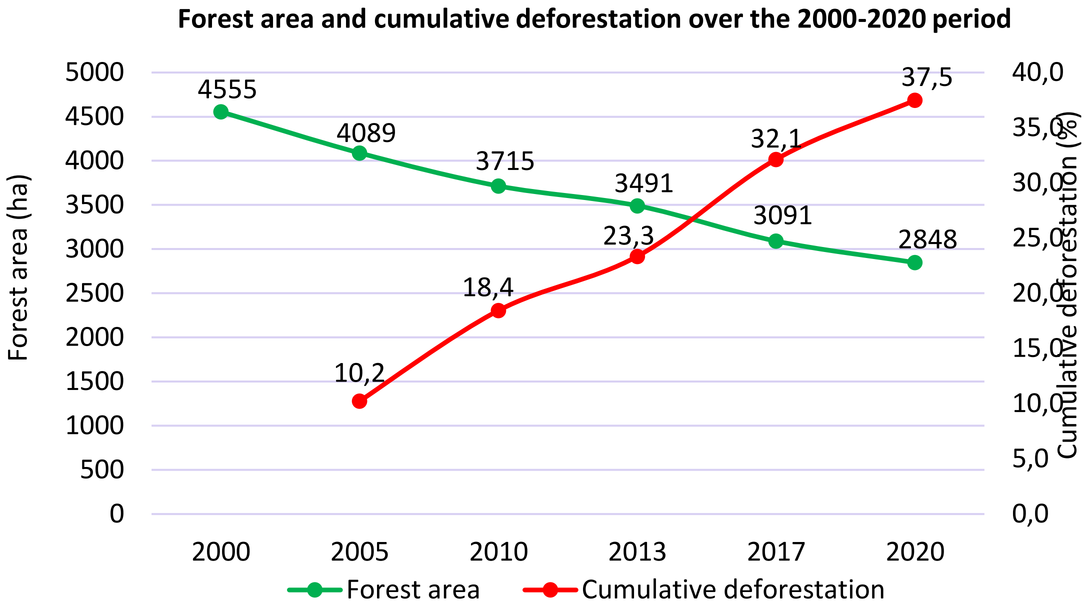

Figure 5 : Forest area and Cumulative deforestation over the 2000-2020 period

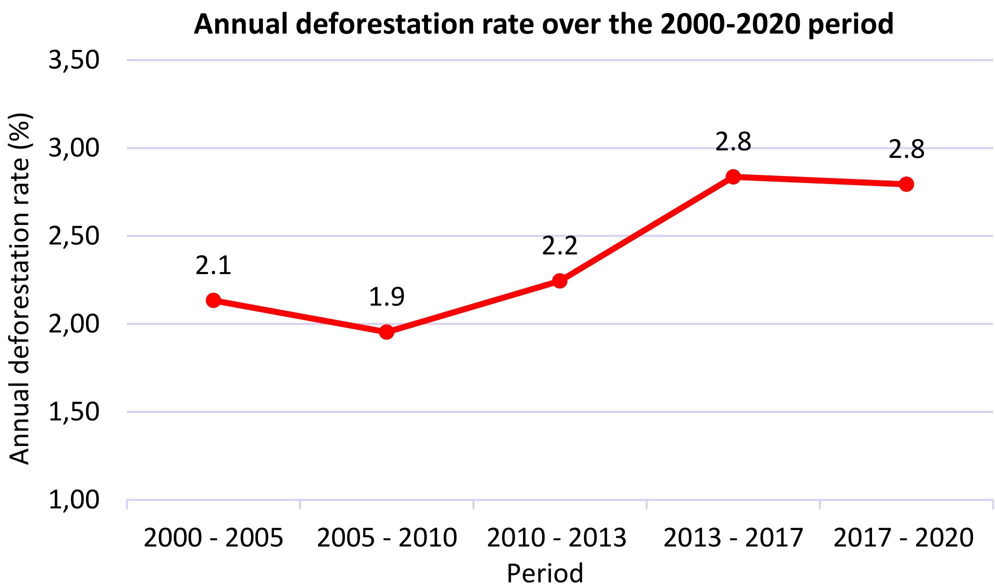

Figure 6 : Annual deforestation rate over the 2000 – 2020 period

2.2.3. Mount Ribaue and M'paluwe forest and deforestation statistics

We calculated forest area and deforestation statistics for Mount Ribaue and M'Paluwé by delineating the mountains as shown in Figure 7. Indeed, two Forest Reserves were established in 1950 within the Ribaue massif (one for each mount) but the existing delimitations of the two Forest Reserves (IIAM archives and World Bank) do not seem to correspond with the boundaries of the two massifs and do not include all forest areas (Figure 8).

