Journal of Environmental Science and Engineering A11 (2022) 13-34
doi:10.17265/2162-5298/2022.01.003

Assessing Land Use/Cover Basing on Connectivity, Changes and Drivers over 20 Years to Recommend Conservation in Incalaue River Basin, Niassa National Reserve in Mozambique

Natumanya Ezrah[1, 2], Natasha Ribeiro[1], Majaliwa Jackson Gilbert Mwanjalolo[2] and Franziska Steinbruch[3]

1. Faculdade de Agronomia e Engenharia Florestal, Universidade Eduardo Mondlane, 3453 Avenida Julius Nyerere, Maputo Mozambique

2. College of Agricultural and Environmental Sciences, Makerere University, P.O Box 7062 Kampala, Uganda

3. National Administration for Conservation Areas, National Administration for Conservation Areas, Avenida 10 de Novembro, n º40, Praceta 1196, Maputo, Mozambique, n º40, Praceta 1196, Maputo, Mozambique

Abstract: Landscape heterogeneity in biodiversity conservation areas can be represented by the size of the geographic range of vegetation cover types and their species composition; and is reflected in historical and contemporary LULC (Land Use/Cover). This study assesses LULC changes in a predominantly vegetated Incalaue river basin in NSR (Niassa Special Reserve) for the years 2001, 2009 and 2019 to recommend conservation targets. LULC was mapped using the best available Landsat imagery of the area which were L7 EMT+ (Landsat 7 Enhanced Thematic Mapper), L5 TM (Landsat 5 Thematic Mapper) and L8 OLI (Landsat 8 Operational Land Imagery). Image classification and remote sensing analysis were done using images of 30-meter resolution using the maximum likelihood supervised classification on ArcGIS ArcMap 10.4.1. Results showed that there were gains in area cover for taller vegetation classes with the major ones being MDW (Medium Density Woodland) which increased by 51.07%; MFS (Mountain Forests) by 36.41%; and HDW (High-Density Woodland) by 17.95% over the studied period. NDVI (Normalized Difference Vegetation Index) maps show 2019 with wetter vegetation than 2001; and both wetter than 2009. The spatially dominant vegetation-class was MDW (Medium Density Woodland) covering 27.29% of the basin area largely in the elevation band 410-430 m a.s.l. Vegetation classes do not necessarily follow landform with rocky upstream section (440-510 m a.s.l) having MFS which also existed in lower altitude areas (370-430 m a.s.l); and woodland being randomly distributed across the basin while there was also WET (Wetland) in both upstream and downstream. There are multiple vegetation species localized in distribution in the landscape which makes these to be hotspot areas for conservation. Local people in the human settlement areas of Ntimbo 1 and Lisongole recognize vulnerability of ecosystems, environmental change as well as human land use/cover and climate change as the main threats. There was a large increase in human settlement area (104.17%) over the study period and this shows a need for mitigating community-wildlife conflict especially along the green vegetation riverine areas during the dry seasons. The study showed need for a plan for human LULC away from wildlife vegetation hotspot areas; identification and consideration of area-demanding threatened species that require landscape scale conservation; and prevention of degradation and loss of water source hotspots for wildlife as well as conservation of sensitive and localized vegetation species. The Mozambican land law allows individual ownership of land by citizens even in conservation areas which creates a danger of human-wildlife interactions; risks land encroachment deeper into the reserve; and potentially causing environmental degradation of this sensitive ecosystem hosting humans and wildlife so there is need for consistent and conservation targeted environmental research to inform policy and LULC decisions.

Key words: Hydrology, landscape, vegetation, woodland.

1. Introduction

LULC (Land Use/Cover) data are important for environmental management in river catchment areas hereafter referred to as river basins. Natural vegetation

Corresponding author: Ezrah Natumanya, M.Sc., research fields: landscape hydrology and water resources management.

cover spatial and temporal distributions are indicators of environmental water availability and this is important knowledge in river basin management [1, 2]. LULC changes resulting in biomass reduction in landscapes negatively affect water balance in river basin [3]. Biomass production in landscapes has been shown to have a positive relationship with water availability for dependent ecosystems [4, 5]. The nature and coverage of vegetation biomass coupled with variations in freshness give an indication of soil water availability [6, 7]. Landscapes mosaics of LULC occur in different geometric and spatial arrangements and this is necessary information for sustainable water resources management especially under climate change and increasing land use change global pressures [8-10].

Knowledge of vegetation-cover patterns and structure and hydrologic connectivity is important for understanding soil and groundwater systems in water resources management [10-12]. Spatial patterns in vegetation LULC can reflect environmental hydrogeology and this knowledge is important to understand water sources from an ecological perspective in water resources management [13]. Forested landscapes are prone to disturbances from local land use changes, extreme climatic events, wildfires, atmospheric pollution and invasive species which affect the provision of forest goods, and environmental services and functions [14].

Vegetation influences ET (Evapotranspiration), soil water infiltration, surface runoff as well as organic matter and soil moisture processes and functions in river basins [15]. LULC changes can have increase or reduction impacts on ET and runoff [12]. LULC patches on a landscape are indicators of environmental water availability reflected in biomass production and vegetation community succession which is important knowledge in river basin management [6]. Knowledge of LULC patterns and dynamics for a landscape is important for water resource managers as it can give indication of landscape water contributing areas and monitoring areas for hydrological changes [16].

Vegetation spatial pattern characterization in a landscape is important in environment management to understand connectivity of locations [17]. Heterogenic units play complementary roles in modifying the water regime and knowledge of their complementarity is important in water resources management in river basins [18, 19]. Landscape heterogeneity is also shown in spatial vegetation patterns which are dependent on water availability. Topographic gradients define water storage in a river catchment and are influential in vegetation growth patterns [20, 21]. LULC such as deforestation or agricultural intensification is a key driver of biodiversity changes manifested in species richness and abundance alterations [22].

Environmental impacts of LULC are often exacerbated by human population growth in river basin where they exist [23, 24]. Information on changes in spatial pattern of vegetation cover in a landscape is key in environmental management to understand the connectivity within ecosystems [25]. Heterogenic units play complementary roles in modifying the water regime and knowledge of their complementarity is important in water resources management in river basins [18, 19]. Presently, the world is experiencing climate change as well as LULC effects resulting from population pressure; and this has effect on vegetation which can be a challenge in wildlife conservation areas. Uncertainty in vegetation landscape cover dynamics and atmospheric weather water cycle factors mean an uncertain future in environmental management [26].

The ecosystems' capacity to provide services for mankind can be constrained by changes in the environment, including climate and human-induced LULC [27, 28]. Understanding dynamics in LULC is important for water resources management in the wake of climate change and increase in human degradation of natural ecosystems this had come with global population increase [29]. LULC change has been identified as an environmental challenge that needs more research in land-atmosphere interfaces [30]. Ecosystems and change research is necessary to provide knowledge for integrated water resources management in river basins [13, 31]. Full understanding of land-cover influence on hydrological processes in a landscape requires comprehensive spatial analysis across topographic divides [32]. Vegetation ecosystems patterns represent factors of soil water, stream flows and groundwater in landscape patches [33-35].

A landscape approach is required for managing green landscapes and this depends on rigorous quantification of the composition and structure and spatial dynamics [36]. A landscape mosaic approach is useful for LULC analysis in landscapes that have spatially heterogenous mosaics of patch types over time [37, 38]. In this paper, LULC change in Incalaue river basin in NSR (Niassa Special Reserve) was assessed over 20 years from 2001 to 2019 in a landscape context with a focus on vegetation cover classification. NSR landscape has a unique vegetation strata organization comprising a mixture of MFS (Mountain Forest), LDW (Low Density Woodland), MDW, HDW (High Density Woodland) and WGL (Wooded Grasslands) vegetation. A vegetation study on LAI (Leaf Area Index) in NSR shows potential variability in landscape hydrology [39]. There was reported vegetation difference in hydrologic characterization of Dambos which are dry season water points [40]. The fact that Incalaue river basin is in a national reserve area with human settlements calls for a thorough understanding of the landscape LULC and the implications for wildlife conservation and people.

Climate and LULC affect landscape processes and have an impact on biodiversity and ecosystem services [41]. The effect in Incalaue basin in NSR and regional Miombo ecosystem remains unknown with a need to document specific evidence [42, 43]. This remains a challenge in this area when LULC effect mitigation efforts require information on the cause-effect relationship in a landscape context. This study targeted to explore, in specific variations in LULC in sub-basins as landscape units [44]. The specific objectives of this study were to (1) quantify change in vegetation cover; and (2) understand the relationship between changes in land-cover and landscape positions at the catchment level.

2. Materials and Methods

2.1 Study Area

Incalaue basin (697.02 Sq. km) is located in NNR (Fig. 1). NSR is approximately between the latitudes 12°8′40″ N and 12°22′40″ N; and 37°21′00″ E and 37°45′00″ E in Northern Mozambique. The river basin was delineated using ArcHydro extension in ArcGIS 10.4 and sub-catchments labeled using default generated by FID (Feature ID). NSR is the country’s largest protected area, spanning 42,300 km^2 and is one of Africa’s most iconic wilderness areas and the largest and best preserved of Miombo woodland left in continent [45]. The most ecologically important tree species in the reserve by the importance value index are *Julbernardia globiflora* (Benth.) Troupin, *Diplorhynchus condylocarpon* (Mull. Arg) and *Brachystegia boehmii* Taub [46]. There are reportedly small and big wildlife in the study area [47]. Incalaue basin hosts community settlements in two settlement areas of Ntimbo 1 and Lisongole. The area is a wildlife migration zone to a bigger and permanent Lugenda river downstream during the dry season as the small rivers get dry in this area with a tropical sub-humid and drought-prone climate [45]. The human settlements in the river basin means human harvest of ecosystem resources, which is a threat to wildlife habitats and potentially crates a human-wildlife conflict [31].

