VEGETATION CLASSIFICATION AND SURVEY
International Association for Vegetation Science (IAVS)

Vegetation Classification and Survey 4: 189–202
doi: 10.3897/VCS.89746

RESEARCH PAPER
AFRICAN VEGETATION STUDIES

Dynamics of inselberg landscapes and their adjacent areas in the Sudano-Guinean zone of Benin through remote sensing analysis

Ranmi Elsa Denise Ayeko[1], Sêwanoudé Scholastique Mireille Toyi[1], Achille Ephrem Assogbadjo[1], Brice Augustin Sinsin[1]

1 *Laboratory of Applied Ecology, Faculty of Agronomic Sciences, University of Abomey Calavi, Abomey-Calavi, Benin*

Corresponding author: Ranmi Elsa Denise Ayeko (ayekodenise@gmail.com)

Academic editor: Reginald Tang Guuroh ♦ **Linguistic editor:** Lynda Weekes
Received 30 June 2022 ♦ **Accepted** 5 May 2023 ♦ **Published** 24 July 2023

Abstract

Aims: Land cover change in inselbergs and adjacent areas was studied from 2003 to 2018 in a region facing anthropogenic pressures to assess dynamics and preserve rare endemic species. **Study area**: Inselbergs and their adjacent areas in the Sudano-Guinean zone of Benin are included in this study. **Methods:** Land cover classes of inselbergs and adjacent areas were obtained through supervised classification of Sentinel-2 (2018) and Spot 5 (2003) satellite images. A Chi-square test was used to compare protected and unprotected LULC classes of inselbergs, with 10 m spatial resolution. **Results:** The results showed that forest and woodland decreased respectively from 8.55% to 3.05% and from 17.63% to 4.79% between 2003 and 2018 while tree and shrub savanna, and grassland increased respectively from 6.52% to 9.49% and from 7.60% to 16.69%. Field and fallow increased from 5.57% in 2003 to 26.12% in 2018 and tree plantation from 6.05% to 13.47%. The analysis of spatial comparisons using the chi-square test showed that the presence of inselbergs in a protected area has no significant effect on their land use. **Conclusions:** Natural vegetation in inselbergs and adjacent areas is being converted into human-made landscapes by farmers. An urgent conservation plan is needed, including awareness campaigns, tree planting, and sustainable forest management.

Taxonomic reference: Akoègninou et al. (2006).

Abbreviations: DEM = Digital Elevation Model; GCP = Ground Control Point; LULC = Land Use/Land Cover; ROI = Region of Interest; SRTM = Satellite imagery data, Shuttle radar topography mission.

Keywords

anthropogenic pressure, dynamic trend, inselberg, land use/land cover, protected and unprotected inselberg, Sentinel-2, Spot 5

Introduction

Terrestrial ecosystems are essential for human well-being and global survival because they provide a variety of ecosystem services, including food production, air and water purification, climate regulation, crop pollination and biodiversity preservation (Reid et al. 2005). Despite their importance, these ecosystems are facing multiple threats, such as deforestation, urbanization, pollution, overexploitation of natural resources, climate change, and the introduction of invasive species (Ceballos et al. 2015; Lovejoy and Hannah 2019). These threats have a negative impact, leading to biodiversity loss, land degradation, decreased air and water quality and increased natural risks such as flooding and landslides. In light of this situation, urgent action is needed to protect these vital ecosystems for our future and to find sustainable solutions to restore and maintain them in a healthy state. And the best way to achieve this is to preserve examples of each type of ecosystem (de Souza 1987; Adomou et al. 2006; Akoègninou et al. 2006). Among these ecosystems, we have the inselbergs and their adjacent areas.

In 1900, the German geologist Bomhardt introduced the term 'inselberg' to describe granitic or gneissic rocky outcrops that rise above the peneplain of tropical and subtropical regions (Parmentier et al. 2001; Kouassi et al. 2014; Tindano et al. 2015). These ecosystems differ greatly from the surrounding matrix, having unique edaphic-climatic characteristics that select for specialized vegetation with high endemicity (Porembski and Barthlott 2000; Porembski 2007; de Paula et al. 2020). They promote the occurrence of high numbers of geographically restricted, specialized and threatened species (Porembski et al. 2016) and influence the water and nutrient supplies of surrounding landscapes (Schut et al. 2014). Despite their importance, these geological landforms rank among the most poorly surveyed ecosystems in the world (Larson et al. 2000) and are still neglected.

However, over the past two decades, there has been increasing interest in inselberg ecosystems worldwide (Porembski et al. 2016). This revealed that many inselbergs are threatened by alarming rates of mining, weed invasion (de Paula et al. 2015), water harvesting, tourism and urbanization, resulting in biodiversity loss and degradation of their ecosystem services (Buckman et al. 2021). Unfortunately, there are no reliable estimates on global rates of inselberg destruction, which is urgently needed to promulgate effective conservation strategies (Porembski et al. 2016).

To effectively address the issue of inselberg destruction, it is crucial for each country to collect and share information on the status of inselbergs within their own territory. Without reliable data, it is difficult to develop targeted conservation strategies or to monitor progress in protecting these unique habitats. Therefore, it is incumbent upon each country to take responsibility for assessing the condition of their inselbergs. Unfortunately, in Benin, the inselbergs are mainly located in the Sudanian and Sudano-Guinean zones (Sinsin and Kampmann 2010) and are subject to a strong degradation of the vegetation cover (Oloukoi et al. 2006; Agbanou et al. 2018). However, despite a relatively large body of literature that describes the flora of Benin's inselbergs (Oumorou and Lejoly 2003a, 2003b; Yedomonhan et al. 2008), their ecological dynamics are not well understood. Especially as these studies have shown the importance of inselbergs in the conservation of threatened species such as: *Afzelia africana*, *Albizia ferruginea*, *Pterocarpus erinaceus*, *Vitellaria paradoxa*.

Monitoring the change of land use over time around inselbergs is, therefore, a very important way to effectively assess the trends of the dynamics. To this end, the diachronic analysis of land use that allows the showing of the spatial distribution of land use changes is the best way to achieve this.

However, the presence of protected areas such as the classified forests of Dassa-Zounmé and Savalou that contain parts of the inselbergs, offer an opportunity to preserve the inselbergs from human disturbance. Indeed, protected areas are created so that they can play an essential role in protecting representative samples of living organisms, remarkable geological phenomena or particular landscapes in terrestrial and marine environments from disappearing. Evidence from remote sensing suggests that protected areas slow down the rate of change from 'natural' to 'human-modified' land cover (Joppa and Pfaff 2011) and successfully help retain existing forests (Geldmann et al. 2013).

The aim of this study is to analyze the land use/land cover change of inselbergs and their adjacent areas located in the Sudano-Guinean zone of Benin between 2003 and 2018, and to assess the effectiveness of protected areas in preserving inselbergs. In addition, the study seeks to test the hypothesis that natural vegetation has been replaced by anthropogenic landscape features and that inselbergs located in protected areas are under less pressure compared to those outside protected areas.

Study area

The inselbergs and their adjacent areas within the department of "Collines", one of the twelve administrative subdivisions located in the central part of Benin, were considered for this research. The Collines department is located between 7°27' and 8°46' North latitude and between 1°39 'and 2°44' East longitude. It covers an area of 13,931 km² or more than 12% of the national territory (Oloukoi et al. 2006; INSAE 2016) (Figure 1). Three large geological units dominate the study area. These are migmatite gneisses, sandstones and siltstones, biotite and amphibole eye gneisses (Oloukoi et al. 2006). There are a series of steep-sided inselbergs, notably those of Savè, Fita, Dassa-Zoumè and Minifi. The highest points of the relief are located at 465 m a.s.l. on the Dassa-Zoumè granite chain, at 520 m a.s.l. on the Savalou hill, and at about 400 m a.s.l. on the Savè hill (Okioh 1972; Dubroeucq 1977). For this study, we have focused on these three municipalities. The main activity carried out by the population on inselbergs is quarrying to obtain gravel. Logging, manufacturing and commercializing of charcoal, and hunting are also other activities practiced on inselbergs. The soils are tropical ferruginous type on a crystalline base with highly variable characteristics (clay-sandy, gravelly) (Oloukoi et al. 2006). The Collines department is a transition region between subequatorial climate and tropical climates (Bokonon Ganta 1987; Boko 1988; Afouda 1990). This means that they have a rainfall regime that straddles the bimodal distribution in the south and the unimodal distribution in the north. The total number of rainy days in the year varies between 80 and 110. Annual rainfall varies between 800 mm and 1,500 mm and the mean annual temperature ranges from 28 to 30 °C (ASECNA 2018). There are essentially four forests reserves (Ouémé-Boukou, Dassa-Zoumè, Savalou and Logozohè). The natural vegetation is characterized by five types of vegetation: dry forest, woodland, tree savanna, fallow, and meadow.