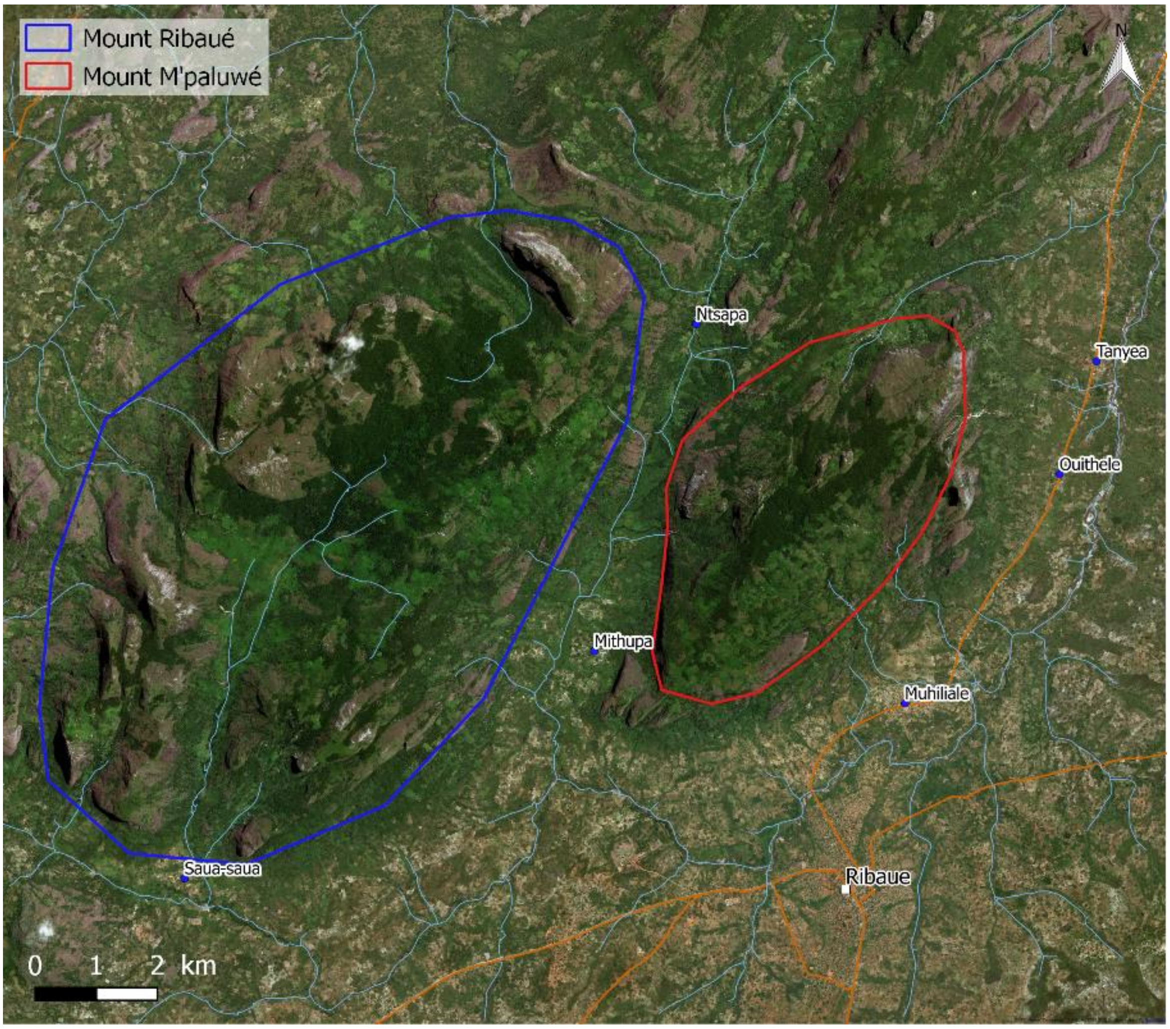

Figure 7: Delimitation of the two mounts used for the statistics calculations

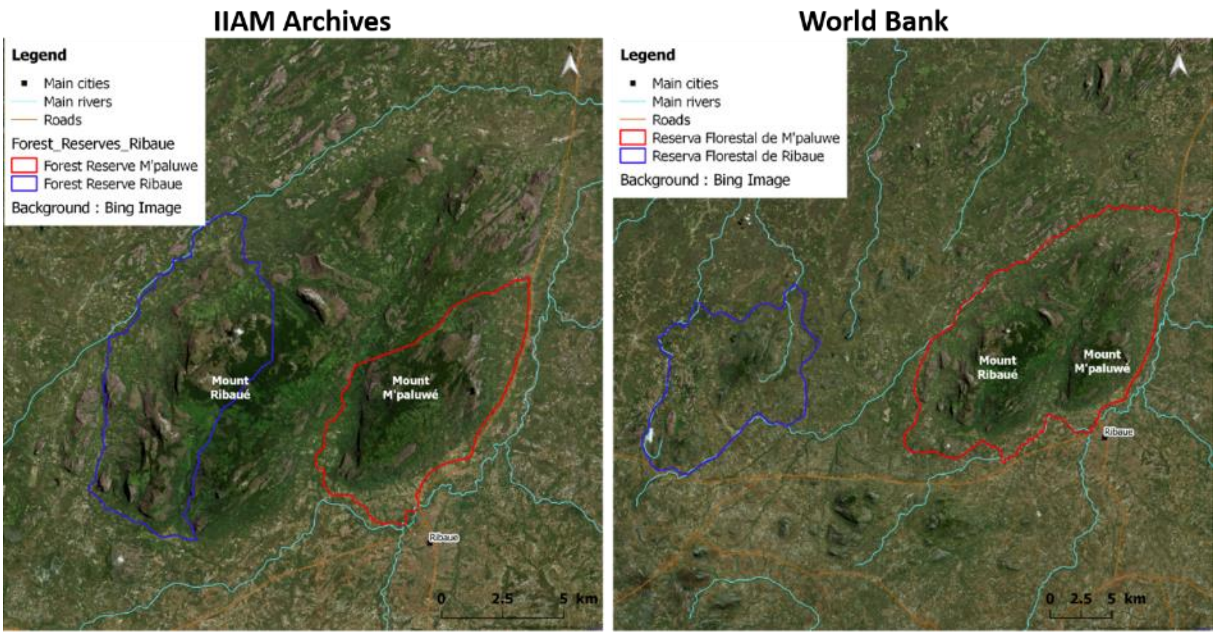

Figure 8: Existing delimitations of the two Forest Reserves (IIAM archives and World Bank)

Forest of the Mount M'paluwe, situated directly above the town of Ribaue, have suffered greater deforestation than the forests of the Mount Ribaue. More than 37% (i.e. 910 ha) and 47% (i.e. 456 ha) of forested areas was lost between 2000 and 2020 on the Mount Ribaue and Mount M'paluwe, respectively (Table 8). Between 2000 and 2020, the average annual deforestation rates are 2.5 % (47 ha per year) and 3.2 % (23 ha per year) for the Mount Ribaue and Mount M'paluwe, respectively (Table 8).

On the Mount Ribaue, remaining forest patches are estimated at 1556 ha in 2020: 1089 ha of moist evergreen forest and 467 ha of Miombo forest (Figure 10). On the Mount M'paluwe, remaining forest patches are estimated at 520 ha in 2020: 402 ha of moist evergreen forest and 118 ha of Miombo forest.

Table 8: Mount Ribaue and M'paluwe deforestation statistics between 2000 and 2020

	Cumulative deforestation from 2000 (ha)		% forest lost compared to 2000		Annual forest loss (ha/an)		Annual deforestation rate (%)	
Period	Ribaue	M'paluwe	Ribaue	M'paluwe	Ribaue	M'paluwe	Ribaue	M'paluwe
2000 - 2005	184	79	7.5	8.1	36.3	15.6	1.5	1.7
2005 - 2010	361	236	14.6	24.2	36.1	32.0	1.6	3.9
2010 - 2013	505	297	20.5	30.4	52.1	22.1	2.6	3.1
2013 - 2017	739	390	30.0	40.0	54.5	21.6	3.0	3.4
2017 - 2020	910	456	36.9	46.7	58.2	22.5	3.6	4.1
2000-2020	910	456	36.9	46.7	47.4	22.8	2.5	3.2