2.2 Research Design

The approach used was to study was to map LULC and add an extra analysis for vegetation cover by assessing organization and transitions of classes in the catchment over 20 years. A decadal analysis of LULC for 2001, 2009 and 2019 was done. Emphasis was placed on zoning vegetation classes which reflect cover density in satellite images of the landscape. This was supported with selection of land cover sites identified from both Google map and visually on the ground (Fig.

1). This strategy helps in capturing the beta diversity within the study area [48]. Vegetation classes were assessed based on characteristics of topography using NDVI (Normalized Difference Vegetation Index) as an indicator of density. Analysis of spatial and temporal patterns of vegetation cover was carried out on the basis of sub-basins since these are river flow contributing landscape units. Land cover transition and spatial-temporal statistical analyses were used to discuss spatial and temporal changes.

2.3 Data Collection

Potential specific representative areas for different LULC classes were identified using rectified and geo-referenced Google satellite images in ArcGIS 10.4 software. Onscreen digitizing of polygons containing homogenous areas of vegetation reflected in the images was performed. In each LULC class, two training sites were selected and these were confirmed on the ground during fieldwork [49]. GPS (Global Positioning System) coordinates were collected at representative points during preliminary field visit. Trainings points for each vegetation class were eventually selected and digitized based on ground visits. Identification of sites was done visually while walking through the reserve to target class representative points [50].

Polygons of 50 m × 50 m containing homogenous areas of vegetation for different land-cover classes were selected using geo-referenced Google satellite images in ArcGIS 10.4 software. Onscreen digitization of these Google images was used to confirm vegetation density in these polygons. Two polygons were chosen for each vegetation class. Each polygon was divided into 25 plots of 10 m × 10 m. One of the plots of 10 m × 10 m in an accessible location in each vegetation polygons would be selected for field vegetation mapping. In selection of study plots, chance was ensured by randomly choosing one plot from the 25 plots. If a chosen plot was inaccessible for vegetation sampling, the nearest accessible one was chosen. Two survey polygons were available for other classes but only one for WET (Wetland) as this area was very risky in both dry and wet season due to wildlife. Identification of sites for laying plots (field points) in vegetation classes was done by tracking to a location using a GPS (*Garmin eTrex*) which has ~3 m accuracy. Field data were collected in November and December 2009 for end of dry season and in April and May 2020 for end of the wet season. The end of seasons sampling was done to fully characterise vegetation species composition.

Mapping and analysis of LULC change was conducted using RS (Remote Sensing) and GIS (Geographical Information System). River basin delineation was done using 30 × 30 m DEM (Digital Elevation Model) obtained from the USGS (United States Geological Survey (https://earthexplorer.usgs.gov/). To investigate historical changes in LULC, we obtained and classified the best available satellite images for the area which were Landsat-7 EMT+ (2001); Landsat-5TM (2009); and Landsat-8 OLI for 2019 (Table 1). Images were downloaded from Path 069 and Row 321 and all had less than 20% cloud cover. Landsat images are good for land-cover mapping [51]. Landsat satellite scenes were obtained from the USGS archives (https://ers.cr.usgs.gov/).

Satellite images captured between July and November (dry season) when the sky is mostly clear were used. This is the time when vegetation is clear excluding flush vegetation. Ancillary data used were from GCP (Ground Control Points) and TM (Topographic Map) at a scale of 1:50,000. Location points representative of land-cover classes were chosen for this study.

The images were atmospherically corrected using Dark Object Subtraction procedure to minimize the atmospheric impact on the sensor [52]. This method searches and removes dark pixel values. Point-based classification was used to map LULC in the area given the wild reserve nature of landscape [53].

Vegetation mapping was done by adopting an existing description of LULC classes in the reserve which was for our landscape multi-year coarse vegetation cover analysis [44]. In order to classify vegetation groups sharing similar floristic composition and structure, we based on the relationship between reflectance values of satellite imagery mapped LULC types combining WGL and wooded gallery grassland to map them as WGL [54]. Accordingly, vegetation classes used were MDW, HDW, WGL, LDW, MFS, as well as WET. Other LULC classes included RBA (Recently Burned Area), ISL (Inselbergs) and BUL (Built-Up Area).

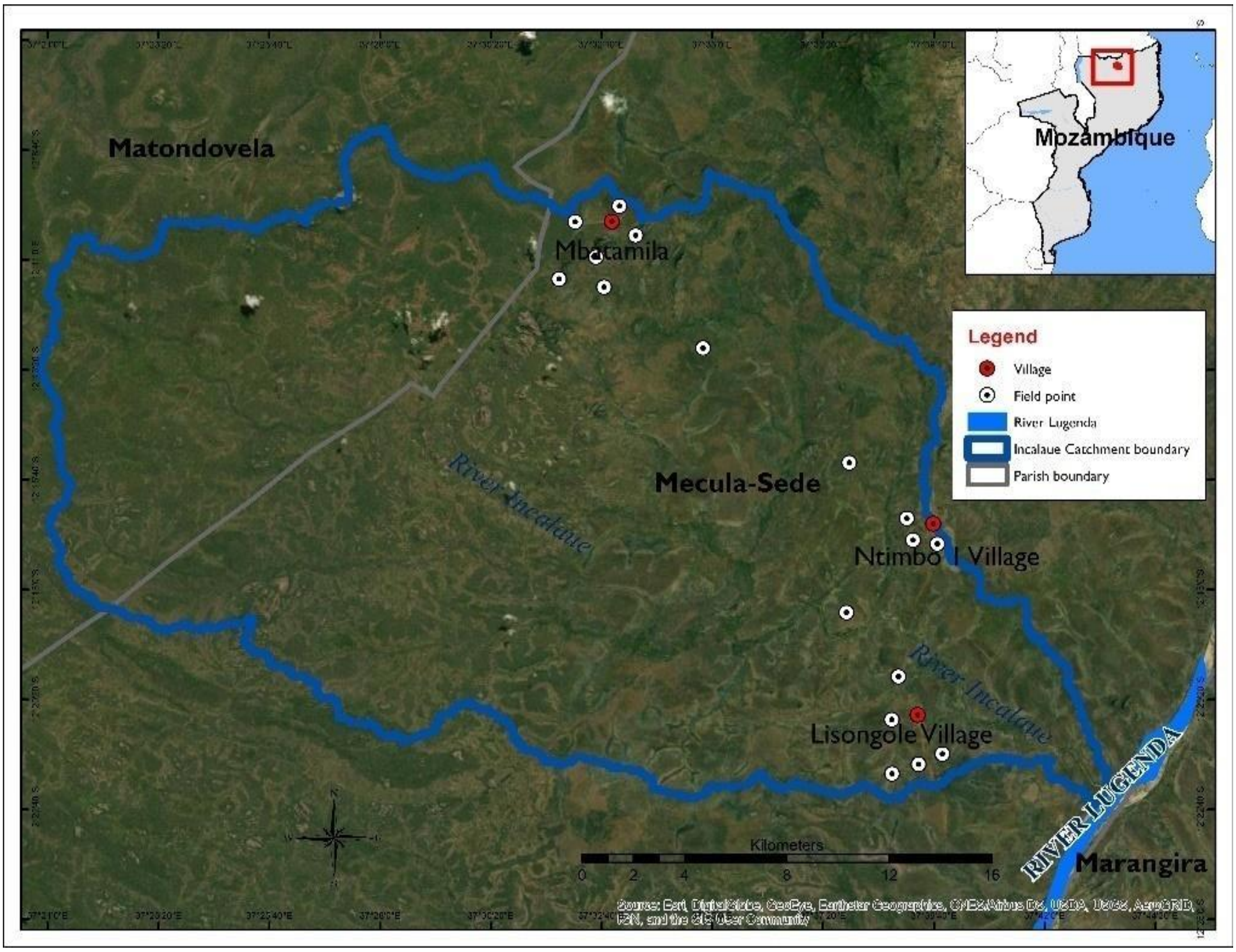


Fig. 1 Vegetation classification point locations.[1]

Table 1 Source and characteristics of images used.

Satellite Data	Path/Row	Image Date	Number of Bands	Spatial Resolution
L7 EMT+	166/069	08/11/2001	3	30 m
L5 TM	166/069	17/07/2009	3	30 m
L8 OLI	166/069	13/017/2019	3	30 m

[1] Field points were chosen at accessible places because the study area is a wildlife reserve area.

Journal of Environmental Science and Engineering A11 (2022) 13-34
doi:10.17265/2162-5298/2022.01.003

2.4 Image Processing and Analysis

Haze Reduction Procedure based was used based on Tasseled Cap Transformation Algorithm on our Landsat images. Exclusion masks were put on “no-data” areas for the images with high haze content or compact clouds (> 10). At the end of this stage, we obtained a set of normalized multiband images and RGB (Red, Blue and Green) composites. The usable band numbers for RGB viewing were 4, 3, 2 for 2019 and the same for 2009; and 3, 2, 1 for 2001 as given above. Image classification was done in ArcGIS 10.4 and ENVI 5.1software version. Our data processing steps included image acquisition, pre-processing and classification. Supervised image classification was verified using Google reference and ground truthing data from the field.

The next step was filtering and accuracy assessment for classification acceptability assessment and this was done using Google map images [50]. The classified images of 2001, 2009 and 2019 were then used for change detection and comparisons.

2.4.1 Satellite Image Processing

Comparative analysis of Landsat data is possible when you reduce errors related to ache sensor, noise from several sources, and uncertainty in scale and geometric conditions [51]. Preprocessing satellite using field collected data was done to minimize those errors.