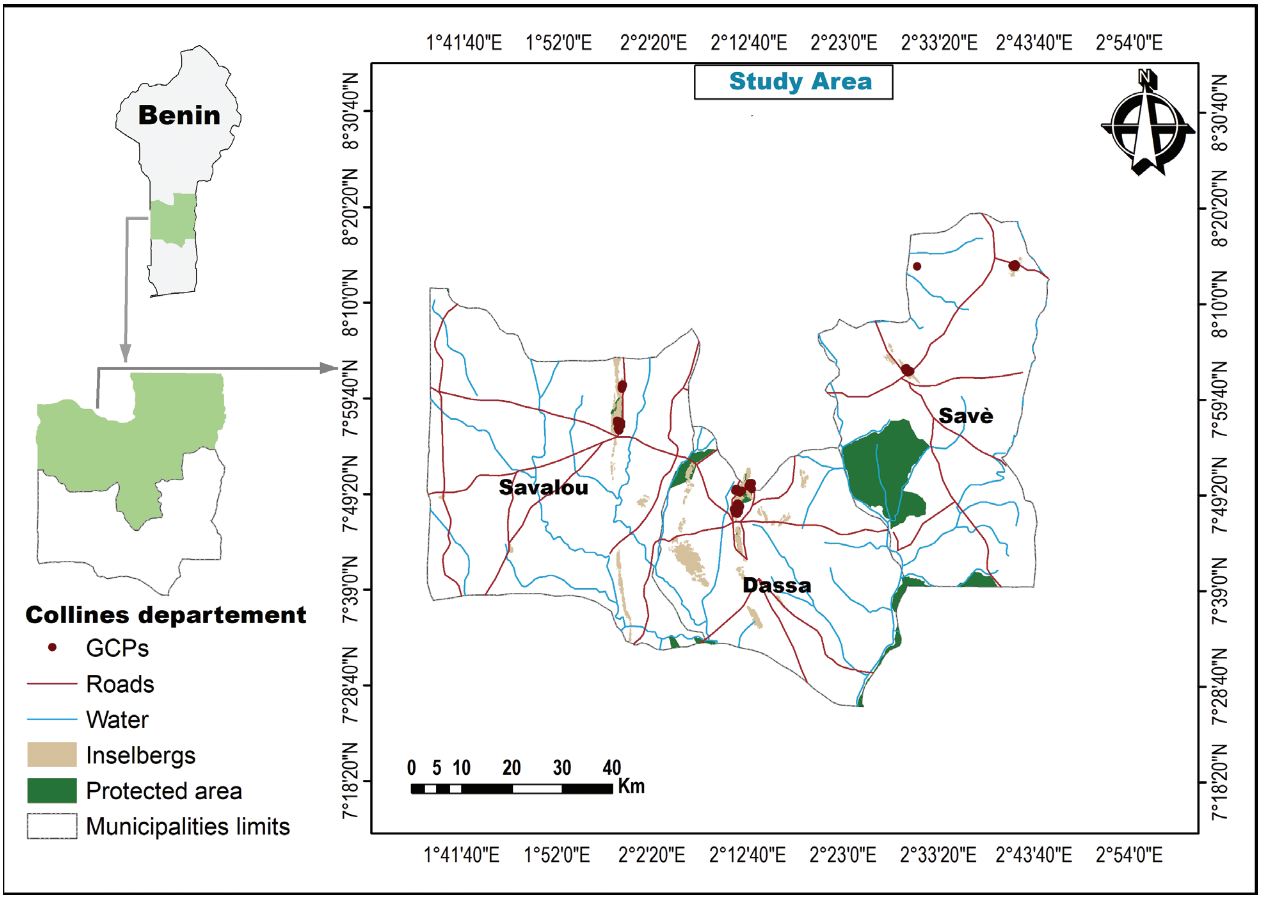

Figure 1. Map of study area. The upper-left map displays the country, with the Collines department highlighted in green to indicate its location. The intermediate map focuses on the Collines department and highlights in white the three municipalities that were studied within this department. The Study Area map provides a closer look at these three municipalities, illustrating their inselbergs, protected areas, and GCPs. GCPs = Ground Control Points.

Methods

Data collection

This work used three datasets: satellite imagery data, Shuttle radar topography mission (SRTM), digital elevation model (DEM), and ground control points (GCPs).

To monitor LULC changes in inselbergs, four Sentinel-2 MSI (multi-spectral instrument, Level-1C) satellite images with 10 m spatial resolution from 4 Jan 2018 covering the study area, were used. Indeed, studies conducted by Pelletier (2017) have shown that the high temporal resolution of Sentinel-2 data is an asset for characterizing land occupations that evolve over time. The Sentinel-2 Level-1C images have the following radiometric and geometric characteristics: top-of-the-atmosphere reflectance; orthorectified; spatial resolution of 10 m after resampling; and fixed cartographic geometry (ESA 2015; Delalay et al. 2019). Another unique aspect of the Sentinel-2 data is the presence of three red edge bands, which capture the strong reflectance of vegetation in the infrared near-infrared portion of the electromagnetic spectrum (Abdi 2020). In contrast, Spot 5 images with the same resolution (10 m) acquired on 27 Dec 2003 were used for 2003 vegetation study. The Spot 5 images were obtained through the "*Observation Spatiale des Forêts d'Afrique Centrale et de l'Ouest*" (OSFACO) project (Djaouga et al. 2021).

Shuttle radar topography mission (SRTM) digital elevation model (DEM) with a resolution of 1 arc-second (approximately 30 m) was used to extract the elevation and slope bands.

A dataset of 110 GCPs was constructed to train the classification algorithms applied to the Sentinel-2 data. Each GCP contains latitude, longitude, and the corresponding observed LULC type (Suppl. material 1). The GCPs were recorded during the 2019 field visit with a Garmin eTrex 10 GPS.

Data processing

Land-Use and Land-Cover Classification

The digital interpretation of satellite images used the supervised classification method with Envi4.7 software (Exelis Visual Information Solutions, Boulder, Colorado). Three bands (Near-infrared (NIR), Red, Green) of multispectral Sentinel-2B and Spot 5 satellite images with a spatial resolution of 10 m were used for the land-use mapping. After choosing our 10 m resolution band, layer stacking was done by combining three bands into one multispectral image. Then ROIs (Regions of Interest) were created by selecting portions of the images graphically or by thresholding. The regions can be irregularly-shaped and were used to extract statistics for classification (Saharan et al. 2018). The training areas were defined to the nearest pixel on all land use units. Once ROIs were created, the maximum likelihood function was used. The spectral characteristics of the LULC classes obtained from the 2018 Sentinel-2 images were used as training areas for the supervised classification of the 2003 Spot 5 images (Mas 2000; Toyi et al. 2013; Arouna et al. 2016). GCPs were used to compare the digital interpretation of images with the field data.

Following the work of Oumorou (2003) four classes were defined: forest, wooded savanna, tree and shrub savanna, and grassland. We added: tree plantations, field and fallow, water surface, bare rock, and settlement. The Kappa coefficient, which is the measure of agreement between the classification results and the validation training samples, was used to evaluate the quality of LULC (Barima et al. 2010; Rawat and Kumar 2015; Yadav and Borana 2017).

Delimitation of inselbergs and their adjacent areas

The SRTM image for the communes of Dassa, Savè, and Savalou was analyzed using ArcGIS 10.4 software. The image was divided into two classes based on elevation. The first class took into account the elevations between 16 and 180 m a.s.l. and the second class, the elevations between 180 and 550 m a.s.l. This was done because the lowest elevation of the inselbergs (a type of rocky hill) was found to be 180 meters during field verification.

The slope of the inselbergs is connected to them by a concave zone whose slopes can exceed 10%, according to studies conducted by Poss (1976). The slope tool of 'Arctoolbox' was used on the SRTM image in ArcGIS 10.4 to visualize the slopes of the study area. The image previously delineated with the altitudes between 180 and 550 m a.s.l. had therefore undergone a second classification to identify the areas of slope greater than or equal to 10%.

Using these two characteristics (elevation and slope), the inselbergs and their adjacent area were identified and then digitalized. The shapefile of the inselbergs including their adjacent areas was created, where the adjacent areas refer to the immediate surroundings of the inselbergs, which are essentially the plains according to the definition of inselbergs (Oumorou 2003)

Land-use and Land cover change analysis

Mapping restitution. The images previously classified using Envi 4.7 software were sent to ArcGIS 10.4. These images had been clipped with the shapefile of inselbergs previously delimited to highlight the different classes of land use of inselbergs. The cartographic restitution was made with ArcGIS 10.4. The same land use classes were observed in both years (2003 and 2018) (Arouna et al. 2016). Inselbergs LULC maps are presented by municipality and by study year to allow for better observation due to the small area of inselbergs in the study area. Indeed, the small proportion represented by inselbergs in the overall study area and the isolation of the different inselbergs blocks did not allow for a good appreciation of the different LULC. **Transition matrix**. The transition matrix is a table consisting of X rows and Y columns. The number of rows (X) in the matrix indicates the number of land-use units in 2003 (year t0) and the number of columns (Y) indicates the number of land-use units in 2018 (year t1). In the context of this study, we have a symmetric matrix. Therefore, the number of rows is the same as the number of columns. The transformations will be observed from rows to columns. The diagonal of the matrix corresponds to the areas of land use units that remained unchanged between 2003 and 2018. Land use unit areas were calculated as the intersection of the 2003 and 2018 land-use layers using ArcGIS 10.4.1 software (Arouna et al. 2016; Rakotondrasoa et al. 2017).

Quantification of the anthropization of inselbergs

The anthropization of inselbergs was quantified using two indices: The dominance and the fragmentation index.

Dominance index (Dj) indicates the proportion of area taken up by the largest patch of class *j* (amax,j) in the total area *aj* (Bogaert et al. 2002; Bamba et al. 2008; Toyi et al. 2013). It is in the interval]0, 100]. The higher the value of the index, the less fragmented the class is

$$Dj = \frac{100a_{\max,j}}{a_j}$$

The fragmentation index (Fj) measures the aggregation of pixels into classes and is considered as a measure of image complexity (Bogaert et al. 2002; Toyi et al. 2013). Fj is in the interval]0, 1]. If Fj is around 0 then the class is less fragmented and if Fj is around 1 then the class is more fragmented.

$$Fj = \frac{n_j - 1}{m_j - 1}$$

nj represents the total number of patches for class *j*; *mj* is usually in a raster file the number of pixels (Monmonier 1974; Toyi et al. 2013).

Assessing the effects of protected areas on inselberg land use/land cover

Inselbergs were classified as protected if their geographic coordinates fell within the boundaries of protected areas in the study area (Figure 1). To analyze land use and land cover (LULC) changes over time within protected and unprotected inselbergs, we used the 'Erase' tool in the ArcGIS toolbox on shapefiles containing inselberg LULC data from 2003 and 2018. The 'Erase' tool created two datasets:

one that included inselbergs inside protected forests and another that included inselbergs outside protected forests. We then used R software (R Core Team 2022) to perform the Chi-square test to compare the proportions of different LULC classes for protected and unprotected inselbergs in the years 2003 and 2018. The purpose of the Chi-square test was to identify any significant differences between the two groups of inselbergs.