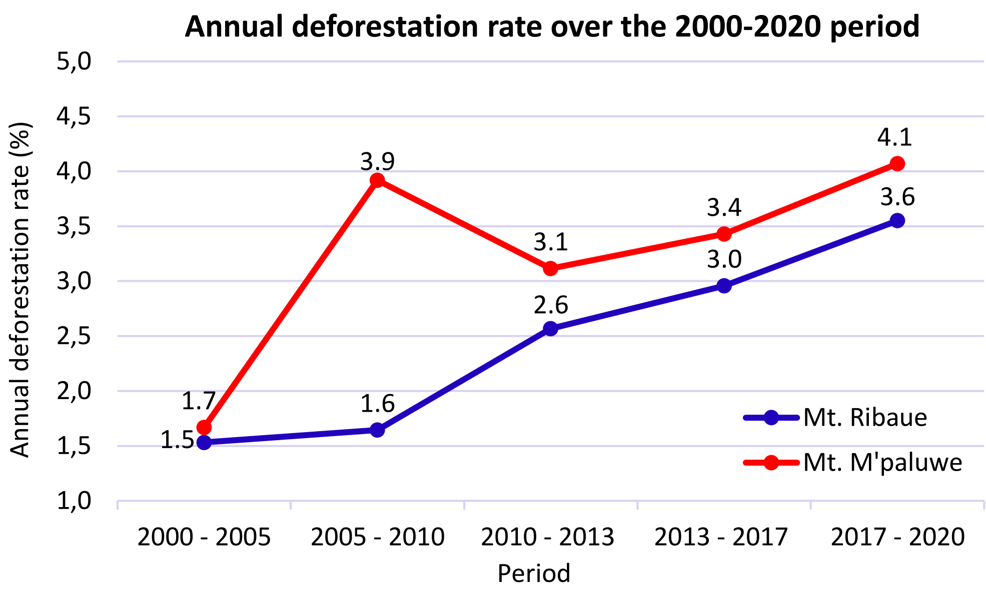

Figure 9: Mount Ribaue and M'Paluwe annual deforestation rate over the 2000 – 2020 period

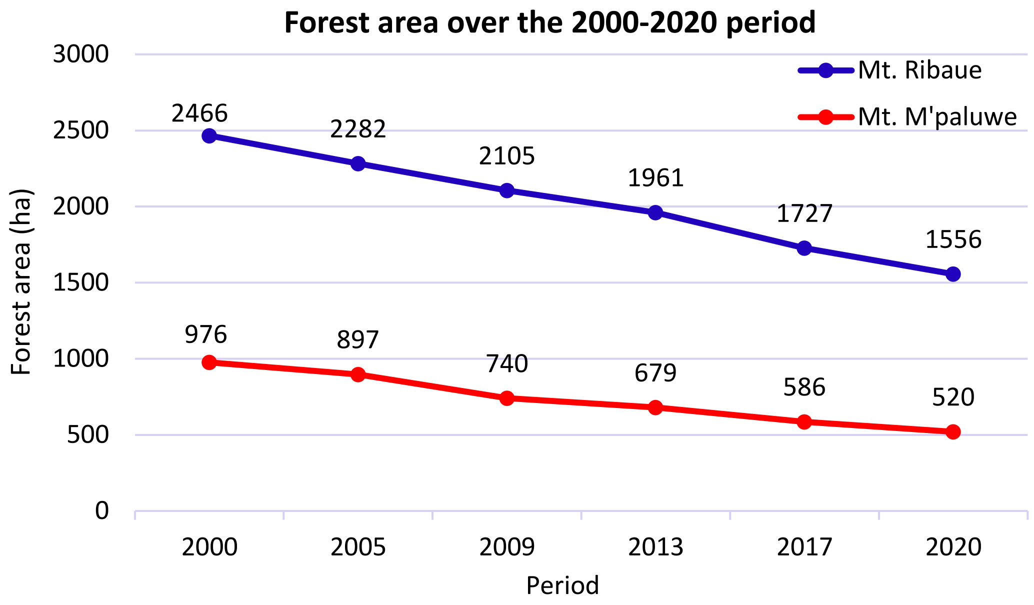

Figure 10: Mount Ribaue and M'Paluwe forest statistics over the 2000-2020 period

3_ Identification of most threatened forests

In this section, we address the question of the location of most threatened forests and therefore of the future deforestation, starting from the assumption that deforestation is not a random phenomenon but occurs in locations that combine advantageous bio-geophysical and socio-economic attributes for deforestation agents. For instance, soil fertility and distance from forested areas, transportations or markets are likely to influence the choice of human settlement and agricultural practices, putting natural forest location at various levels of risk.

3.1. Methodology

The methodology is based on Grinand et al. (2019) method. We use a machine learning algorithm (RandomForest) combined with datasets of potential spatial deforestation factors to provide a map of deforestation risk.

First, ten potential explanatory variables of deforestation were converted into spatially explicit layers and included in the analysis (Table 9). These variables are related to accessibility: distance to Ribaue, villages and road, distance to forest edge; and natural constraints: slope, aspect (slope orientation in degree), elevation, distance to river, soil moisture (estimated using the Topographic Wetness Index – TWI), and distance to rock (use as a proxy of soil depth).