Radiometric correction was done in ENVI 5.1 where raw data from the sensors (DNs) were converted to top-of-atmosphere reflectance. The images were atmospherically corrected using Dark Object Subtraction procedure to minimize the atmospheric impact on the sensor [55]. Images were pre-georeferenced for WGS 84/UTM (World Geodetic System 1984) zone 37S. A composite with natural colors was created combining 3 colors, i.e. red, green and blue. Geometric correction of the 2019 Landsat-8 OLI using the field GPCs taken from TM at a scale of 1:50,000 provided the basis for the 2001 and 2009 image-to-image registration [51].

The study benefitted from use of Landsat-5TM image for 2009 as this avoided the effect of those missing data in 7 ETM+ for this year due to SLC (Scan Line Corrector) failure from 2003 till 2013 that would result in data losses [51]. There is slight passable error in Landsat-5 TM in some applications, such as monitoring land use change and crop quality but this does not significantly affect classification for our purpose [56]. The resolution of Landsat-8 OLI imagery and Landsat-7 ETM+ was sharpened from 30 m to 15 m by merging spatial data in the high-resolution panchromatic bands with color information in the multispectral bands using the nearest neighbor diffusion pan sharpening technique to create a higher resolution colour image that improves mapping and classification accuracy [51]. Given that panchromatic band is not available for Landsat-5 TM image captured in 2001, we also resampled data from 30 to 15 m using the nearest neighbor technique to ensure consistency with OLI and ETM+ data used for other years in this study [51].

2.4.2 Image Classification

Satellite image classification is used to assign different spectral signatures to pixels into finite number of vegetation classes [51, 57, 58]. Effective satellite image classification for land-cover mapping was possible for this largely inaccessible landscape using the approach of Alawamy et al. [51]. This study used existing knowledge of land use/cover in the wider area; reconnaissance field survey; and information from previous studies to map vegetation cover.

Image classification was done using algorithms in ENVI software version 5.1 for spectral reflectance clustering to determine land-cover spectral classes for the catchment delineated [59]. Sub-catchments separation and labels thereafter are default generated by FID. The images were atmospherically corrected using Dark Object Subtraction procedure to minimize the atmospheric impact on the sensor [52]. Dark Object Subtraction is an empirical atmospheric correction method for satellite imagery used to bring out the pixels that are hidden in complete shadow [60]. Point-based classification was used to map LULC in the area given the wild reserve nature of landscape and this approach has been used in previous studies [53].

Two methods of classification were used to classify the composite images. Iso Cluster unsupervised classification was done and maximum likelihood classification used create a classified raster output. The combination of supervised and unsupervised classification was used for land-cover mapping to confirm accuracy of classification. Emphasis was placed on zoning vegetation classes (Fig. 1). This strategy helps in capturing the beta diversity within the study area [48].

2.4.3 Classification Accuracy Assessment

Classification accuracy was tested using Kappa statistics [61, 62]. A set of 100 random points were put on a Google Earth image and Kappa statistics analysis was performed using the form below.

$$K = \frac{N \sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} (x_i + x + i)}{N^2 - \sum_{i=1}^{r} (x_i + x + i)} \quad (1)$$

where,

r = Number of rows/columns in confusion matrix;

x_{ii} = Number of observations in row i and column i;

x_i = Total number of rows i;

$x + i$ = Total number of columns i;

N = Number of observations.

Kappa values of > 0.79 are excellent; values between 0.6 and 0.79 are substantial; and values of 0.59 or less are moderate [62].

The results of Landsat-7EMT+ supervised classification of image of 2001 gave a kappa statistic of 0.788. This shows that the classification was good. High accuracy was also obtained for Landsat-5TM (2009) and Landsat-8OLI (2019) supervised classifications which gave classification accuracy of 0.828 and 0.80 respectively.

To assess mapping accuracy of classification, we used confusion matrix, an overlap-area-based zonal statistics table for testing mapping of reference sample polygons and points [63, 64]. In this process, a total of 400 points were randomly selected basing on the classified image of 2019 and only 287 were at accessible locations (Table 2). We selected reference pixel cells for our basin areas that could be clearly identified on Google map and some locations traced during ground truthing [65]. Reference cells for classification accuracy assessment were selected using the best guess approach for reference point to enable use of independent data [66]. These were put on a Google map and potential for access determined using local knowledge and basing on river basin delineated field map.

2.5 Determination Vegetation Density and Topographic Zones

Emphasis was placed on zoning vegetation classes which reflect cover density as in satellite images of the landscape. This strategy helps in capturing the beta diversity within the study area [48]. Field sample points were chosen in field using Google digitized

Table 2 Confusion matrix.

	HDW	MDW	LDW	WGL	MFS	RBA	ISL	TOTAL	Correctly sampled
HDW	34	2	0	0	2	0	0	38	34
MDW	1	23	2	0	1	0	0	27	23
LDW	1	4	31	6	2	0	0	44	31
WG	0	1	6	72	0	0	0	79	72
MF	0	0	0	0	26	0	0	26	26
RBA	0	0	0	0	0	29	3	32	29
ISL	0	0	0	0	0	10	31	41	31
Total	36	30	39	78	31	39	34	287	246

The overall classification accuracy = percentage ratio of number of correct points. Accuracy = (246/287) × 100% = 85.71%. These results are good in classification of diversity of vegetation communities in land use/cover mapping [67].

images. Google map showed different sections of dense forest vegetation and during fieldwork, it was confirmed that there existed sections in chosen plots with taller and more vegetation.

A combination of NDVI and ground truthing was used for vegetation density mapping. NDVI was used to compare vegetation location points for study years to approximate environment change impact over the study time. A total of 100 location points were used for change comparisons for transition NDVI changes over the years. NDVI is good for vegetation cover density mapping even in water stress conditions when assessed along meteorological conditions as was considered in this study [68-70].

$$NDVI = (NIR-Red)/(NIR+Red) \tag{2}$$

NIR: near-infrared

The values of NDVI range from -1 to 1. Dense vegetative land cover gives a high NDVI.

DEM TM points were used which represent the orthometric height.

The geoid undulation of each point was calculated for subsequent transformation of ellipsoidal height to orthometric height [71]. This is used for calculating the EE (Elevation Errors). The difference between the values of the reference elevation from the elevation value of each DEM was used to get differences field points [71, 72]. In the field, this was done by sampling of coordinate depressions for coordinates and using them to check against DEM elevations [73].

It is important to identify zones and spatial typologies in physical geography, because it is the base of geographic classifications, applied in landscape descriptions and in spatial analyses [74]. The DEM was downloaded from GLOVIS (Global Visualization Viewer) with altitude values. Spatial analysis modelling was performed by zonal modelling where the output is a result of computations performed on all cells that belong to each input zone; and a zone represents a cell of LULC. Zonal statistics were generated for the elevation values of DEM within the zones of each vegetation-cover type.

In landscapes, vegetation cover at topographical and in soil zones forms units of variations of lateral (interflow); and vertical processes (soil moisture, infiltration and ET) and can be visualized in soil and vegetation [75, 76]. Soil properties were assumed to be homogenous for each vegetation unit in our study area for a given topography area.

In assessment of land-cover, plant species in the basin were also identified to further explain vegetation land-cover. The checklist of Miombo woodlands vegetation species vernacular plant names in Mozambique [77]; together with scientific names of species in the reserve [78] were used. Local names were confirmed by community consultations with at least 3 elders in Yao and Makua local languages. Scientific names were further gotten from plants of the world online database (https://powo.science.kew.org/) as well as the website of South African National Biodiversity Institute (http://newposa.sanbi.org/) where pictures and botanical names are given. The above community approach in vegetation species classification had been used in vegetation classification [79]. Plant samples including six plants which could not be classified in the field were brought to the herbarium for classification at Eduardo Mondlane University in Maputo.

2.6 Land-Cover Change Detection

Land use/cover was assessed for percentages for the different classes for the different years. Changes were estimated for the land use/cover types in periods studied:

$$D = ((Ab - Aa)/Aa) \times 100\% \tag{3}$$

where, D refers to rate of change; Aa is the area in the initial year; and Ab is the area in the terminal year.

3. Results

3.1 Land Use and Cover

The basin has 6 vegetation classes by 2019 (Table 3). The rest of the catchment is under built up area, burned areas and ISL. LDW is predominant in lower altitude areas of 370 m to 430 m (Fig. 2). WGLs are evenly distributed in open areas and mainly around inundated valley wet areas where dambos exist [80]. During the study period, there were no major changes in LULC types apart from some losses and gains for classes (Table 3).

Analysis has also been done for study years; progressive land cover changes show MFS and LDW as the main losers; and WGLs and HDW as the main losers (Table 4).

There was increase of area covered by taller vegetation for the study period in the order of MDW> HDW >MFS. There were losses for LDW and WET for vegetation and significant gains for ISL and built-up environment (Table 5).

Table 3 LULC(Sq. km).

No.	LULC	2001		2009		2019	
		Area	%	Area	%	Area	%
1	MFS	78.54	11.27	88.13	12.64	106.95	15.34
2	LDW	154.62	22.18	173.07	24.83	43.54	6.25
3	MDW	88.17	12.65	114.52	16.43	133.2	19.11
4	HDW	161.24	23.13	196.02	28.12	190.19	27.29
5	WGL	200.49	28.76	103.99	14.92	200.49	28.76
6	RBA	2.11	0.30	1.88	0.27	2.03	0.29
7	BULT	0.24	0.03	0.37	0.05	0.48	0.07
8	WET	3.56	0.51	3.49	0.50	3.14	0.45
9	ISL	8.05	1.15	15.55	2.23	17	2.44
	Total	697.02	100.00	697.02	100.00	697.02	100.00

Table 4 LULC change (% area).