Results

Inselbergs land use/land cover

The overall accuracy is 84.734% for 2003 and 83.599% for 2018 and the Kappa coefficients for the year 2003 and year 2018 maps were 0.823 and 0.784 respectively. The LULC Classifications results for 2003 and 2018 are illustrated in Table 1. The information extracted from satellite images reveals nine classes of LULC on the inselbergs: forest, wooded savanna, tree and shrub savanna, grassland, tree plantation, fields and fallow, water surface, bare rock, settlement (Figures 2–7). For each of the municipalities, there was a predominance of bare rock and natural formations (forest, wooded savanna and tree and shrub savanna) in 2003. But in 2018 the area of these classes had decreased in favor of fields and fallows and tree plantations. The area covered by settlements had increased significantly in the municipality of Savè, in contrast to the municipalities of Dassa and Savalou, where a decrease was more noticeable.

Table 1. Land use/land cover classes area (km²) and percentage (%).

Land cover classes	Years			
	2003		2018	
	km²	%	km²	%
Forest	464.58	3.69	187.46	1.49
Wooded savanna	2230.21	17.73	319.70	2.54
Tree and shrub savanna	365.03	2.90	677.45	5.38
Grassland	663.58	5.27	2225.20	17.69
Tree plantation	957.48	7.61	1358.01	10.79
Field and fallow	652.20	5.18	4719.72	37.51
Water surface	7.12	0.06	14.52	0.12
Bare rock	6349.60	50.47	2795.59	22.22
Settlement	892.04	7.09	284.18	2.26
Total	12581.84	100.00	12581.84	100.00

Inselbergs land use/land cover change

The land-use changes of the inselbergs are illustrated by the transition matrix (Table 2). It shows that there were three main processes from 2003 to 2018 on the LULCs: Stability (the data along the diagonal), progression (the data on top of the diagonal), and regression (the data on the bottom of the diagonal).

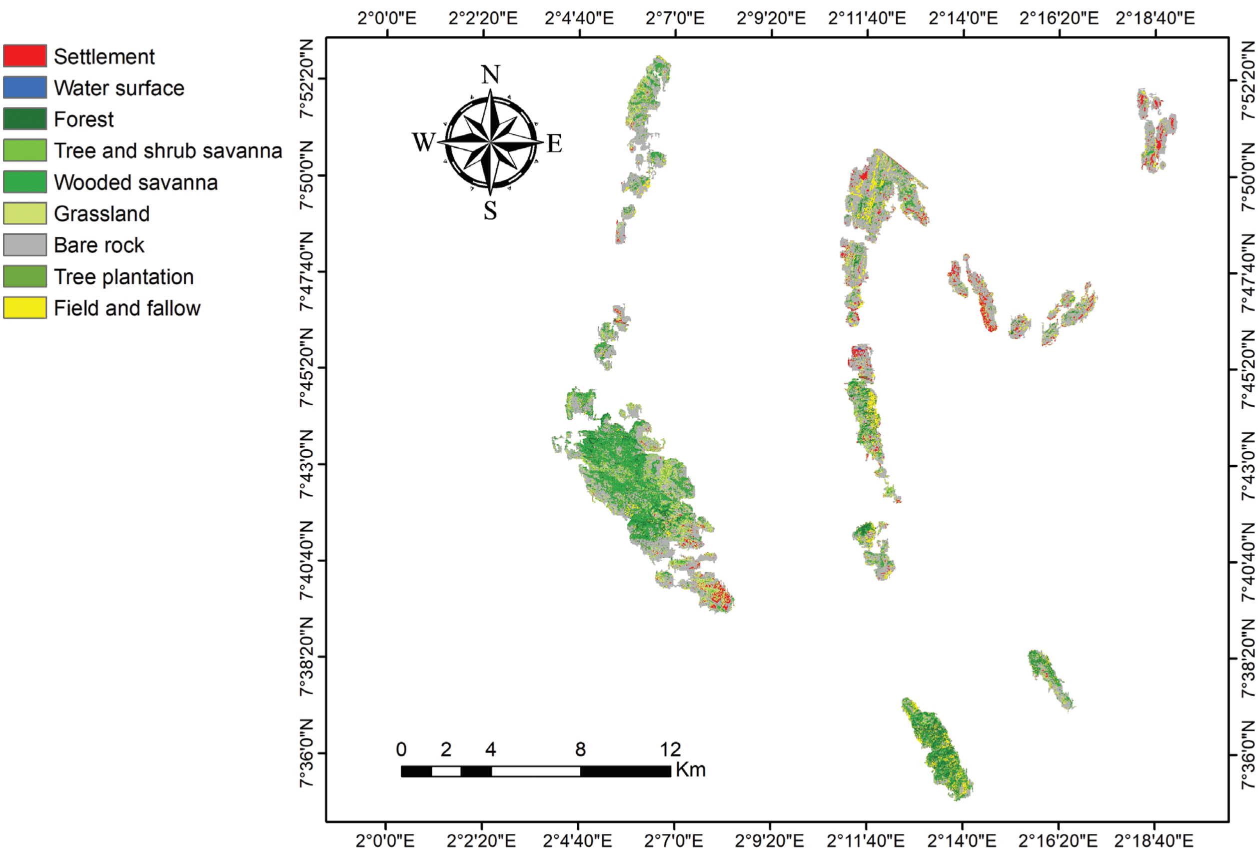

Figure 2. Land use map of the Dassa-Zoumè inselbergs in 2003 (Spot5 image).

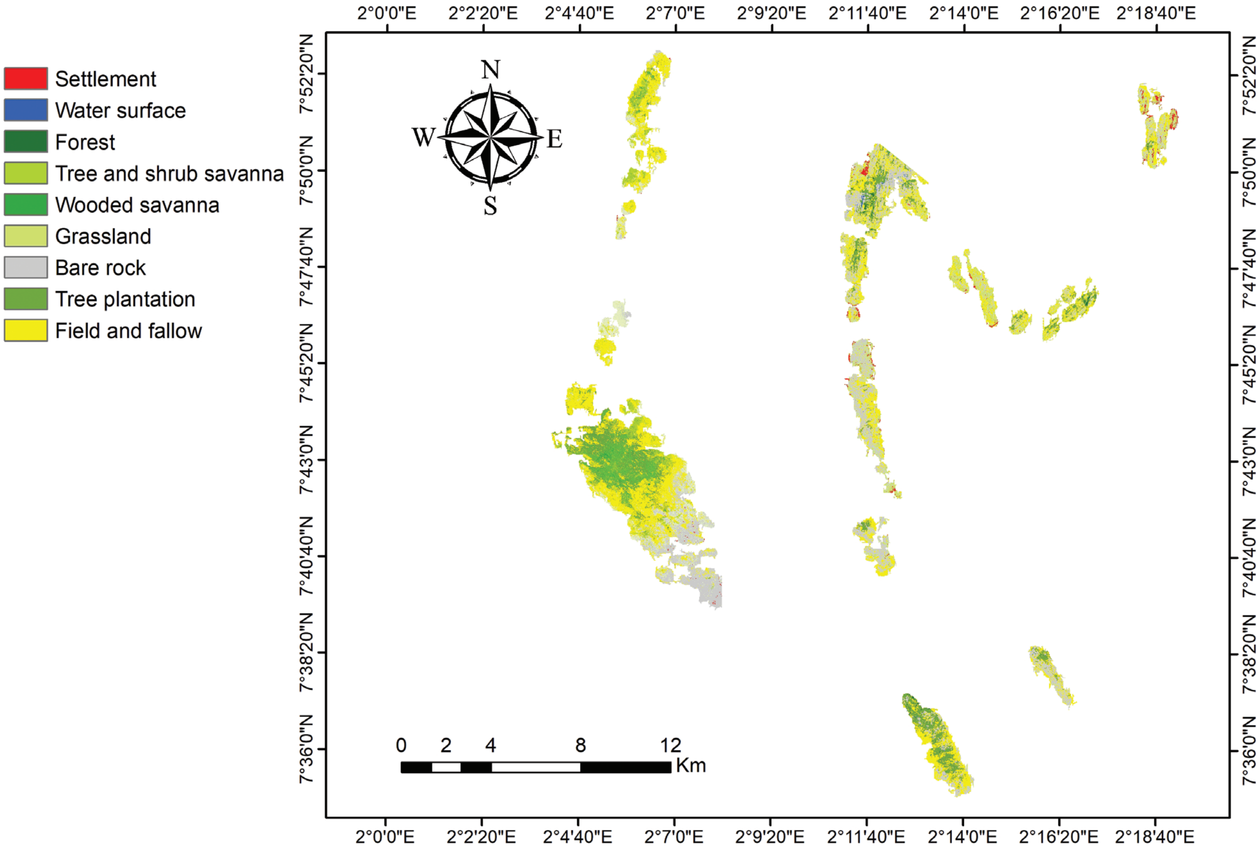

Figure 3. Land use map of the Dassa-Zoumè inselbergs in 2018 (Sentinel-2 image).