Then, an analysis of drivers of deforestation was conducted, using extractions of spatial predictor values. We analyze the relative importance of each variable by testing the correlation between (i) observed deforestation derived from the historical deforestation analysis (see Analysis of historical deforestation section) and (ii) datasets of geo-referenced deforestation factors. We used a stratified random sampling scheme by randomly sampling 1000 points in forest loss patches and 1000 points in forest. A datasets of 2000 observations were compiled. We also used a linear regression model to assess the importance of each variable. Finally, an ensemble model was calibrated using the datasets to predict and map deforestation risk (or probability of deforestation) based on the potential explanatory variables. The methodology is summarized in figure 11.

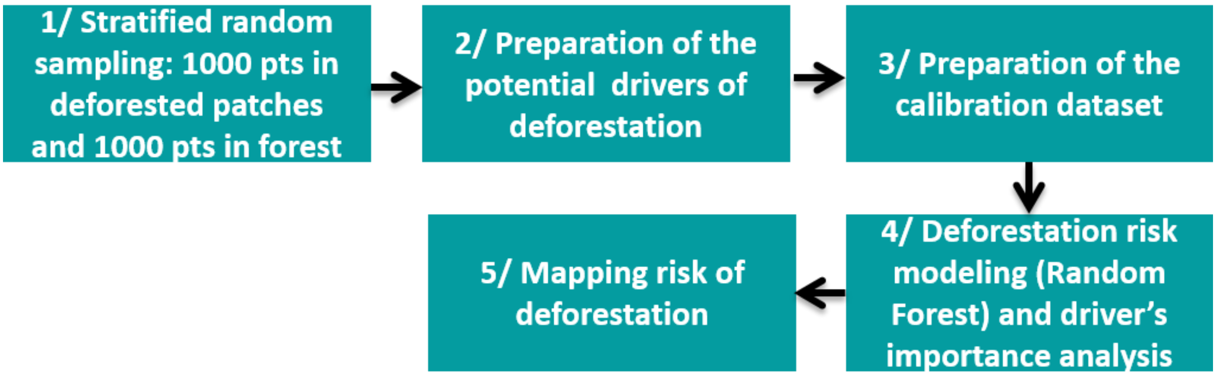

Figure 11: Processing chain applied for the deforestation risk mapping

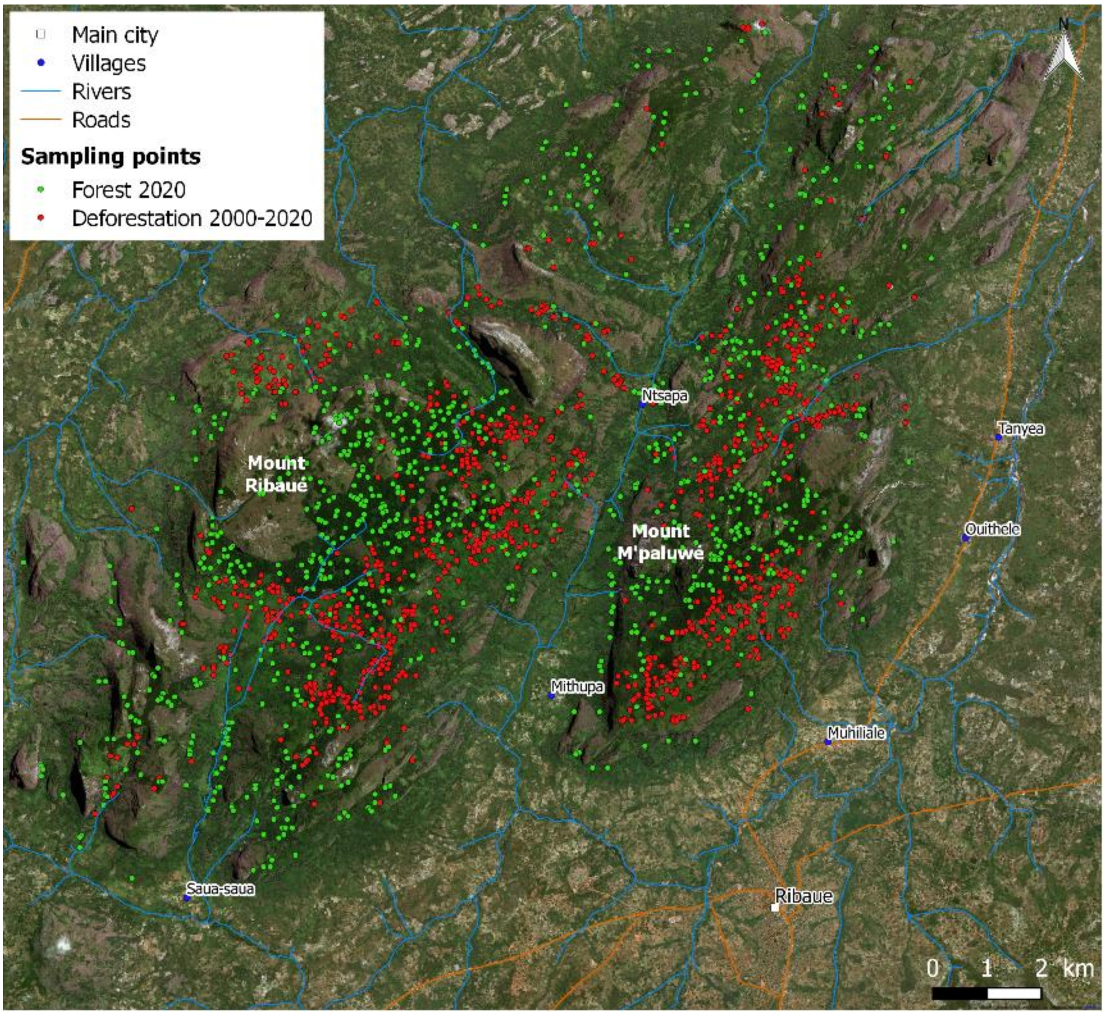

Figure 12: Sampling points in forest 2020 and deforestation between 2000 and 2020 and other potential explanatory variables

Table 9 : Potential drivers of deforestation used in the analysis

Name	Description	Source	Range	Unit
Slope	Slope	SRTM 30	0 - 79	%
Aspect	Exposition	SRTM 30	0 - 360	Degree
TWI	Topographic Wetness Index	SRTM 30	4 - 18	
Elevation	Elevation	SRTM 30	444 - 1684	Metre
Dist city	Distance to Gurue	WB	0 – 20.1	Km
Dist_village	Distance to small villages	Nitidae	0 – 6.7	Km
Dist roads	Distance to road	Nitidae	0 – 9.0	Km
Dist rivers	Distance to rivers	SRTM 30	0 – 2.0	Km
Dist forest edge	Distance to forest edge	Nitidae	0 - 9521	Metre
Dist rock	Distance to rock	Nitidae	0 – 3656	Metre

3.2. Results

3.2.1. Drivers importance