No.	LDC	2001 to 2009	2009 to 2019	2001 to 2019
1	MFS	12.21	21.35	36.17
2	LDW	11.93	-74.84	-71.84
3	MDW	29.89	16.31	51.07
4	HDW	21.57	-2.97	17.95
5	WGL	-48.13	92.80	0.00
6	RBA	-10.90	7.98	-3.79
7	BULT	54.17	29.73	100.00
8	WET	-1.97	-10.03	-11.80
9	ISL	93.17	9.32	111.18

Table 5 Land-cover change transition matrix between 2001 and 2019 (Sq. km).

	MFS	MDW	HDW	WGL	LDW	WET	RBA	ISL	BUL	Total
MFS	26.87	27.22	20.14	5.87	25.99	0.32	0	0.52	0.02	106.95
MDW	17.97	14.4	26.45	24.36	47.66	1.48	0	0.86	0.02	133.2
HDW	18.33	27.8	91.75	18.61	31.7	0.4	0.18	1.37	0.05	190.19
WGL	7.68	8.48	7.78	135.01	40.34	0.28	0.31	0.61	0	200.49
LDW	2.57	5.65	12.12	15.38	5.3	0.69	0.28	1.53	0.02	43.54
WET	0.54	0.68	0.61	0.16	0.76	0.39	0	0	0	3.14
RBA	0.04	0.26	0.4	0	0.04	0	1.18	0	0.11	2.03
ISL	4.48	3.63	1.91	1.06	2.76	0	0	3.16	0	17
BUL	0.06	0.05	0.08	0.04	0.07	0	0.16	0	0.02	0.48
Total	78.54	88.17	161.24	200.49	154.62	3.56	2.11	8.05	0.24	697.02

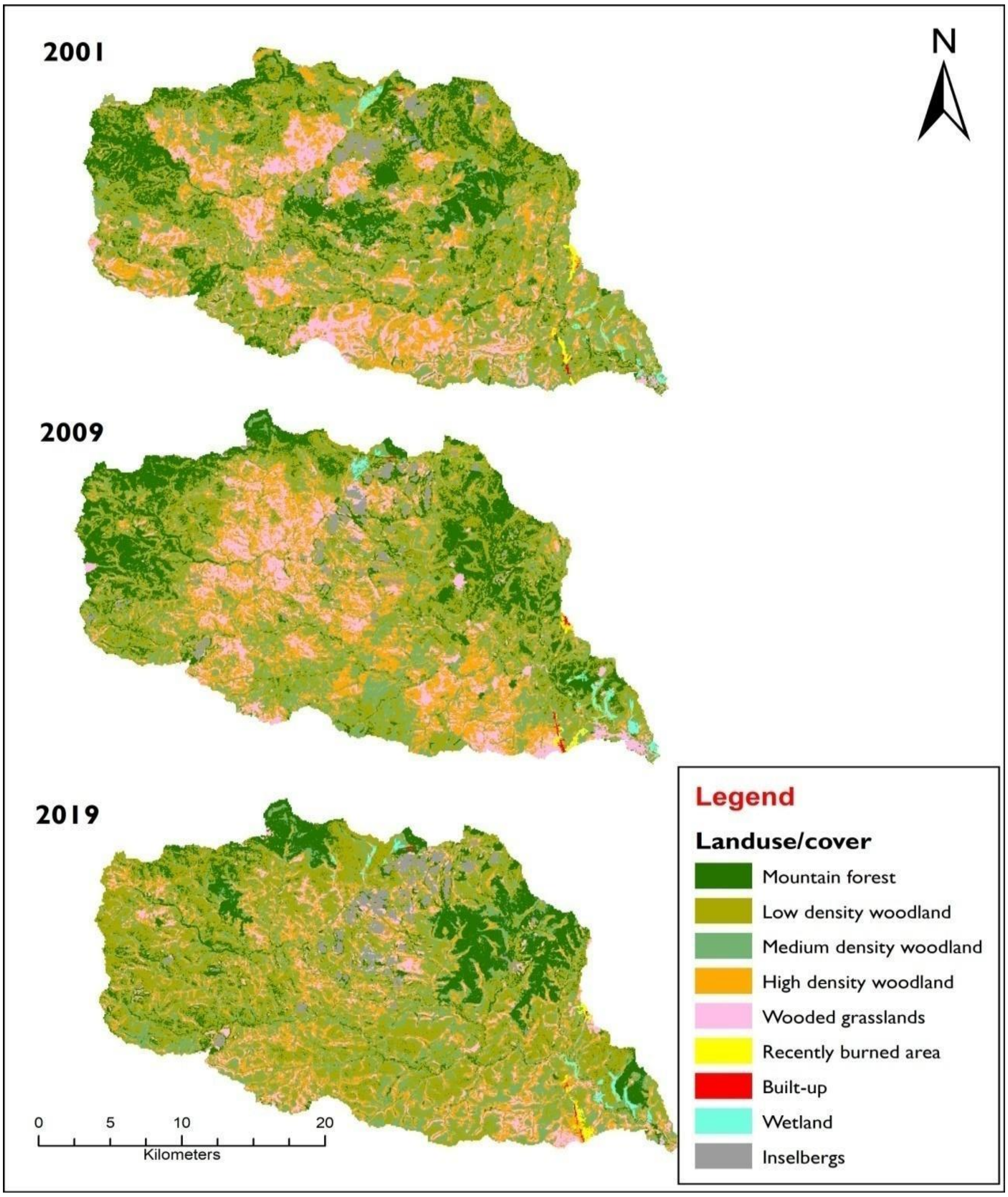


Fig. 2 Land-cover in study years.

The increase in the area covered by ISL was possibly from soil erosion opening up rock and area loss of RBA which reduces for 2019. This can also result from opened up area because the area has vegetation that shades their leaves burning. Overall, there is a larger share of green vegetation (Fig. 2). The increase in vegetation cover density can be because soil bedrock is perhaps young geology or that rocks weather very quickly, and thus the top layer is intensely altered over a short time due to climate in northern Mozambique [81, 82].

3.2 Vegetation Species

Several vegetation species were found by the study. The vegetation species are reportedly used by the local human population and wildlife thus a risk of human-wildlife conflict [40, 44, 78, 83-85]. The species found in rock dominated environment in upstream and midstream dry environment were mainly taller trees dominated by non-canopy species (Table 6).

All upstream and midstream tree species above were also found in the riverine and valley areas. The downstream and riverine environments have additional species which is visibly denser (Table 7).

Grass and shrub-species were found in lowland and riverine environments though visibly dry season weakened with some stems bent in open areas; but these got wetter as you move closer to the river in downstream area and in sandy soil trapped rock areas especially where there was shade (Table 8).

3.3 NDVI Variations

NDVI values showed sections of vegetation got denser over the years while some got drier so there was no visible trend over the study years (Table 9).

The NDVI maps show 2019 with wetter vegetation than 2001; and both more than 2009 (Fig. 3). This may be attributed to the high coverage of shade vegetation in 2019 that support undergrowth vegetation.

Table 6 Vegetation species in upstream and midstream areas.

Scientific name	Local name
Julbernardia globlifera (Benth.) Troupin.	Ntchenga
Barleria natalensis Lindau.	Chingala
Brachystegia boehmii Taub.	Ndjombo
Sterculia schliebenii Mildbr.	Ngonza
Millettia stuhlmannii Taub.	Mpanda
Pteleopsis myrtifolia (M. A. Lawson) Gere & Boatwr.	Nepa
Brachystegia spiciformis Benth	Mpapa
Terminalia sericea Burch. ex DC.	Ntchizo
Adansonia digitata L.	Nongi

Table 7 Vegetation species in riverine and valley areas.

Scientific name	Local name
Pseudolachnostylis maprouneifolia Pax.*var. maprouneifolia*	Nsolo
Pterocarpus angolensis DC.	Ntumbati
Burkea Africana Hook.	Nkalati
Acacia goetzei Harms.	Nangware
Casuarina junghuhniana Miq.	Nakajenjema
Cissampelos pareira L. var. *hirsuta* (Burch. ex DC.)	Nakananduru
Combretum kraussii Hochst.	Rwevera
Combretum mossambicense (Klotzsch) Engl.	Njanjajuni
Croton gossweileri Hutc*h.*	Likoba
Cyphostemma spinosopilosum (Gilg & M. Brandt) *Desc.*	Lijumba
Dichrostachys cinerea subsp. *africana var* (L.) Wight & Arn.	Nhacanunganunga
Flacourtia indica (Burm. f.) Merr.	Nzerekete
Jacaranda mimosifolia D. Don.	Nakangwale
Julbernardia globiflora (Benth.) Troupin.	Nakaperemendi
Landolphia kirkii Dyer ex Hook. f.	Nakakunde
Pterocarpus lucens Lepr. Ex Guill. & Perr. subsp. Antunesii (Taub.) Rojo.	Nzomba
Strychnos spinosa Lam.	Nakalunga
Syzygium guineense (Willd.) DC.	Ntepera
Vachellia davyi (N.E.Br.) Kyal. & Boatwr.	Nalundatara
Tribulus cistoides L.	Ntimbamwizi
*Vangueriainfausta*Burch. subsp. *infausta*	Ndururu

Table 8 Grass and shrub vegetation species in lowland riverine wetter areas.

Species
Trichocladum panicum. Hack. ex K. Schum
Hyparrhenia variabilis Stapf
Xerophytaspekei Baker

Sansevieria ehrenbergii Schweinf. ex Baker
Dewildemaniana pycnostachys Robyns & Lebrun, Rev
Themeda triandra Forssk.
Hyparrhenia newtonii (Hack.) Stapf *var. macra Stapf.*
Aristida adscensionis L.

Table 9 NDVI values for the studied years.