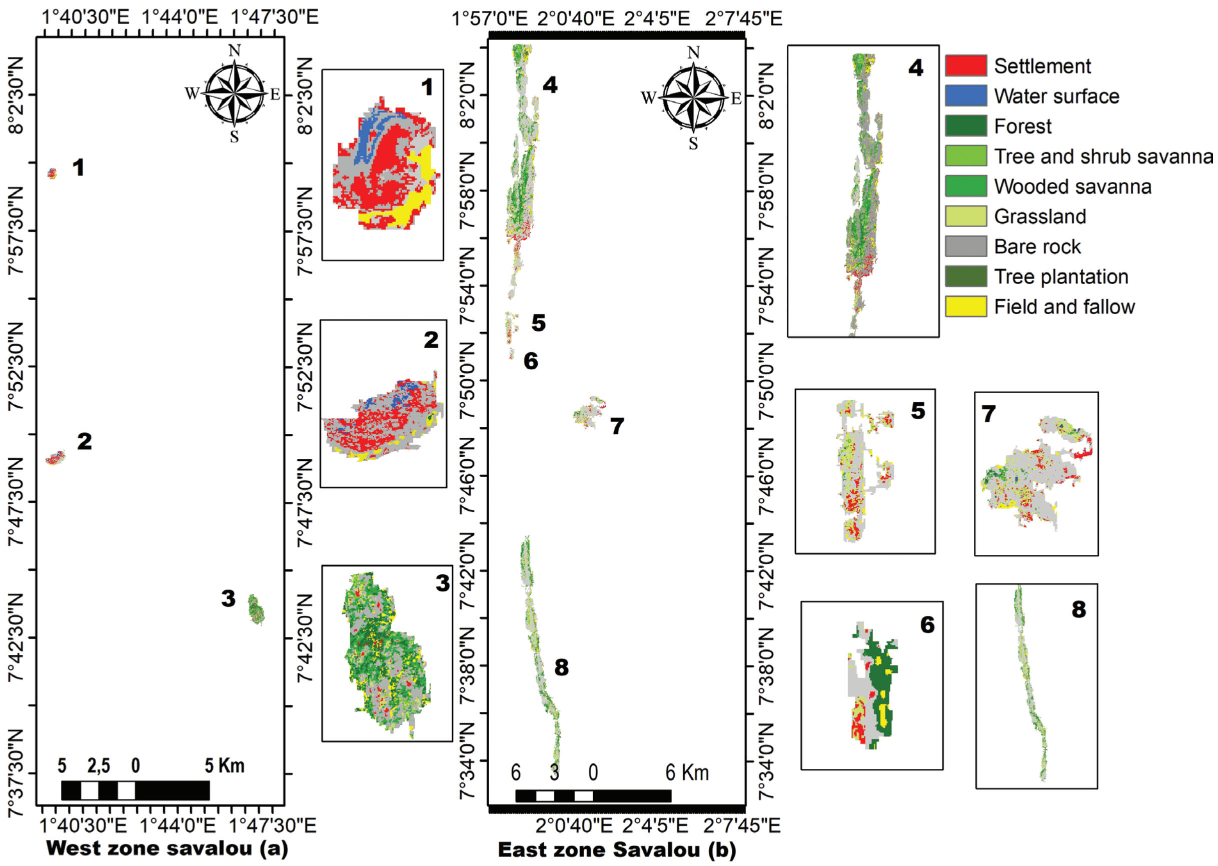

Figure 4. Land use map of the inselbergs of the west zone (**a**) and the east zone of Savalou (**b**) in 2003 (Spot5 image).

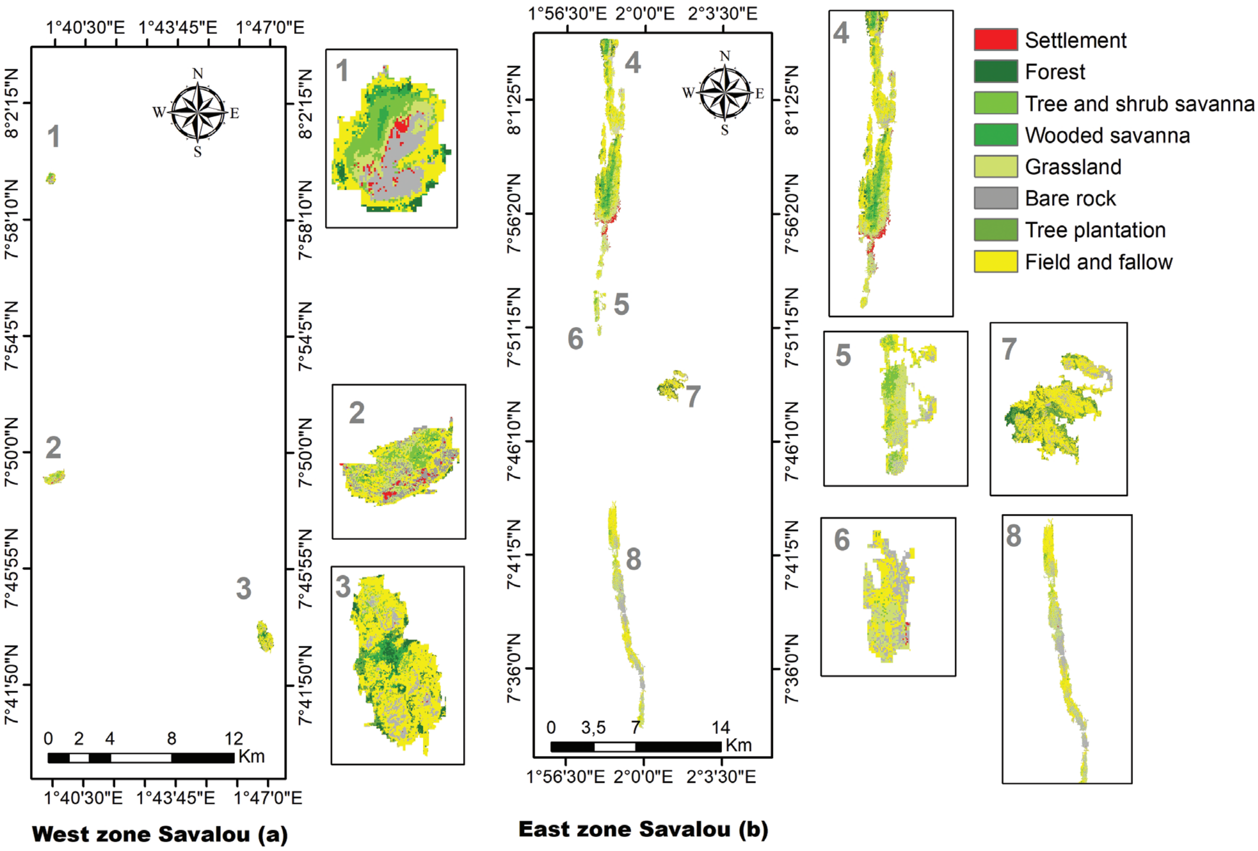

Figure 5. Land use map of the inselbergs of the west zone (**a**) and the east zone of Savalou (**b**) in 2018 (Sentinel-2 image).

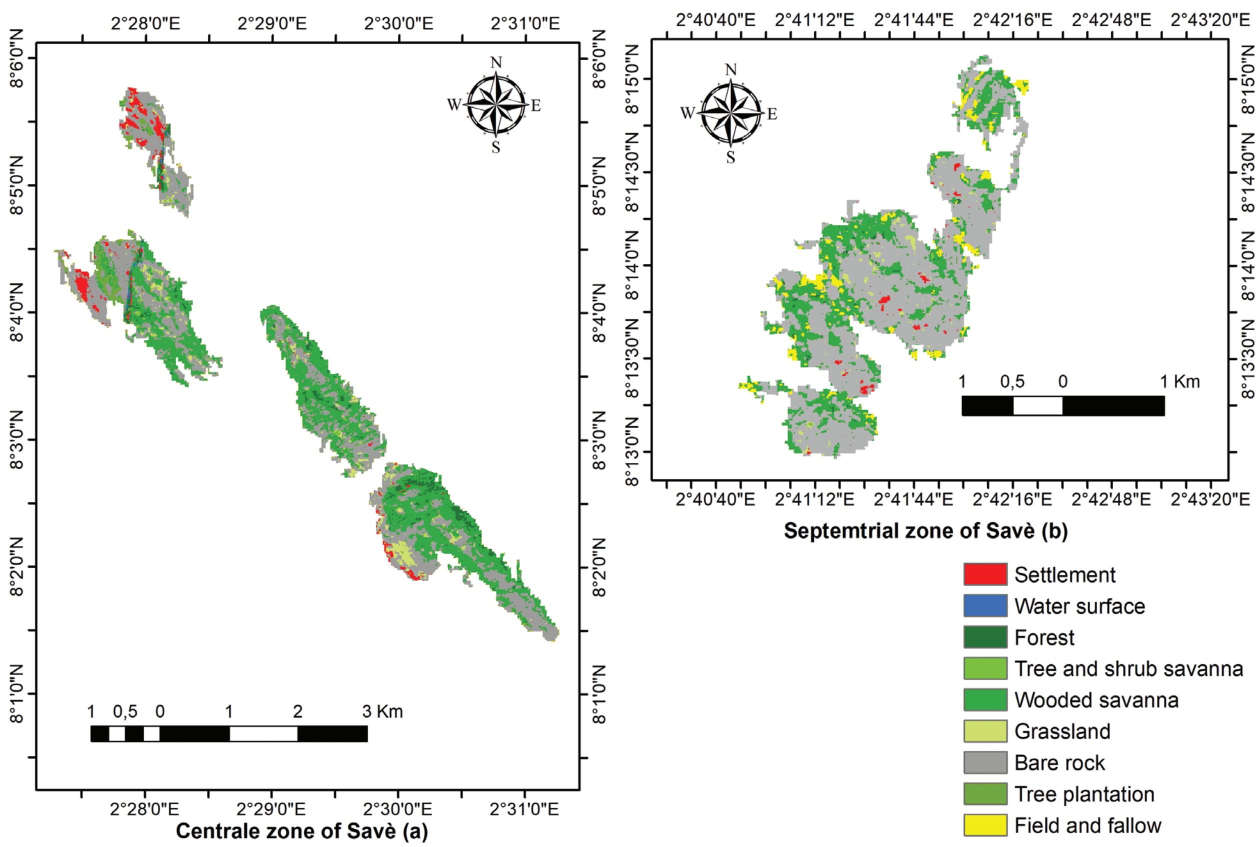

Figure 6. Land use map of the inselbergs of the central zone (**a**) and the northern zone of Savè (**b**) in 2003 (Spot5 image).