The importance of factors was analyzed using a regression method to assess the relation between observed deforestation and the selected potential drivers (Table 10). Among the 10 potential drivers, slope, distance to city, aspect and soil moisture (TWI) were the most important.

Slope was the first driver explaining deforestation in this study. Deforestation is more likely to occur in low slope areas (<17 % - 9.7 °) (Figure 13). Proximity to Ribaue town is affecting the probability of deforestation, with high values up to 4.2 km corresponding to the nearest forest patches on Mount M'paluwe and between 6.2 and 8.5 for Mount Ribaue.

The analysis shows that the slope orientation (aspect) has an influence on deforestation, but this is clearly related to the orientation of the massif and the most accessible areas from the town or villages. Soil moisture seems to have low influence on deforestation and we observed a slight increase of deforestation in areas with high soil moisture. Deforestation is more likely to occur more than 100 m from the rocks where soils are deeper. Remaining forests are probably those with shallow soils (shallow granitic bedrock) and little organic matter.

Table 10 : Results of linear logistic regression

	Estimate	Std. error	Z-value	Significance	
(Intercept)	7.305e+00	7.384e-01	9.893	< 2e -16	***
Slope	-8.992e-02	8.128e-03	-11.063	< 2e -16	***
Aspect	-2.617e-03	5.131e-04	-5.101	3.37e-07	***
TWI	-2.195e-01	4.405e-02	-4.983	6.27e-07	***
Elevation	-4.086e-04	3.991e-04	-1.024	0.3059	
Dist city	-2.763e-04	2.718e-05	-10.167	< 2e -16	***
Dist village	-1.949e-04	7.914e-05	-2.462	0.0138	*
Dist road	-2.698e-05	3.618e-05	-0.746	0.4558	
Dist rivers	-3.149e-04	1.660e-04	-1.897	0.0578	.
Dist forest edge	-5.489e-04	6.358e-04	-0.863	0.3880	
Dist rock	1.398e-03	6.068e-04	2.304	0.0212	*