	Lowest	Highest	Mean	Standard deviation
2001	0.075797	0.294118	0.170697	0.070305
2009	0.040816	0.370787	0.235522	0.079987
2019	0.141511	0.325352	0.255082	0.040070

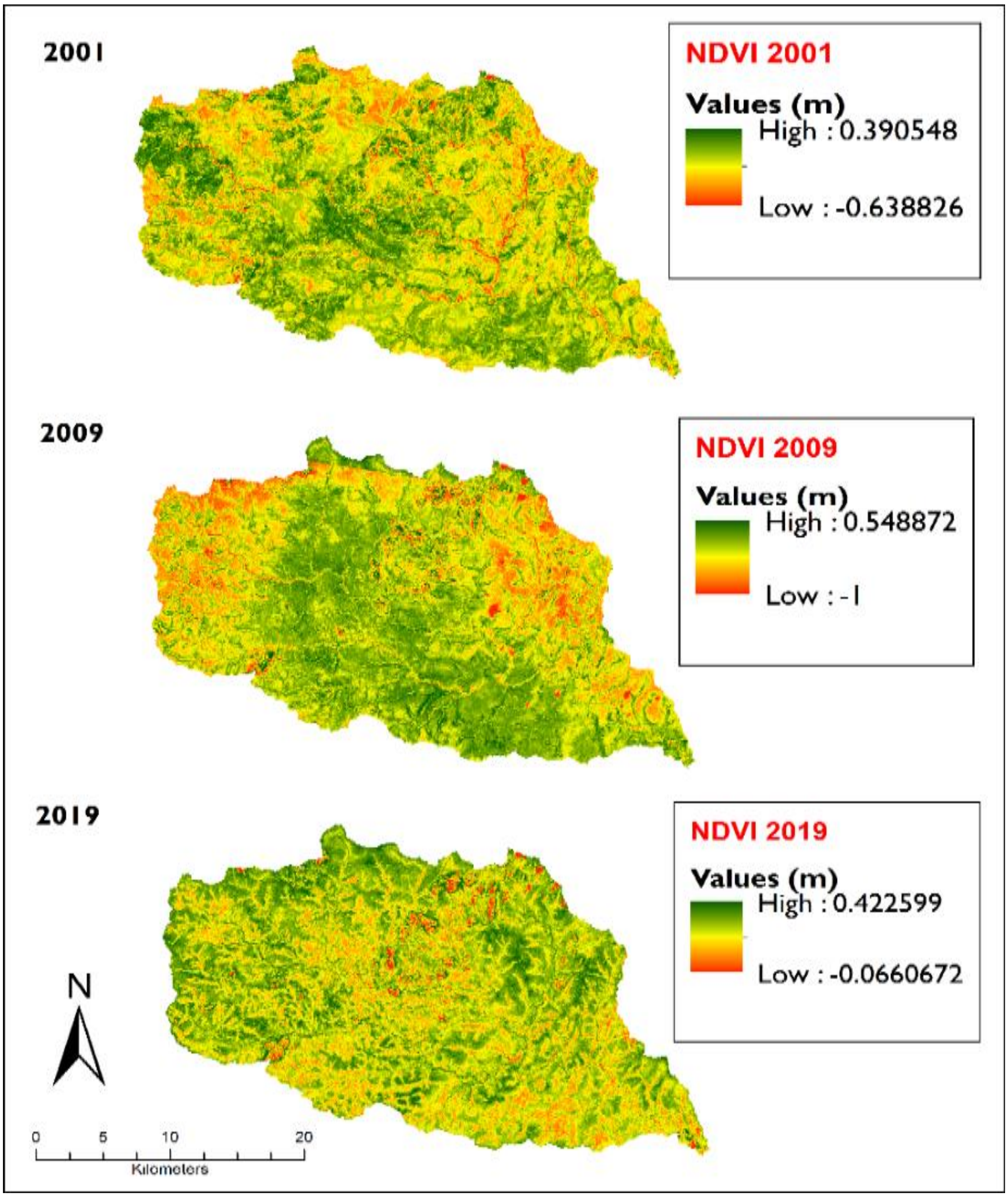
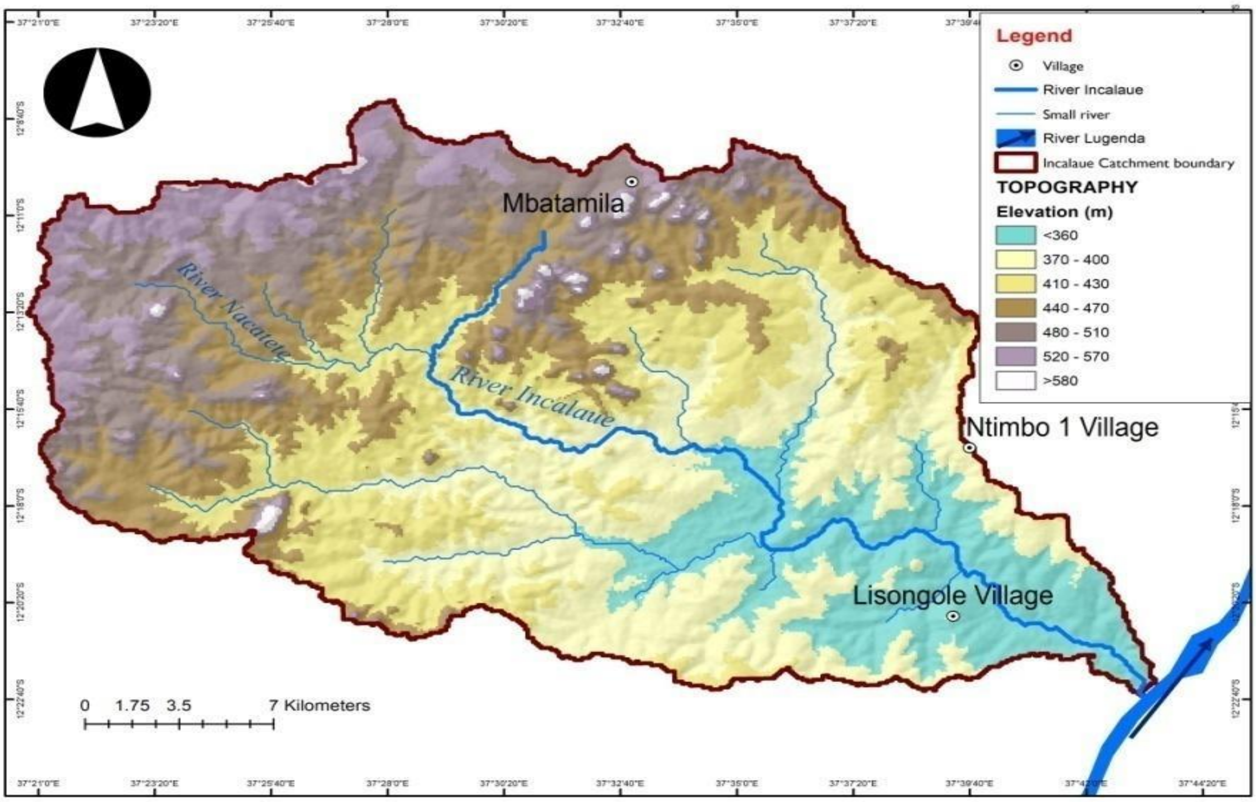
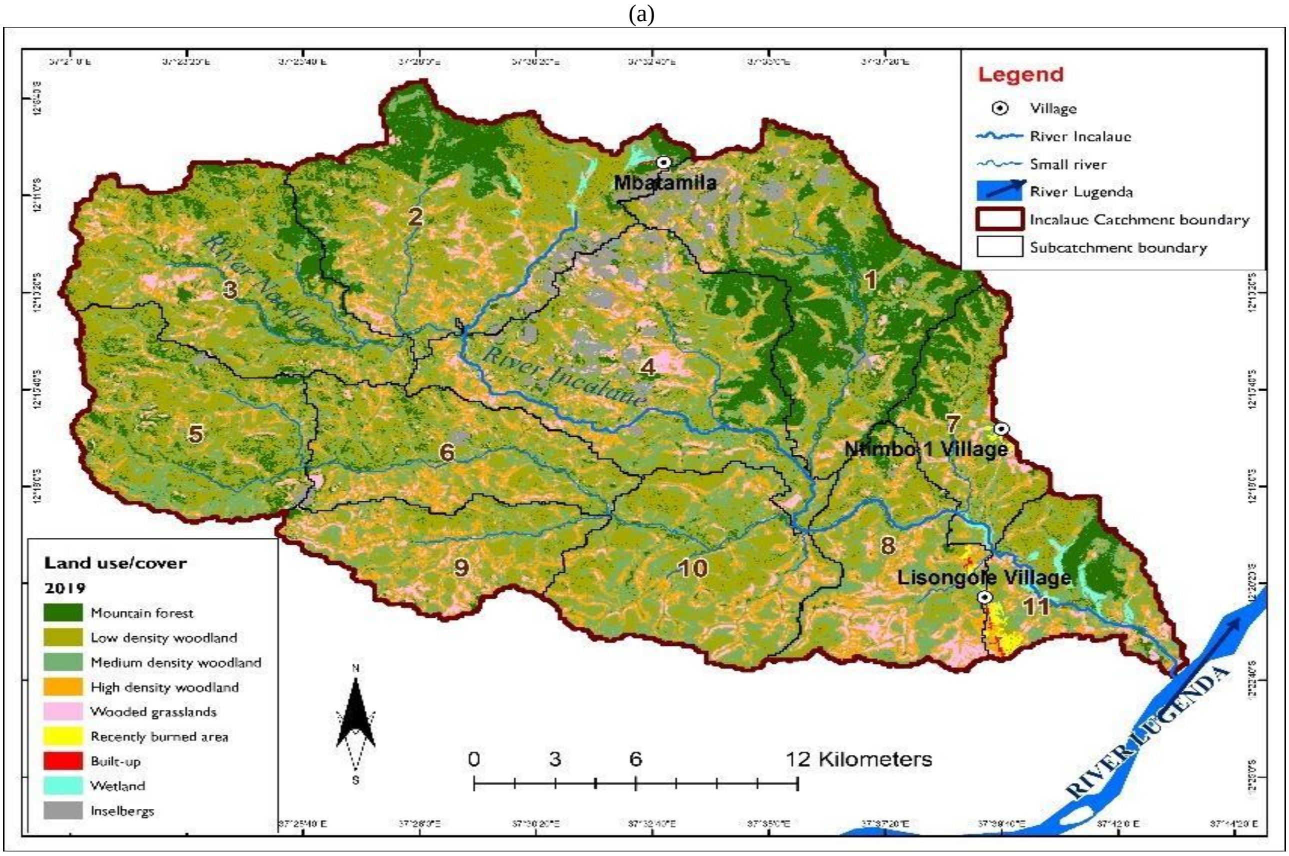


Fig. 3 NDVI maps.