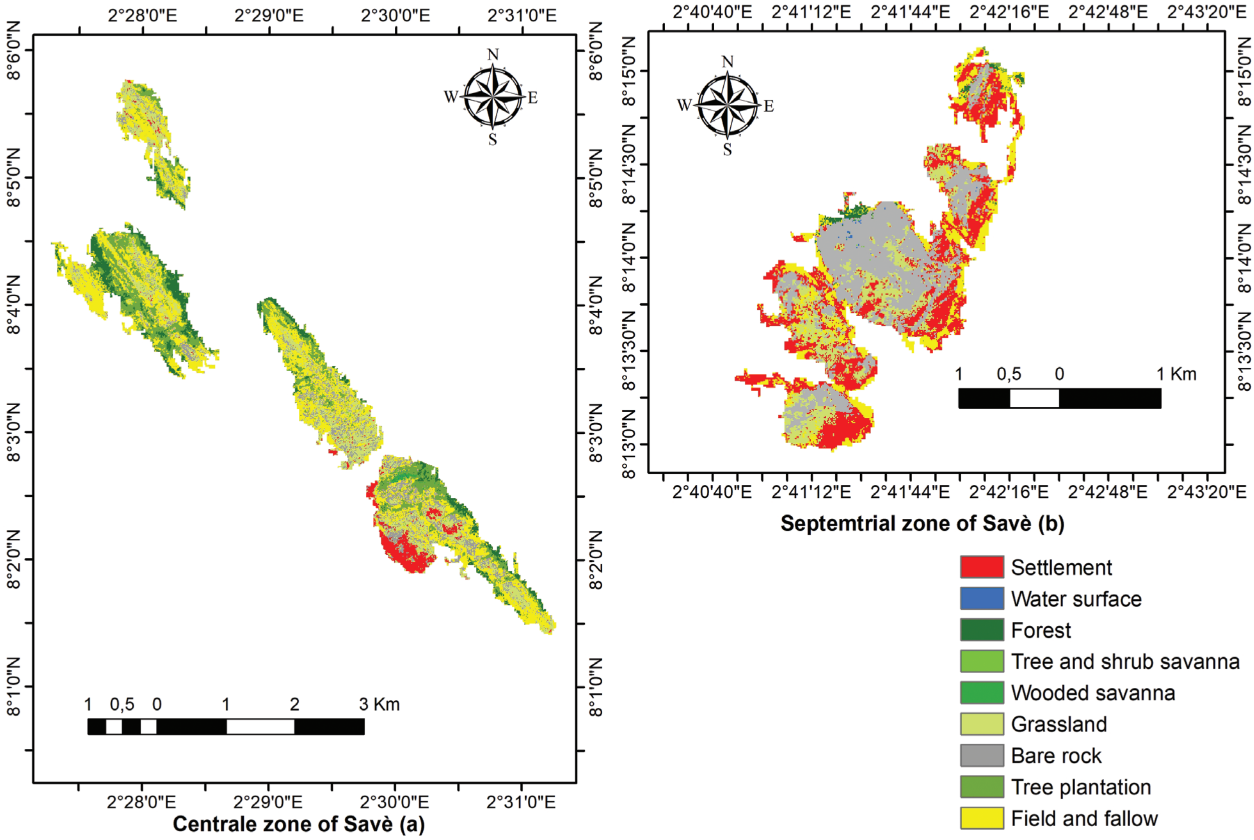

Figure 7. Land use map of the inselbergs of the central zone (**a**) and the northern zone of Savè (**b**) in 2018 (Sentinel-2 image).

Table 2. Inselberg land-use transition matrix in % between 2003 and 2018. Br = Bare rock; W = Water surface; Se = Settlement; Ff = Field and fallow; Tp = Tree plantation; Gr = Grassland; Ts = Tree and shrub savanna; Ws = Wooded savanna; Fo = Forest.

2003/ 2018	Br	W	Se	Ff	Tp	Gr	Ts	Ws	Fo	Total 2003
Br	11.99	0.21	0.75	10.29	4.37	8.61	4.45	1.46	0.89	43.01
W	0.04	0.00	0.00	0.04	0.01	0.04	0.01	0.00	0.00	0.14
Se	1.70	0.01	0.25	1.16	0.15	1.33	0.27	0.03	0.03	4.93
Ff	1.24	0.03	0.07	1.80	1.12	0.57	0.19	0.08	0.48	5.57
Tp	1.51	0.02	0.55	1.49	0.69	1.26	0.16	0.02	0.35	6.05
Gr	1.95	0.04	0.09	2.00	0.77	1.63	0.84	0.24	0.02	7.60
Ts	1.31	0.02	0.02	1.75	0.90	1.02	0.96	0.46	0.07	6.52
Ws	2.92	0.21	0.02	4.83	3.48	1.71	1.93	1.78	0.76	17.63
Fo	1.34	0.09	0.02	2.75	1.99	0.52	0.69	0.70	0.46	8.55
Total 2018	24.01	0.62	1.76	26.12	13.47	16.69	9.49	4.79	3.05	100.00

Anthropization of inselbergs

Table 3 presents the anthropization indices of the different LULC classes of inselbergs in 2003 and 2018. The Dominance index (Dj) increases between 2003 and 2018 for the field and fallow, grassy savanna, tree and shrub savanna and forest classes in contrast to the bare rock, settlement, tree plantation, and wooded savanna classes. The fragmentation index (Fj) increases for all LULC classes between 2003 and 2018 except for the plantation class where it decreases and the field and fallow class where it did not change. However, it is higher for the natural cover classes: water, dense dry forest, open forest and wooded savanna, and tree and shrub savanna.

Effects of protected areas on inselberg land use/land cover

The percentage of different LULC on protected and unprotected inselbergs in 2003 and 2018 can be seen in Figure 8. In 2003, natural vegetation was almost equally present on both protected and unprotected inselbergs. However, settlements were more prevalent on protected inselbergs, while tree plantations stood out on unprotected inselbergs. In 2018, an expansion of fields and fallow land was observed on both categories of inselbergs, with a decrease in settlements and bare rocks, and an increase in grassland. On protected inselbergs, a significant increase in tree plantations was noticed. Finally, tree and shrub sa-

Table 3. Anthropization indices for 2003 and 2018 inselberg land use classes. Br = Bare rock; W = Water surface; Se = Settlement; Ff = Field and fallow; Tp = Tree plantation; Gr = Grassland; Ts = Tree and shrub savanna; Ws = Wooded savanna; Fo = Forest.

LULC	Br	W	Se	Ff	Tp	Gr	Ts	Ws	Fo
					(Year 2003)				
Dj_{2003}(%)	4.76	0.01	3.71	0.22	1.59	0.22	0.04	5.41	0.04
Fj_{2003}	0.02	0.16	0.04	0.06	0.97	0.05	0.15	0.03	0.18
					(Year 2018)				
Dj_{2018}(%)	3.52	0.01	0.29	5.50	1.23	3.71	0.55	0.22	0.07
Fj_{2018}	0.12	0.58	0.09	0.06	0.11	0.11	0.20	0.19	0.23

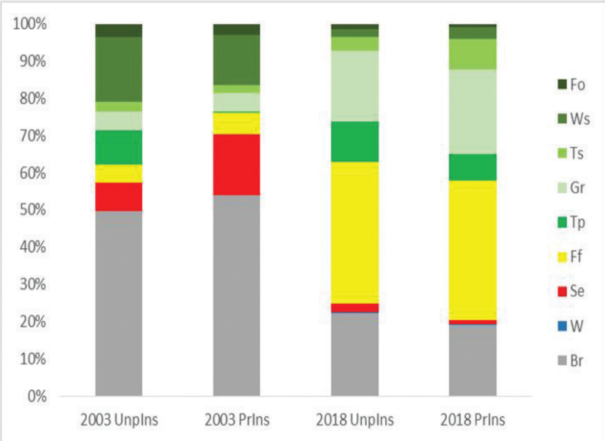

Figure 8. Land use land cover proportion of protected and unprotected inselbergs in 2003 and 2018. 2003 UnpIns = 2003 unprotected inselberg (Inselbergs outside protected areas), 2003 PrIns = 2003 protected inselberg (Inselbergs inside protected areas), 20018 UnpIns = 2018 unprotected inselberg (Inselbergs outside protected areas), 2018 PrIns = 2018 protected inselberg (Inselbergs inside protected areas), Br = Bare rock; W = Water surface; Se = Settlement; Ff = Field and fallow; Tp = Tree plantation; Gr = Grassland; Ts = Tree and shrub savanna; Ws = Wooded savanna; Fo = Forest.

vanna showed better growth on protected inselbergs than on unprotected inselbergs.

The analysis of spatial comparisons using the chi-square test showed however, that there was no statistically significant difference in inselberg LULC between protected and unprotected areas in both 2003 and 2018 ($\chi 2=12.637$, df=8, p=0.125; $\chi 2=4.204$, df=8, p=0.8383).

Discussion

Open access geospatial data have already been used for the analysis of land use and land cover changes (LULC) of inselbergs (Kidane et al. 2012; Hailemariam et al. 2016; Shawky et al. 2020). Landsat imagery (30m resolution) has been subject to classification in these studies. In the present study, as inselbergs are complex three-dimensional (3D) ecosystems with several spatial microhabitats (Aristizàbal-Botero et al. 2020), we opted to use high-resolution Sentinel 2 images (10 m), the highest amongst freely available satellite products (Abdi 2020). When analyzing changes over time using remote sensing data, it is essential to use data from the same type of sensor, ideally acquired around the same date, to minimize the influence of external factors that could affect the accuracy of the analysis, such as variations in sun angle, seasonal changes, and differences in vegetation growth stages (Lu et al. 2004). The Sentinel 2 image archives were not available for the year 2003, therefore the use of Spot 5 imagery for the year 2003 was a necessary alternative. The differences in sensor characteristics with regard to spatial, spectral, and radiometric resolution may pose challenges in interpreting our results. However, the use of Sentinel 2 and Spot 5 imagery to assess land cover changes has already been implemented in several studies (Deng et al. 2019; Furberg et al. 2019; Ljuša et al. 2021). Given these research findings, land-cover maps from both Spot 5 and Sentinel 2 data at different points in time, in order to make spatio-temporal comparisons and evaluate environmental impact, is considered a reliable method.