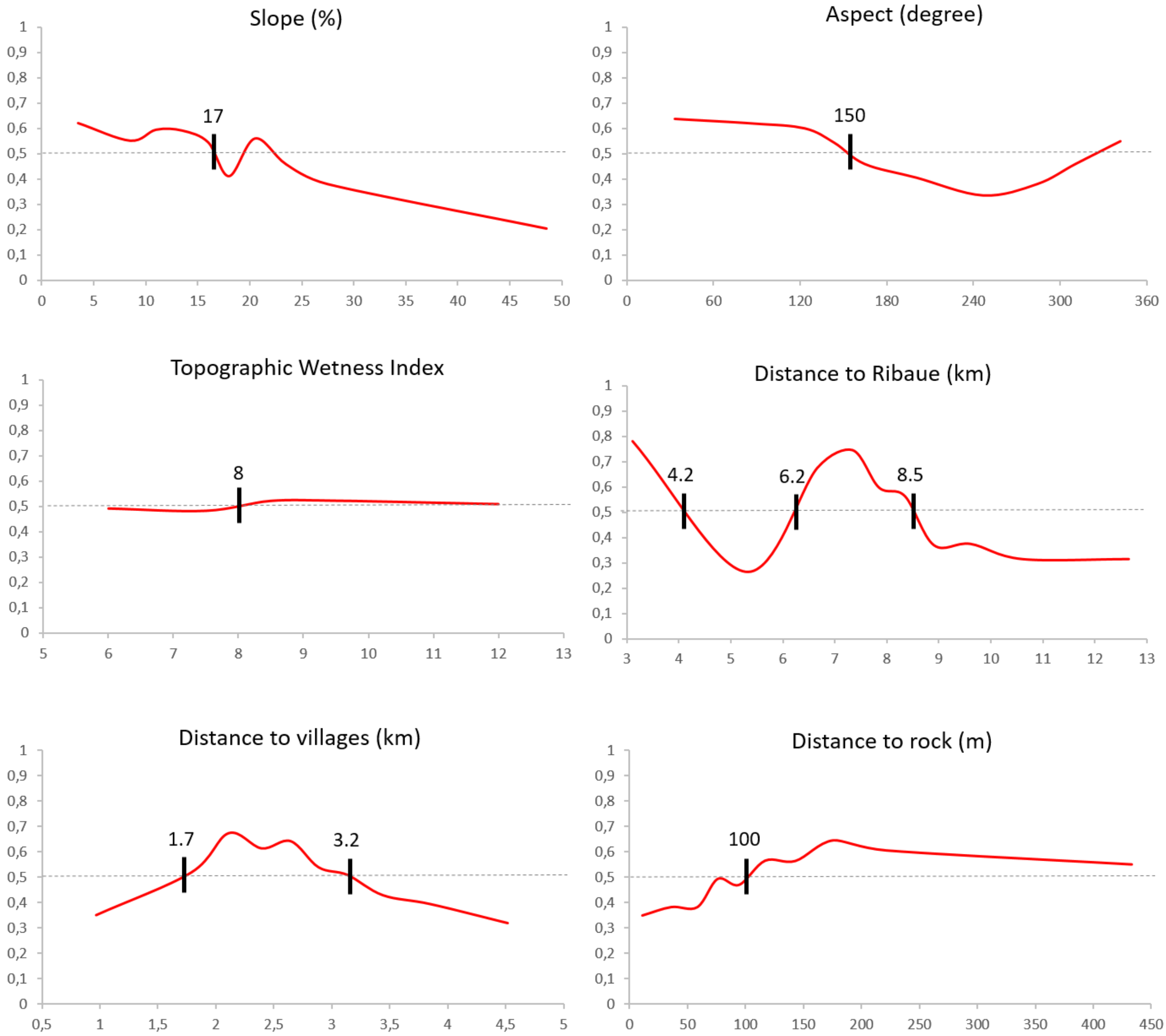

Figure 13 : Probability distribution of deforestation observation. The dashed line represents the 50% probability (value above indicates high probability of deforestation).

3.2.2. Deforestation risk map

A large part of the remaining forest patches present a high risk of deforestation (19% of the remaining forest patches present a deforestation probability greater than 50%) (Figure 14). These forest patches are mainly accessible areas located on slight slopes.