(a)



(b)

Fig. 4 (a) Topographic map of the study area;(b) Vegetation cover in sub-basins.

3.4 Vegetation Cover in Elevation Zones

Vegetation structure and plant diversity are influenced by soil traits across landscape formations [86-88]. This vegetation relationship with elevation is important for execution of proactive plans for the maintenance of biodiversity as water availability in water held in soil determines physiognomic gradient [1, 89, 90]. The basin is in an area that has shallow soils on a granite rock base which makes them well drained [91].

The landscape area has high elevation rocky section of the steep gradient which can contribute to erosion deposition in lowland areas and contributes to vegetation classes there (Fig. 4a). Topography ranges from 360 m a.s.l to 580 m. a.s.l with the largest vegetation-class dominance being MDW (27.29%) in the elevation band 410 m a.s.l to 430 m a.s.l (Fig.4b). MFS is easily accessible from Mbatamila and Ntimbo 1 and grow at < 580 m.a.s.l. Vegetation largely characterized by woodlands in the area below this elevation. HDWs are most common in sub-catchment 3 where interestingly there is no small-scale agriculture which is possibly an indicator of vegetation succession section dominance. WETs are common in sub-catchment 11 downstream of the basin which is hydrologically expected for a flood plain. There is more MDW in sub-catchment 10 and this is the sub-catchment with evenly distributed vegetation cover.

Analysis of land-cover using sub-catchments as landscape units was done to provide more data of vegetation distributions and combinations (Table 10).

Vegetation types do not necessarily follow landform as observed in classification with upstream (440-510 m a.s.l) having MFS which also existed in lower altitude areas (370-430 m a.s.l). Apart from WET, all the other land-cover classes exist in the midstream section. Except for RBA and built up, the upstream section had the same classes as downstream.

3.5 Socio-Economic Factors and Perceptions of Local People

Community consultations were used to assess socio-economic drivers of LULC change and experiences on trends (Table 11). Attendance of these meetings was by 49.3% of household heads in Ntimbo 1 and 67.9%in Lisongole. Our estimated number of households was 56 for Lisongole and 67 for Ntimbo 1. Data were collected using open ended questions for interviews on experiences and respondent opinion on experiences in LULC change over the last 10 years and perceptions. All respondents consulted in this study had stayed in the area for over 10 years (100%).

Table 10 Land-cover distribution in sub-catchments (Sq. km).

Sub-catchment	Built-up	MDW	HDW	WGL	ISL	RBA	MFS	WET	LDW	Total
1		10.15	5.95	17.52	19.82	30.60			3.43	87.46
2	0.12	15.84	2.82	28.66	22.09	21.39		0.99	5.59	97.51
3		12.10	0.06	29.83	17.30	11.78			3.61	74.68
4		20.98	6.86	20.74	28.44	13.11			9.70	99.83
5		8.10	0.55	26.29	15.95	8.33			1.49	60.71
6		12.72	0.58	16.19	15.48	3.41			2.49	50.86
7	0.04	5.61	0.00	9.09	8.81	7.52	0.50	0.42	1.96	33.95
8	0.07	14.66	0.17	11.34	16.57	2.25	0.30	0.03	6.68	52.07
9		12.17		10.42	12.89	1.06			3.44	39.98
10		14.54		21.80	22.33	1.83			3.10	63.60
11	0.24	6.29		8.24	10.41	5.65	1.24	1.69	2.59	36.36
Grand Total	0.47	133.16	17.00	200.12	190.09	106.93	2.03	3.14	44.08	697.02

Table 11 Community reports on groundwater points and landscape ecology.

	Question	Lisongole village	Ntimbo 1 village	Remarks
1	Presence of animals around the human settlement areas	Yes (100%)	Yes (100%)	There are wildlife habitats around human settlement areas.
2	Land use change near areas where they see wildlife	All respondent (100%) reported that there has been a significant change near communities; another group (39.5%) reported that there has been small change; and 5.3% could not be specific.	A big fraction (99.2%) said there has been change; and 33.3% small change.	Community recognizes land use change in the area around them where wildlife is a threat.
3	Seasonal vegetation patterns	A small fraction of all respondents (46.3%) reported that there has vegetation patters change; and 53.7%said they could not be specific on wet vegetation change in seasons.	All (100%) reported that there have been changes in vegetation patterns; 39.5% reported more dry seasons causing early vegetation leaf shed; and 47.2% reported more riparian vegetation in the wet seasons.	Different seasonal vegetation patterns around human settlement areas.
4.	General comment on LULC change	All respondents (100%) reported change towards reduced green vegetation in wet seasons; 96.7% reported land clearance for agriculture has increased; and 6.5% reported LULC to still be the same.	A large fraction 53.7% reported less green vegetation cover in the wet season; 95.9% reported growth of human settlements; 1.6% reported less medicinal wild plants in the area; and 74.8% reported more land under agriculture in the dry season.	Community members recognize LULC change
5	Main drivers of land use cover/change	All people (100%) reported change in seasons; and 72.4% reported human population growth for settlements.	All people (100%) reported change in seasons; and 82.1% reported human population growth for settlements.	Changes in seasons and LULC recognized by local communities

4. Discussion

Our study contributes answers to the call to conserve connectivity in protected areas through habitat corridors ecosystem classification and protection so as to enable species migration within their climatic niches in the Selous-Niassa trans-frontier conservation area which has been a knowledge gap [92]. The study collected data in the end rainy season and end of dry season which are the appropriate months of animal migration in the dry-humid climate for a seasonal river tributary in this wildlife reserve [92, 93].

WGL spread across the basin can be attributed to favourable climate and space availability in canopy openings for wooded vegetation. The increase in taller vegetation class types is perhaps due to conservation efforts in this reserve area also hosting human settlement. This is a good environmental conservation achievement of efforts in this region where there is vegetation cover reduction and degradation due to anthropogenic activities widely reported [92]. The change of vegetation cover in the study time towards higher cover levels was pronounced with LDW with grasslands as the main losers; and LDW and HDW as the ones that increased mostly over the study period. The existence of all types of vegetation in upstream ISL dominated area can possibly be attributed to weathering and erosion processes in the possibly young geology of the area but more research is needed on this.

The low values of NDVI found with minimum of 0.040816 maximum 0.370787 can be attributed to the area rocky nature of the landscape with dense vegetation widely interspersed with WGL. Both the highest and lowest NDVI values were for 2009 and were accompanied by a reduction from 2001 to 2019, which may be attributed to land-cover change to taller sparse vegetation and differences in times of image capture in this dry mid-climate season in this area with vegetation shedding leaves during the dry season.

There are indications of vegetation distribution in relation with topography, soil factors and human influences with sub-catchment 3 having the highest LDW cover and no human settlements. Recently burnt areas in the landscape are mostly close to human settlement area. MFS vegetation losses in human settled conservation areas have also been reported in

Miombo woodlands in Gorongosa National Park in central Mozambique [94]. The relief variations and unevenness of elevation causes differences in soil depth and soil moisture and uneven distribution of MFS [95].

The main vegetation classes found were expected although some species were not on record for the NSR [39, 46, 80]. Some vegetation assemblages are quite discrete, such as the MFS, but others overlap considerably, such as LDW, MDW and WGLs. Efforts that have been made to do vegetation classification for the reserve have been found similar classes [78, 96]. We noted that there was a significant research gap in the Incalaue landscape on vegetation cover change classification given the type of land use and this study provided information [44, 78, 85]. Our study picks out the high moist rainfall MFS Miombo vegetation class which was also reported for the region in the First National Report on the Conservation of Biological Diversity in 1997 [97].

The largest decreases are for WGLs (71.84%), WETs (11.2%) and RBA (3.79%) which shows vegetation change towards taller vegetation and open areas in the season. A 0.9% woodland loss in NSR had been previously reported between 2001 and 2014 and was largely attributed to expanding agriculture around settlements and along main roads [45]. Incalaue basin hosts communities in communities of Ntimbo 1 and Lisongole and is located near Mecula town, so potential community vegetation harvesting and degradation may have an impact on vegetation cover.

It has been shown that biomass production in NSR is significantly related to climate, which mainly means annual rainfall, and it thus is susceptible to disturbances [39]. The results show need for land-use management to promote conservation by highlighting changes in vegetation cover over study time and for projected climate change impacts in Mozambique marked with increase in temperature and reduction in precipitation [98].

In context of the study area being wildlife reserve, this study showed the need and we propose landscape hydrology as an approach to land-use management. Spatial and temporal trend analysis of land use and LULC done in this study can be useful in landscape environmental conservation for development of hypotheses on hydrological processes underlying vegetation diversity patterns.

In 1995, a new Mozambique NLP (National Land Policy) was approved and the Land Law formulated in 1997. This policy established a clear rights-based approach to freely guarantee land for Mozambicans and supporting rural community land rights thus opening up restricted landscapes with vegetation areas to possible degradation. Currently, land tenure rights are given as DUAT (Direito de Uso e Aproveitamento da Terra), a state-granted land right.