The land use classes observed on the inselbergs and their adjacent areas in the Sudano-Guinean zone of Benin are the same as those observed in the Bale Mountain Eco-Region of Ethiopia (Kidane et al. 2012; Hailemariam et al. 2016). This is indicative of several spatial microhabitats in this ecosystem. However, between 2003 and 2018, an increase in fields and fallows over the natural vegetation land cover was observed. This is similar to the changing trends in vegetation cover in the Collines department that is the subject of our study (Oloukoi et al. 2006). Many studies conducted by researchers in the context of landscape dynamics in different landscapes of Benin have revealed the same trend (Tchibozo and Domingo 2014; Avakoudjo et al. 2014; Arouna et al. 2016). This regression is associated with the practice of slash-and-burn agriculture, logging for charcoal production, and the rising population in the zone (Oloukoi et al. 2006; Brink and Eva 2009; Barima et al. 2010). Also, the rapid population growth (greater than 3% per year) (Bidou et al. 2019), impacts fallow periods that are not long enough to allow adequate reconstitution of soil fertility and restoration of land productivity (Goma Boumba and Samba-Kimbata 2019). This reduces the availability of farmland and may justify the conversion of natural land use to fields and fallow. But, inselbergs have long been considered unsuitable for agriculture (Porembski et al. 2016), and thus escape its impacts because of their low agronomic value (Oumorou 2003). Despite this, the same regressive trend of forest land cover to fields and fallows has already been observed in the mountainous formations of Bale Eco-Region of Ethiopia (Kidane et al. 2012; Hailemariam et al. 2016; Shawky et al. 2020). The investigations conducted in the field revealed that the acquisition of agricultural land on the inselbergs is adopted by farmers in the Collines department to resolve the problem of transhumance. Transhumance is the seasonal movement of people and their livestock between different pastures or grazing lands in search of better foraging and water resources ((Sossou et al. 2016). In the Collines department, transhumance is quite recurrent and leads to deadly and bloody conflicts between these herders and farmers (Sossou et al. 2016). Thus, the limited movement of animals due to the altitude and high slopes of the inselbergs, reduces the impact of farmer-herder conflicts which are common in the region.

Aside from human activities, the global temperature increase caused by climate change has a significant impact on the vegetation of inselbergs. According to Dobrowski et al. (2013), climate change has led to changes in temperature and precipitation patterns, affecting ecosystems across the globe. One of the most important impacts of climate change on inselberg vegetation is the modification of water availability. Inselbergs are often located in arid and semi-arid regions (Gomes and Alves 2010) where water is scarce, and any decrease in the amount of available water has serious consequences for their vegetation. Studies have shown that a decrease precipitation in arid areas has led to a reduction in vegetation density. Furthermore, as the global temperature continues to rise, evapotranspiration is also increasing, that can further reduce water availability for plants (Barthlott et al. 2007). Myers et al. (2000) identified inselbergs as one of the biodiversity hotspots that are particularly vulnerable to climate change.

In addition, climate change can also increase the frequency and intensity of forest fires on inselbergs, which can have serious consequences on its vegetation. Indeed, every year, all the vegetation on inselbergs is consumed by dry season vegetation fires (Oumorou 2003). The increase in the frequency of vegetation fires can also lead to the conversion of some land use classes from dense natural vegetation to less dense natural vegetation.

In addition to the decline in natural vegetation land cover classes, inselbergs and their adjacent areas have also been subject to increases in anthropogenic land cover classes, which are reflected in an increase in the class of bare rock to grassland and fields and fallow land. Indeed, the water that flows over the inselbergs is a source of rock alteration that favors colonization by grassy vegetation (Sarthou and Grimaldi 1992). Along with the increase in plant biomass, the depth of the soils grows, increasing their water retention capacity and thus allowing the development of more abundant and woody vegetation (Freycon et al. 2003; Oumorou 2003; Freschet et al. 2018). This would explain the conversion of grassland and bare rock into fields and fallow and the growth in natural vegetation classes. The adjacent areas of inselbergs can also be fertile and suitable for agriculture, as they can benefit from nutrient input from the surrounding slopes and hills. There would have been significant support for the establishment of low-rooting crops such as maize and cowpea, and the densification of certain topsoil use classes.

To appreciate the level of the anthropization of the inselbergs, the anthropization indices were calculated. They show an increase in the fragmentation index for natural land use classes. Fragmentation is recognized as the first consequence of the landscape transformation process (Fahrig 2003; Alongo et al. 2013). It is often associated with agricultural intensification (Benton et al. 2003) as demonstrated by the drastic increase in the dominance index (Dj) of the field and fallow class during this study. This is not without consequences on the quality of habitats (Alohou et al. 2016) and therefore on the quality of Benin inselbergs. Slowly we may see a reduction in the quantity of natural habitat (Ouinsavi and Sokpon 2010), an increase in the number of habitat patches, an increase in the isolation of patches, and an increase in the proportion of edges (Collier and Smith 2000; Halla 2002; Alongo et al. 2013). This fragmentation may cause the absence of all animal life on inselbergs, which are known to conserve endemic biodiversity. We can then conclude that there is a regressive dynamic of the natural vegetation cover of the inselbergs of Benin.

In 2003, natural vegetation was equally present on both protected and unprotected inselbergs. However, settlements were more common on protected inselbergs, while tree plantations were more prevalent on unprotected inselbergs. By 2018, there had been an expansion of fields and fallow land on both protected and unprotected inselbergs, with a decrease in settlements and bare rocks, and an increase in grassland. This is consistent with previous research on LULC change in protected areas in Benin, which found that protected status alone may not be enough to prevent land use changes. For example, a study by Avakoudjo et al. (2014) found that the W National Park in northwestern Benin experienced significant LULC changes between 2003 and 2013, with a decline in forest cover and an increase in cropland. Similarly, the studies by Orekan and Oladokoun (2018) and Azonnakpo et al. (2020) in protected forests of Savalou and Dassa-Zoumé respectively, found that the protected forest in the Collines department experienced significant deforestation and land use change between 1986 and 2016 for Dassa-Zoumé protected forest and between 2006 and 2016 for Savalou protected forest, both with a large part of inselbergs, with a decline in forest cover and an increase in cropland.

Interestingly, on protected inselbergs there was a significant increase in tree plantations, which may suggest efforts by conservation authorities to promote reforestation in protected areas. The finding that tree and shrub savanna grew better on protected inselbergs is in line with studies that have shown that protected areas can have positive effects on biodiversity and ecosystem functioning (Dudley 2008; Butchart et al. 2010).

It is important to note, however, that the results of the chi-square test revealed no statistically significant differences in inselberg LULC between protected and unprotected areas in both 2003 and 2018. While the changes in LULC on protected and unprotected inselbergs suggest that protection measures may have some impact on land use, the lack of statistical significance suggests that other factors are also influencing land use patterns. These results are consistent with previous research that has shown that a range of social, economic, and environmental factors can influence land use decisions and patterns (Turner et al. 1994; Lambin et al. 2003). Indeed, the populations around the inselbergs mostly practice quarrying to obtain gravel (Oumorou 2003). This economic activity represents a real threat to the inselbergs whose support is exploited for economic purposes.

Conclusions

The analysis of land-use changes of inselbergs and their adjacent area was carried out in the Collines department. Sentinel 2 and Spot 5 satellite images of 10 m resolution were used for this purpose. The most observed trends are conversions from natural LULC classes to anthropogenic LULC, particularly with a significant increase of fields and fallows. In addition, while protected areas may have some impact on inselberg land use, other factors are also important in shaping these patterns. Further research is needed to better understand the complex social, economic, and environmental factors that influence land use decisions and patterns on protected and unprotected inselbergs. Also, protected areas in Benin may be facing increasing pressure from land use change and development. It is therefore urgent to develop a conservation and restoration plan for inselbergs of Benin for better conservation of their biological diversity through the following activities:

- Conduct awareness campaigns to educate the local population on the importance of the inselbergs and the benefits of its restoration.
- Establish a participatory planning process that includes the local population in decision-making and implementation of restoration activities.
- Replant trees through seed collection, plant production, tree planting and tree maintenance.
- Establish a sustainable forest management system to prevent illegal activities such as over-cutting, hunting, and mining on the inselbergs.
- Promote agroforestry by planting trees in agricultural fields to provide forest products and reduce pressure on the inselbergs.

The involvement of the local population in the restoration and conservation of the inselbergs is crucial for ensuring the long-term sustainability of the project. By working together with the local population, we can restore and conserve the inselbergs and ensure its benefits for future generations.

Data availability

The data that support the findings of this study are available from https://scihub.copernicus.eu/ for Sentinel 2 images. Spot 5 images are available from the "Observation spatiale des forêts tropicales" (OSFACO) project (Djaouga et al. 2021). However, data are also available from the authors upon request.

Author contributions

R.E.D.A., S.S.M.T. and A.E.A. planned the research, R.E.D.A. conducted the field work, performed the images analyses and led the writing, while all authors critically revised the manuscript.

Acknowledgements

We would like to thank Dr. Thierry Agbanou and Mr. Chiméi Ahouangan for all the advices and help provided in the image processing, and to the administration of the Forest Inspectorate of the Collines department for its availability and advice. We also express gratitude to the villages chiefs of the localities we visited, whose consent facilitated the realization of the present work.

References

Abdi AM (2020) Land cover and land use classification performance of machine learning algorithms in a boreal landscape using Sentinel-2 data. GIScience & Remote Sensing 57: 1–20. https://doi.org/10.1080/15481603.2019.1650447

Adomou AC, Sinsin B, Van Der Maesen LJG (2006) Phytosociological and chorological approaches to phytogeography: A meso-scale study in Benin. Systematics and Geography of Plants 76: 155–178.

Afouda F (1990) L'eau et les cultures dans le Bénin central et septentrional: étude de la variabilité des bilans de l'eau dans leurs relations avec le milieu rural de la savane africaine. Ph.D. thesis, Paris IV (Sorbonne) University, Paris.

Agbanou T, Martin P, Toko II, Tente B (2018) Modelisation des changements d'occupation des terres en region soudanienne au Nord-Ouest du Bénin. European Scientific Journal 14: 248–266. https://doi.org/10.19044/esj.2018.v14n12p248

Akoègninou A, Van Der Burg WJ, Van Der Maesen LJG (2006) Flore analytique du Bénin. Backhuys Publishers, Leiden, 1034 pp.