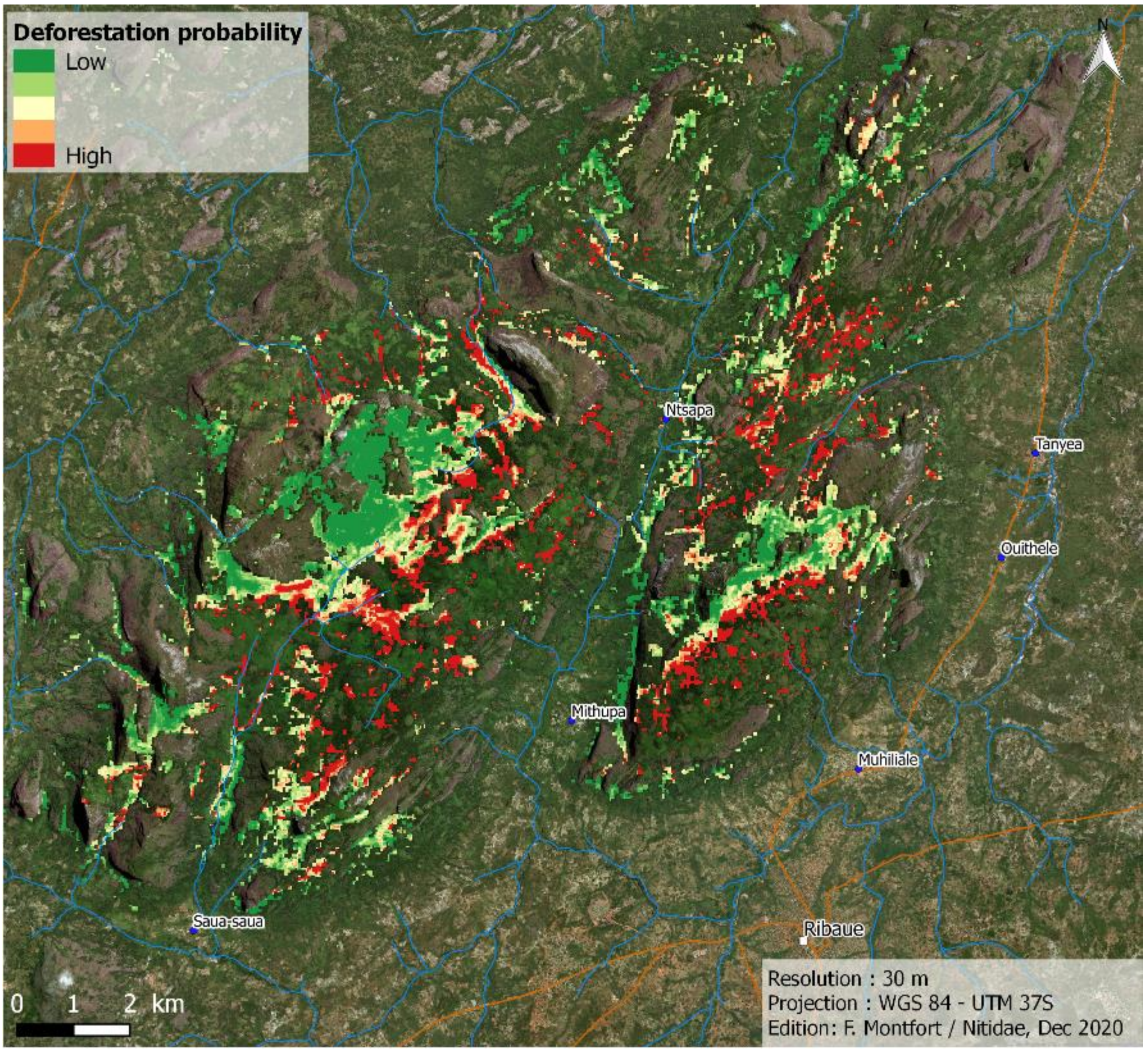

Figure 14: Deforestation risk map

4_ Conclusion

We mapped forest extent and deforestation in Ribaue Mountains over the 2000-2020 period, using Landsat images. Forest of the Mount M'paluwé, situated directly above the town of Ribaué, have suffered greater deforestation than the forests of the Mount Ribaue. More than 37% (i.e. 910 ha) and 47% (i.e. 456 ha) of forested areas was lost between 2000 and 2020 on the Mount Ribaue and Mount M'paluwe, respectively. Between 2000 and 2020, the average annual deforestation rates are 2.5 % (47 ha per year) and 3.2 % (23 ha per year) for the Mount Ribaue and Mount M'paluwe, respectively. In 2020, remaining forests (moist evergreen forest and Miombo forest) are estimated at 1556 ha and 520 ha on the Mount Ribaue and M'paluwe, respectively.

Based on this analysis of historical deforestation and comprehension of the deforestation drivers, we mapped future threatened forest patches. Accessible forest patches located on slight slope present a high risk of deforestation. 19% of the remaining forest patches present a deforestation probability greater than 50%.

This analysis stress the urgent need to address the lack of management of Mount Ribaue and M'paluwe Forest Reserve to control the drivers of deforestation, mainly slash and burn agriculture, and unsustainable use of natural resources to preserve its endemic biodiversity and the provision of ecosystems services, in particular potable freshwater to the city of Ribaue and neighboring population.

5_ References

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