The DUAT can be acquired in three ways, which are long-standing occupancy; customary occupation of the land by individual persons and by local communities; and based on good faith to individual national persons who have been using the land in good faith for at least ten years. This process of land acquisition is silent on protection of wildlife conservation areas. There is potential risk of environmental degradation due to human encroachment in the future due to population growth and expansion of the existing communities. This study further shows that there is need for identification and management of biodiversity hotspot areas as state institutions focus on the conservation as well as socio-economic developmental as has previously been shown [98].

5. Conclusions

This study assessed LULC change using relief and vegetation spatial and temporal patterns to detect changes in Incalaue basin for the years 2001, 2009 and 2019. The study shows that river sub-catchments as landscape hydrologic divisions are useful to map environmental differences, change and LULC over time and space. This study used landscape characteristics for mapping LULC; and added vegetation species identification for mapping situation and changes in Incalaue river basin. This study provides information useful for guidance to conservation institutions in Mozambique for vegetation cover trend analysis and potential conservation management hotspot areas in seasons for wildlife in NSR. There are multiple vegetation species with some localized by distribution which makes these environmental management hotspot areas. There are human settlement areas and these have expanded over time; and the study shows a need for mitigating human-wildlife conflict in the green vegetation riverine areas during the dry season. There is a challenge for LULC management due to the Mozambican legislation which creates a danger of human settlement, ownership and use of land; and potential degradation in this wildlife conservation area. There is need for a land use plan for areas of road and other landscape opening LULC infrastructure construction away from wildlife dry season vegetation hotspot areas. This study showed that vegetation cover dominates among LULC types and holds potential as the LULC change monitoring. The study proposes identification and consideration of area-demanding threatened species that require landscape scale habitat conservation; and prevention of degradation and loss of water access hotspots and those areas with sensitive and localized vegetation species. The overall conclusion of this study is that LULC and its spatial and temporal cover change holds potential for landscape-based conservation planning and environmental monitoring in Incalaue river basin.

Author contributions: Conceptualization, data collection, data analysis and write-up up: Ezrah Natumanya; Fieldwork supervision and fundraising support: Franziska Steinbruch and Natasha Ribeiro; Academic supervision and guidance in writing up the paper: Natasha Ribeiro, Franziska Steinbruch, Majaliwa. J. G. Mwanjalolo.

Acknowledgments: We acknowledge the logistical support by WCS (Wildlife Conservation Society) which supported fieldwork for this research. We sincerely thank all the local communities of Ntimbo 1 and Lisongole for welcoming and supporting this research where it was necessary. The authors sincerely appreciate USGS Earth Explorer for free acquisition of satellite images used from their archive.

References

[1] De Castro Nunes Santos Terra, M., Santos, R. M. D., Prado Júnior, J. A. D., De Mello, J. M., Scolforo, J. R. S., Fontes, M. A. L., Schiavini, I., Dos Reis, A. A., Bueno, I. T., Magnago, L. F. S., and Ter Steege, H. 2018. “Water Availability Drives Gradients of Tree Diversity, Structure and Functional Traits in the Atlantic-Cerrado-Caatinga Transition, Brazil.” *Journal of Plant Ecology* 11 (6): 803-14. doi:10.1093/jpe/rty017.

[2] Sianga, K., and Fynn, R. 2017. “The Vegetation and Wildlife Habitats of the Savuti-Mababe-Linyanti Ecosystem, Northern Botswana.” *Koedoe* 59 (2): 1-16. doi:10.4102/koedoe. v59i2.1406.

[3] Liu, J., Zhang, C., Kou, L., and Zhou, Q. 2017. “Effects of Climate and Land Use Changes on Water Resources in the Taoer River.” *Advances in Meteorology* 2017 (5): 1-13. doi: https://doi.org/10.1155/2017/1031854.

[4] Brauman, K. A., Meulen, S. Van Der, and Brils, J. 2014. *Ecosystem Services and River Basin Management*, edited by J. Brils. Heidelberg, Utrecht, The Netherlands: Springer-Verlag Berlin, pp. 265-94. doi:10.1007/978-3-642-38598-8_10.

[5] Brockerhoff, E. G., Barbaro, L., Castagneyrol, B., Forrester, D. I., Gardiner, B., Lyver, P. O. B., Meurisse, N., and Oxbrough, A. 2017. “Forest Biodiversity, Ecosystem Functioning and the Provision of Ecosystem Services.” *Biodiversity and Conservation* 26: 3005-35. doi:10.1007/s10531-017-1453-2.

[6] Goslee, S. C., Brooks, R. P., and Cole, C. A. 1997. “Plants as Indicators of Wetland Water Source.” *Plant Ecology* 131 (2): 199-206. doi:10.1023/A:1009731904915.

[7] European Commission. 2014. *Study on Soil and Water in a Changing Environment*. doi:10.2779/20608.

[8] Chisola, M. N., Laan, M. Van Der, and Bristow, K. L. 2020. “A Landscape Hydrology Approach to Inform Sustainable Water Resource Management under a Changing Environment. A Case Study for the Kaleya River Catchment, Zambia.” *Journal of Hydrology: Regional Studies* 32 (9).

[9] Hokanson, K. J., Peterson, E. S., Devito, K. J., and Mendoza, C. A. 2020. “Forestland-Peatland Hydrologic Connectivity in Water-Limited Environments: Hydraulic Gradients Often Oppose Topography.” *Environmental Research Letters* 15 (3): 034021. doi:10.1088/1748-9326/ab699a.

[10] Hallema, D. W., Moussa, R., Sun, G., and McNulty, S. G. 2016. "Surface Storm Flow Prediction on Hillslopes Based on Topography and Hydrologic Connectivity." *Ecological Processes* 5 (1): 1-13. doi:10.1186/s13717-016-0057-1.

[11] Olsson, L., Barbosa, H., Bhadwal, S., Cowie, A., Delusca, K., Flores-Renteria, D., Hermans, K., Jobbagy, E., Kurz, W., Sonwa, D. J., and Stringer, L. 2019. "Land Degradation." In *Climate Change and Land: An IPCC Special Report on Climate; Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, edited by P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte,

[12] Malhi. Y.,Franklin. J.,Sedon. N., Solan. M., Turner. M. G., Field. C. B and Knowlton. N. 2020. "Climate change and ecosystems: threats, opportunities and solutions." *Philosophical Transactions B*. (2020). 375: 20190104. https://doi.org/10.1098/rstb.2019.0104

[13] Yang, X., Ren, L., Singh, V. P., Liu, X., Yuan, F., Jiang, S., and Yong, B. 2012. "Impacts of Land Use and Land Cover Changes on Evapotranspiration and Runoff at Shalamulun River Watershed, China." *Hydrology Research* 43 (1-2): 23-37. doi:10.2166/nh.2011.120.

[14] Clarke, R. T. 2009. "On the Complementary Roles of the Hydrological Analyst and the Decision-Maker in Water Resources Management." *IAHS-AISH Publication* 327: 18-23.

[15] Thompson, I., Mackey, B., McNulty, S., Mosseler, A., and Change, C. 2009. "Forest Resilience, Biodiversity, and Climate Change. A Synthesis of the Biodiversity/Resilience/Stability Relationship in Forest Ecosystems." *Secretariat of the Convention on Biological Diversity, Montreal.*Technical Series No. 43, pp. 1-67.

[16] Luo, J., Zhou, X., Rubinato, M., Li, G., Tian, Y., and Zhou, J. 2020. "Impact of Multiple Vegetation Covers on Surface Runoff and Sediment Yield in the Small Basin of Nverzhai, Hunan Province, China." *Forests* 11 (3): 329. doi: 10.3390/f11030329.

[17] Zhang, F., Kung, H. T., and Johnson, V. C. 2017. "Assessment of Land-Cover/Land-Use Change and Landscape Patterns in the Two National Nature Reserves of Ebinur Lake Watershed, Xinjiang, China." *Sustainability* 9 (5): 724. doi:10.3390/su9050724.

[18] Hlásny, T., Sitková, Z., and Barka, I. 2013. "Regional Assessment of Forest Effects on Watershed Hydrology: Slovakia as a Case Study." *Journal of Forest Science* 59 (10): 405-15.

[19] Raihan, A., and Haroon, S. 2016. "Derivation of Ecological Indicators for Assessing Landscape Health and Habitat Disturbance in Lower Barpani Watershed of Assam (India) Derivation of Ecological Indicators for Assessing Landscape Health and Habitat Disturbance in Lower Barpani Watershed." *Forum Geografic*. 15 (1): 80-90. doi:10.5775/fg.2016.018. i.

[20] Gao, H., Sabo, J. L., Chen, X., Liu, Z., Yang, Z., Ren, Z., and Liu, M. 2018. "Landscape Heterogeneity and Hydrological Processes: A Review of Landscape-Based Hydrological Models." *Landscape Ecology* 33 (9): 1461-80. doi:10.1007/s10980-018-0690-4.

[21] Nyman, P., Sheridan, G. J., and Lane, P. N. J. 2013. "Hydro-Geomorphic Response Models for Burned Areas and Their Applications in Land Management." *Progress in Physical Geography: Earth and Environment* 37 (6): 787-812. doi:10.1177/0309133313508802.

[22] Jung, M., Rowhani, P., and Scharlemann, P. W. J. 2019. "Biodiversity Globally." *Nature Communications* 10: 5474. doi:10.1038/s41467-019-13452-3.

[23] Butsic, V., Kelly, M., and Moritz, M. A. 2015. "Land Use and Wildfire: A Review of Local Interactions and Teleconnections." *Land* 4: 140-56. doi:10.3390/land4010140.