Alohou C, Ouinsavi C, Sokpon N (2016) Facteurs déterminants de la fragmentation du bloc forêt classée-forêts sacrées au Sud-Bénin. Journal of Applied Biosciences 101: 9618–9633.

Alongo S, Visser M, Drouet T, Kombele F, Collinet G (2013) Effets de la fragmentation des forêts par l'agriculture itinérante sur la dégradation de quelques propriétés physiques d'un ferralsol échantillonné à Yangambi, R.D. Congo. Tropicultura 31: 36–43.

Aristizàbal-Botero A, Pàez-Pérez D, Realpe E, Vanschoenwinkel B (2020) Mapping microhabitat structure and connectivity on a tropical inselberg using UAV remote sensing. Progress in Physical Geography: Earth and Environment 45: 1–19. https://doi.org/10.1177/0309133320964327

Arouna O, Etene CG, Issiako D (2016) Dynamique de l'occupation des terres et état de la flore et de la végétation dans le bassin supérieur de l'Alibori au Bénin. Journal of Applied Biosciences 108: 10531–10542. https://doi.org/10.4314/jab.v108i1.7

ASECNA (2018) BENIN data portal. Climatologie. http://benin.opendataforafrica.org/kbekwme/climatologie-statistiques-sur-la-climatologie [Accessed 14 Apr 2020]

Avakoudjo J, Mama A, Toko I, Kindomihou V, Sinsin B (2014) Dynamique de l'occupation du sol dans le Parc National du W et sa périphérie au Nord-Ouest du Bénin. International Journal of Biological and Chemical Sciences 8: 2608–2625. https://doi.org/10.4314/ijbcs.v8i6.22

Azonnakpo JPG, Azonnakpo OV, Vodounou JBK (2020) Conditions de réhabilitation de La Foret Classee de Dassa-Zoume. International Journal of Progressive Sciences and Technologies 21: 223–238.

Bamba I, Mama A, Neuba DFR, Koffi KJ, Traore D, Visser M, Sinsin B, Lejoly J, Bogaert J (2008) Influence des actions anthropiques sur la dynamique spatio-temporelle de l'occupation du sol dans la province du Bas Congo (République Démocratique du Congo). Sciences & Nature 5: 49–60. https://doi.org/10.4314/scinat.v5i1.42151

Barima YSS, Egnankou MW, N'doumé CTA, Kouamé FN, Bogaert J (2010) Modélisation de la dynamique du paysage forestier dans la région de transition forêt-savane à l'Est de la Côte d'Ivoire. Télédétection 9: 129–138.

Barthlott W, Hostert A, Kier G, Kueper W, Kreft H, Mutke J, Rafiqpoor MD, Henning J, Sommer JH (2007) Geographic patterns of vascular plant diversity at continental to global scales. Erdkunde 61: 305–315. https://doi.org/10.3112/erdkunde.2007.04.01

Benton TG, Vickery JA, Wilson JD (2003) Farmland Biodiversity: is habitat heterogeneity the key? Trends in Ecology & Evolution 18: 182–188. https://doi.org/10.1016/S0169-5347(03)00011-9

Bidou JE, Droy I, Houesse R, Mering C (2019) Dynamiques démographiques, vulnérabilité et évolution du couvert végétal au nord Bénin: des interactions complexes. Espace populations sociétés, 2018. https://doi.org/10.4000/eps.8083

Bogaert J, Zhou L, Tucker CJ, Myneni RB, Ceulemans R (2002) Evidence for a persistent and extensive greening trend in Eurasia inferred from satellite vegetation index data. Journal of Geophysical Research 107: ACL 4–1–ACL 4–14. https://doi.org/10.1029/2001JD001075

Boko M (1988) Climat et communautés rurales au Bénin: rythmes climatiques et rythmes de développement. Ph.D. thesis, Bourgogne University, Dijon.

Bokonon-Ganta EB (1987) Les climats de la région du Golfe du Bénin (Afrique Occidentale). Ph.D. thesis, Paris IV (Sorbonne) University, Paris.

Brink AB, Eva H (2009) Monitoring 25 years of land cover change dynamics in Africa: A sample-based remote sensing approach. Geography 29: 501–512. https://doi.org/10.1016/j.apgeog.2008.10.004

Buckman S, Morris RH, Bourman RP (2021) Fire-induced rock spalling as a mechanism of weathering responsible for flared slope and inselberg development. Nature communications 12: e2150. https://doi.org/10.1038/s41467-021-22451-2

Butchart SH, Walpole M, Collen B, Van Strien A, Scharlemann JP, Almond RE, Baillie JEM, Bomhard B, Brown C, ... Watson R (2010) Global biodiversity: indicators of recent declines. Science 328: 1164–1168. https://doi.org/10.1126/science.1187512

Ceballos G, Ehrlich PR, Barnosky AD, García A, Pringle RM, Palmer TM (2015) Accelerated modern human–induced species losses: Entering the sixth mass extinction. Science Advances 1: e1400253. https://doi.org/10.1126/sciadv.1400253

Collier KJ, Smith BJ (2000) Interactions of adult stoneflies (Plecoptera) with riparian zones I. Effects of air temperature and humidity on longevity. Aquatic Insects 22: 275–284. https://doi.org/10.1076/0165-0424(200010)22:4;1-Y;FT275

de Paula LFA, Negreiros D, Azevedo LO, Fernandes RL, Stehmann JR, Silveira FAO (2015) Functional ecology as a missing link for conservation of a resource-limited flora in the Atlantic forest. Biodiversity and Conservation 24: 2239–2253. https://doi.org/10.1007/s10531-015-0904-x

de Paula LFA, Azevedo LO, Mauad LP, Cardoso LJT, Braga JMA, Kollmann LJC, Fraga CN, Menini Neto L, Labiak PH, … Forzza RC (2020) Sugarloaf Land in south-eastern Brazil: a tropical hotspot of lowland inselberg plant diversity. Biodiversity Data Journal 8: e53135. https://doi.org/10.3897/BDJ.8.e53135

de Souza S (1987) Flore du Bénin. Catalogue des plantes du Bénin. Tome 1. Université nationale du Bénin, Cotonou.

Delalay M, Tiwari V, Ziegler A, Gopal V, Passy P (2019) Land-use and land-cover classification using Sentinel-2 data and machine-learning algorithms: Operational method and its implementation for a mountainous area of Nepal. Journal of Applied Remote Sensing 13: e014530. https://doi.org/10.1117/1.JRS.13.014530

Deng J, Huang Y, Chen B, Tong C, Liu P, Wang H, Hong Y (2019) A Methodology to Monitor Urban Expansion and Green Space Change Using a Time Series ofMulti-Sensor SPOT and Sentinel-2A Images. Remote Sensing 11: e1230. https://doi.org/10.3390/rs11101230

Djaouga M, Arouna O, Zakari S, Kouta S, Moumouni YI, Mertens B, Imorou IT, Thomas O (2021) Cartographie de la déforestation dans le département de l'Alibori (nord du Benin) grâce aux images satellitaires SPOT. Revue Française de Photogrammétrie et de Télédétection 223: 200–216. https://doi.org/10.52638/rfpt.2021.577

Dobrowski SZ, Abatzoglou J, Swanson AK, Greenberg JA, Mynsberge AR, Holden ZA, Schwartz MK (2013) The climate velocity of the contiguous United States during the 20th century. Global Change Biology 19: 241–251. https://doi.org/10.1111/gcb.12026

Dubroeucq D (1977) Carte pédologique de reconnaissance de la République Populaire du Bénin au 1/200 000, feuille de Savè. ORSTOM, Paris.

Dudley N [Ed.] (2008) Guidelines for applying protected area management categories. IUCN, Gland. https://doi.org/10.2305/IUCN.CH.2008.PAPS.2.en

ESA (2015) Sentinel-2 user handbook (section 1.10.4). https://sentinel.esa.int/documents/247904/685211/Sentinel-2_User_Handbook [Accessed 20 May 2022]

Fahrig L (2003) Effects of habitat fragmentation on biodiversity. Annual Review of Ecology, Evolution, and Systematics 34: 487–515. https://doi.org/10.1146/annurev.ecolsys.34.011802.132419

Freschet GT, Violle C, Roumet C, Garnier E (2018) Interactions entre le sol et la végétation: structure des communautés de plantes et fonctionnement du sol. In: Lemanceau P, Blouin M (Eds) Les sols au coeur de la zone critique 6: écologie. ISTE, London, 83–99. https://doi.org/10.3917/re1.091.0006

Freycon V, Sabatier D, Paget D, Ferry B (2003) Influence du sol sur la végétation arborescente en forêt guyanaise: état des connaissances. Revue forestière française 20: 60–76. https://doi.org/10.4267/2042/5787

Furberg D, Ban Y, Nascetti A (2019) Monitoring of urbanization and analysis of environmental impact in Stockholm with Sentinel-2A and SPOT-5 multispectral data. Remote Sensing 11: e2408. https://doi.org/10.3390/rs11202408

Geldmann J, Barnes M, Coad L, Craigie ID, Hockings M, Burgess ND (2013) Effectiveness of terrestrial protected areas in reducing habitat loss and population declines. Biological Conservation 161: 230–238. https://doi.org/10.1016/j.biocon.2013.02.018

Goma Boumba HB, Samba-Kimbata MJ (2019) Analyse de l'impact des déterminants de dégradation du couvert végétal sur les composantes environnementales de la réserve de chasse de la Lefini (Congo). Revue de Géographie Tropicale et d'Environnement 1: 75–89.

Gomes P, Alves M (2010) Floristic diversity of two crystalline rocky outcrops in the Brazilian northeast semi-arid region. Brazilian Journal of Botany 33: 661–676. https://doi.org/10.1590/S0100-84042010000400014

Hailemariam SN, Soromessa T, Teketay D (2016) Land Use and Land Cover Change in the Bale Mountain Eco-Region of Ethiopia during 1985 to 2015. Land 5: e41. https://doi.org/10.3390/land5040041

Halla F (2002) A century of urban development planning for Dar es Salaam City in Tanzania. Building and Land Development 9: 28–46.

INSAE (2016) Cahier des villages et quartiers de ville du département des Collines (RGPH-4, 2013). Ministère du Plan et du Development, Porto Novo, 30 pp.

Joppa LN, Pfaff A (2011) Global protected area impacts. Proceedings of the Royal Society B: Biological Sciences 278: 1633–1638. https://doi.org/10.1098/rspb.2010.1713

Kidane Y, Stahlmann R, Beierkuhnlein C (2012) Vegetation dynamics, and land use and land cover change in the Bale Mountains, Ethiopia. Environmental Monitoring and Assessment 184: 7473–7489. https://doi.org/10.1007/s10661-011-2514-8

Kouassi RH, Tiébré MS, Kouassi KH, Kouakou EN (2014) Diversité floristique des inselbergs Brafouéby et Mafa-Mafou (Sud-Est de la Côte d'Ivoire). Journal of Animal & Plant Sciences 22: 3407–3418.

Lambin EF, Geist HJ, Lepers E (2003) Dynamics of land-use and land-cover change in tropical regions. Annual review of Environment and Resources 28: 205–241. https://doi.org/10.1146/annurev.energy.28.050302.105459

Larson DW, Matthes U, Kelly PE (2000) Cliff Ecology: Pattern and Process in Cliff Ecosystems. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511525582

Ljuša M, Čustović H, Taletović J, Ponjavić M, Karabegović A (2021) Using satellite data for assessing the land use and land cover change in Bosnia and Herzegovina. In: Ademović N, Mujčić E, Akšamija Z, Kevrić J, Avdaković S, Volić A (Eds) Advanced Technologies, Systems, and Applications VI: Proceedings of the International Symposium on Innovative and Interdisciplinary Applications of Advanced Technologies (IAT) 2021. Springer International Publishing, Cham, 694–708. https://doi.org/10.1007/978-3-030-90055-7_56

Lovejoy T, Hannah L (2019) Changing the Biosphere. In: Lovejoy TE, Hannah L (Eds) Biodiversity and Climate Change: Transforming the Biosphere. Yale University Press, New Haven, 3–11. https://doi.org/10.2307/j.ctv8jnzw1.6

Lu D, Mausel P, Brondizio E, Moran E (2004) Change detection techniques. International Journal of Remote Sensing 25: 2365–2401. https://doi.org/10.1080/0143116031000139863

Mas JF (2000) Une revue des méthodes et des techniques de télédétection du changement. Canadian Journal of Remote Sensing 26: 349–362. https://doi.org/10.1080/07038992.2000.10874785

Monmonier MS (1974) Measures of pattern complexity for choroplethic maps. American Cartographer 1: 159–169. https://doi.org/10.1559/152304074784107728

Myers N, Mittermeier RA, Mittermeier CG, Da Fonseca GA, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403: 853–858. https://doi.org/10.1038/35002501

Okioh L (1972) Contribution à l'étude morphologique des reliefs résiduels de la région de Dassa-Zoumé, Fita et Savalou (Dahomey). Ph.D. thesis, Paris VII University, Paris.

Oloukoi J, Mama VJ, Agbo FB (2006) Modélisation de la dynamique de l'occupation des terres dans le département des Collines au Bénin. Revue Télédétection 6: 305–323.

Orekan V, Oladokoun A (2018) Dynamique de l'occupation des terres de la forêt classée de savalou au Bénin. Regard sud. https://regardsuds.org/dynamique-de-loccupation-des-terres-de-la-foret-classee-de-savalou-au-benin/ [Accessed 27 Feb 2023]

Ouinsavi C, Sokpon N (2010) Morphological variation and ecological structure of iroko (*Milicia excelsa* Welw. C. C. Beng) populations across different biogeographical zones in Benin. International Journal of Forestry Research 6: 17–27. https://doi.org/10.1155/2010/658396

Oumorou M (2003) Etude écologique, floristique, phytogéographique et phytosociologique des inselbergs du Bénin. Ph.D. thesis, Bruxelles University, Bruxelles.

Oumorou M, Lejoly J (2003a) Aperçu de la végétation de quelques inselbergs du Bénin. Systematics and Geography of Plants 73: 215–236.

Oumorou M, Lejoly J (2003b) Écologie, flore et végétation de l'inselberg Sobakpérou (nord-Bénin). Acta Botanica Gallica 150: 65–84. https://doi.org/10.1080/12538078.2003.10515987

Parmentier I, Lejoly J, Nguema N (2001) La végétation des inselbergs de Piedra Nzas (Guinée Équatoriale continentale). Acta Botanica Gallica 148: 341–365. https://doi.org/10.1080/12538078.2001.10515920

Pelletier C (2017) Cartographie de l'occupation des sols à partir de séries temporelles d'images satellitaires à hautes résolutions: Identification et traitement des données mal étiquetées. Ph.D. thesis, Toulouse University, UT3 Paul Sabatier, Toulouse.

Porembski S (2007) Tropical inselbergs: habitat types, adaptive strategies and diversity patterns. Revista Brasileira de Botanica 30: 579–586. https://doi.org/10.1590/S0100-84042007000400004

Porembski S, Barthlott W (2000) Granitic and gneissic outcrops (inselbergs) as centers of diversity for desiccation-tolerant vascular plants. Plant Ecology 151: 19–28. https://doi.org/10.1023/A:1026565817218

Porembski S, Silveira F, Fiedler P, Watve A, Rabarimanarivo M, Kouamé F, Hopper S (2016) Worldwide destruction of inselbergs and related rock outcrops threatens a unique ecosystem. Biodiversity and Conservation 25: 2827–2830. https://doi.org/10.1007/s10531-016-1171-1

Poss R (1976) Caractérisation d'une séquence a la périphérie d'un inselberg en zone ferralitique de savane (Côte d'Ivoire). Mesures physiques et approche de la dynamique de l'eau saturante. OSTROM, Abidjan, 156 pp.

R Core Team (2022) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Austria. https://www.R-project.org/ [Accessed 14 Feb 2023]

Rakotondrasoa LO, Malaisse F, Bogaert J (2017) Modélisation de la dynamique du paysage forestier de la Réserve Spéciale d'Ambatovaky (Nord-Est de Madagascar). Tropicultura 35: 312–324. https://doi.org/10.25518/2295-8010.1102

Rawat JS, Kumar M (2015) Monitoring land use/cover change using remote sensing and GIS techniques: a case study of Hawalbagh Block, District Almora, Uttarakhand, India. The Egyptian Journal of Remote Sensing and Space Sciences 18: 77–84. https://doi.org/10.1016/j.ejrs.2015.02.002

Reid WV, Mooney HA, Cropper A, Capistrano D, Carpenter SR, Chopra K, Dasgupta P, Dietz T, Duraiappah AK, ... Zurek MB (2005) Ecosystems and human well-being – Synthesis: A report of the Millennium Ecosystem Assessment. Island Press, Washington DC.

Saharan MA, Vyas N, Borana SL, Yadav SK (2018) Classification and assessment of the land use – land cover changes in Jodhpur City using remote sensing technologies. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLII-5: 767–771. https://doi.org/10.5194/isprs-archives-XLII-5-767-2018

Sarthou C, Grimaldi C (1992) Mécanismes de colonisation par la végétation d'un inselberg granitique en Guyane Française. Revue d'Ecologie, Terre et Vie 47: 329–349. https://doi.org/10.3406/revec.1992.2067

Schut M, van Paassen A, Leeuwis C, Klerkx L (2014) Towards dynamic research configurations. A framework for reflection on the contribution of research to policy and innovation processes. Science and Public Policy 41: 207–218. https://doi.org/10.1093/scipol/sct048

Shawky M, Mohammed A-B, Talal A-A (2020) Monitoring land use and land cover changes in the mountainous cities of Oman using GIS and CA-Markov modelling techniques. Land Use Policy 91: e104414. https://doi.org/10.1016/j.landusepol.2019.104414

Sinsin B, Kampmann D [Eds] (2010) Atlas de la Biodiversité de l'Afrique de l'Ouest, Tome I: Bénin. Cotonou & Frankfurt/Main.

Sossou AG, Adjahossou S, Degbetchevi DM (2016) Conflits de l'espace agricole entre éleveurs et agriculteurs dans la commune de Glazoué (Bénin) [Technical Report]. EPAC/UAC, Abomey-Calavi. http://biblionumeric.epac-uac.org:8080/jspui/handle/123456789/1887

Tchibozo EA, Domingo E (2014) Occupation du sol et analyse de la structure spatiale des forêts classées: cas de Dogo-Kétou, dans le Centre-Est du Bénin. Revue de géographie du laboratoire Leïdi 12: 137–153.

Tindano E, Ganaba S, Sambar O, Thiombiano A (2015) La végétation des inselbergs du sahel Burkinabè. Bois & forêts des tropiques 325: 21–33. https://doi.org/10.19182/bft2015.325.a31270.

Toyi SM, Barima SYS, Mama A, Andre M, Bastin J-F, De Cannière C, Sinsin B, Bogaert J (2013) Tree plantation will not compensate for natural woody vegetation cover loss in the Atlantic Department of southern Benin. Tropicultura 31: 61–70.

Turner B, Meyer WB, Skole DL (1994) Global land-use/land-cover change: towards an integrated study. Ambio 23: 91–95.

Yadav SK, Borana SL (2017) Monitoring and temporal study of mining area of Jodhpur City using remote sensing and GIS. International Research Journal of Engineering and Technology (IRJET) 4: 1732–1736.

Yedomonhan H, Houndagba C, Akoegninou A, Van der Maesen L (2008) Structure et diversité floristique de la végétation des inselbergs du secteur méridional du Centre-Bénin. Systematics and Geography of Plants 78: 111–125.

E-mail and ORCID

Ranmi Elsa Denise Ayeko (Corresponding author, ayekodenise@gmail.com)
Sêwanoudé Scholastique Mireille Toyi (mireille.toyi@gmail.com)
Achille Ephrem Assogbadjo (assogbadjo@gmail.com)
Brice Augustin Sinsin (bsinsin@gmail.com)

Supplementary material

Supplementary material 1
Inselbergs LULC Ground Control Points (table)
Link: https://doi.org/10.3897/VCS.89746.suppl1