[24] Jhariya, M. K., and Raj, A. 2014. "Effects of Wildfires on Flora, Fauna and Physico-Chemical Properties of Soil—An Overview." *Journal of Applied and Natural Science* 6 (2): 887-97.

[25] Peters-lidard, C. D., Clark, M., Samaniego, L., Verhoest, N. E. C., Van, T., Uijlenhoet, R., Achieng, K., Franz, T. E., and Woods, R. 2017. "Scaling, Similarity, and the Fourth Paradigm for Hydrology Christa." *Hydrol Earth Syst Sci.* 21 (7): 3701-13. doi:10.5194/hess-2016-695.

[26] Sheil, D. 2018. "Forests, Atmospheric Water and an Uncertain Future: The New Biology of the Global Water Cycle." *Forest Ecosystems* 5 (1). doi:10.1186/s40663-018-0138-y.

[27] Haines-Young, R. 2009. "Land Use and Biodiversity Relationships." *Land Use Policy* 26 (suppl. 1): 178-86. doi: 10.1016/j.landusepol.2009.08.009.

[28] Grizzetti, B., Lanzanova, D., Liquete, C., Reynaud, A., and Cardoso, A. C. 2016. "Assessing Water Ecosystem Services for Water Resource Management." *Environmental Science and Policy* 61: 194-203. doi: 10.1016/j.envsci.2016.04.008.

[29] Mwangi, J. G., Ondimu, K. N., Owuor, G., Eshiamwata, G. W., and Obwoyere, G. O. 2014. "Factors Influencing Adoption of Sustainable Water resource Management Practices in Upper and Middle Mara River Basin, Kenya." *International Journal of Development and Sustainability* 3 (6): 1326-39.

[30] Pan, S., Liu, D., Wang, Z., Zhao, Q., Zou, H., Hou, Y., Liu, P., and Xiong, L. 2017. "Runoff Responses to Climate and Land Use/Cover Changes under Future Scenarios." *Water* 9 (7): 475. doi:10.3390/w9070475.

[31] Brauman, Kate A., Daily, Gretchen C., Duarte, T., and Ka'eo, A. 2017. "The Nature and Value of Ecosystem

Services: An Overview Highlighting Hydrologic Services." *Annual Review of Environment and Resources* 32 (1): 67-98. doi: 10.1146/annurev.energy.32.031306.102758.

[32] Asbjornsen, H., Goldsmith, G. R., Alvarado-Barrientos, M. S., Rebel, K., Van Osch, F. P., Rietkerk, M., Chen, J., Gotsch, S., Tobón, C., Geissert, D. R., Gómez-Tagle, A., Vache, K., and Dawson, T. E. 2011. "Ecohydrological Advances and Applications in Plant-Water Relations Research: A Review." *Journal of Plant Ecology* 4 (1-2): 3-22. doi:10.1093/jpe/rtr005.

[33] Dirnböck, T., and Grabherr, G. 2000. "GIS Assessment of Vegetation and Hydrological Change in a High Mountain Catchment of the Northern Limestone Alps." *Mountain Research and Developmen* 20 (2): 172-9. doi:10.1659/0276-4741(2000)020[0172: gaovah]2.0.co;2.

[34] Jiang, H., Liu, S., Sun, P., An, S., Zhou, G., Li, C., Wang, J., Yu, H., and Tian, X. 2004. "The Influence of Vegetation Type on the Hydrological Process at the Landscape Scale." *Canadian Journal of Remote Sensing* 30 (5): 743-63. doi:10.5589/m04-033.

[35] Sayer, J. A., Margules, C., Boedhihartono, A. K., Sunderland, T., Langston, J. D., Reed, J., Riggs, R., Buck, L. E., Campbell, B. M., Kusters, K., Elliott, C., Minang, P. A., Dale, A., Purnomo, H., Stevenson, J. R., Gunarso, P., and Purnomo, A. 2017. "Measuring the Effectiveness of Landscape Approaches to Conservation and Development." *Sustainability Science* 12 (3): 465-76. doi:10.1007/s11625-016-0415-z.

[36] Tello, E., Marull, J., Padró, R., Cattaneo, C., and Coll, F. 2020. "The Loss of Landscape Ecological Functionality in the Barcelona Province (1956-2009): Could Land-Use History Involve a Legacy for Current Biodiversity?" *Sustainability* 12 (6): 1-15. doi:10.3390/su12062238.

[37] Lagro, J. 1991. "Assessing Patch Shape in Landscape Mosaics." *Photogrammetric Engineering & Remote Sensing* 57 (3): 285-93.

[38] Mbanze, A. A., Martins, A. M., Rivaes, R., Ribeiro-Barros, A. I., and Sofia Ribeiro, N. 2019. "Vegetation Structure and Effects of Human Use of the Dambos Ecosystem in Northern Mozambique." *Global Ecology and Conservation* 20: e00704. doi: 10.1016/j.gecco.2019.e00704.

[39] Cowles, J., Boldgiv, B., Liancourt, P., Petraitis, P. S., and Casper, B. B. 2018. "Effects of Increased Temperature on Plant Communities Depend on Landscape Location and Precipitation." *Ecology and Evolution* 8 (11): 5267-78. doi:10.1002/ece3.3995.

[40] Mozambique, R. 2006. *National Report on Implementation of the Convention on Biological Diversity in Mozambique*, Cbd.Int, No. June.

[41] Franklin, J., Serra-Diaz, J. M., Syphard, A. D., and Regan, H. M. 2016. "Global Change and Terrestrial Plant Community Dynamics." *Proceedings of the National Academy of Sciences of the United States of America* 113 (14): 3725-34. doi:10.1073/pnas.1519911113.

[42] Ribeiro, N. S., Saatchi, S. S., Shugart, H. H., and Washington-Allen, R. A. 2008. "Aboveground Biomass and Leaf Area Index (LAI) Mapping for Niassa Reserve, Northern Mozambique." *Journal of Geophysical Research: Biogeosciences* 113 (3): 1-12. doi:10.1029/2007JG000550.

[43] Allan, J. R., Grossmann, F., Craig, R., Nelson, A., Flower, K., Bampton, J., Deffontaines, J., Miguel, C., Araquechande, B., and Watson, J. E. M. 2017. "Patterns of Forest Loss in One of Africa's Last Remaining Wilderness Areas: Niassa National Reserve." *PARKS* 23 (1): 39-50.

[44] Ribeiro, N., Matos, C. N., Moura, I. R., Washington-Allen, R. A., and Ribeiro, A. I. 2013. "Monitoring Vegetation Dynamics and Carbon Stock Density in Miombo Woodlands." *Carbon Balance and Management* 8 (1): 11. doi:10.1186/1750-0680-8-11.

[45] Report, N. C. P. 2016. *OECD Annual Report Dutch*.

[46] Tan, L., Fan, C., Zhang, C., von Gadow, K., and Fan, X. 2017. "How Beta Diversity and the Underlying Causes Vary with Sampling Scales in the Changbai Mountain Forests." *Ecology and Evolution* 7 (23): 10116-23. doi:10.1002/ece3.3493.

[47] Cingolani, A. M., Renison, D., Zak, M. R., and Cabido, M. R. 2004. "Mapping Vegetation in a Heterogeneous Mountain Rangeland Using Landsat Data: An Alternative Method to Define and Classify Land-Cover Units." *Remote Sensing of Environment* 92 (1): 84-97. doi:10.1016/j.rse.2004.05.008.

[48] Hu, Q., Wu, W., Xia, T., Yu, Q., Yang, P., Li, Z., and Song, Q. 2013. "Exploring the Use of Google Earth Imagery and Object-Based Methods in Land Use/Cover Mapping." *Remote Sensing* 5 (11): 6026-42. doi:10.3390/rs5116026.

[49] Alawamy, J. S., Balasundram, S. K., Hanif, A. H. M., and Sung, C. T. B. 2020. "Detecting and Analyzing Land Use and Land Cover Changes in the Region of Al-Jabal Al-Akhdar, Libya Using Time-Series Landsat Data from 1985 to 2017." *Sustainability* 12 (11): 4490. doi:10.3390/su12114490.

[50] Schroeder, T. A., Cohen, W. B., Song, C., Canty, M. J., and Yang, Z. 2006. "Radiometric Correction of Multi-temporal Landsat Data for Characterization of Early Successional Forest Patterns in Western Oregon." *Remote Sensing of Environment* 103 (1): 16-26. doi: 10.1016/j.rse.2006.03.008.

[51] Santos, C. L. M. de O., Lamparelli, R. A. C., Figueiredo, G. K. D. A., Dupuy, S., Boury, J., Luciano, A. C. dos S., Torres, R. da S., and le Maire, G. 2019. "Classification of Crops, Pastures, and Tree Plantations along the Season with Multi-sensor Image Time Series in a Subtropical Agricultural Region." *Remote Sensing* 11 (3): 334.

doi:10.3390/rs11030334.

[52] Hernández-Stefanoni, J. L., and Dupuy, J. M. 2007. "Mapping Species Density of Trees, Shrubs and Vines in a Tropical Forest, Using Field Measurements, Satellite Multiespectral Imagery and Spatial Interpolation." *Biodiversity and Conservation* 16 (13): 3817033. doi:10.1007/s10531-007-9182-6.

[53] Al-khaqani, E. T. 2013. "Dark Object Subtraction of Landsat MSS Satellite Images." *Journal of Babylon University/Pure and Applied Sciences* 21 (8).

[54] Andrefouet, S., Bindschadler, R., Colstoun, E. B. de., Choate, M., Chomentowski, W., Christopherson, J., Doorn, B., Hall, D. K., Holifield, C., Kranenburg, C., and Howard, S. 2003. *Preliminary Assessment of the Value of Landsat 7 ETM+ Data Following Scan Line Corrector Malfunction Contributors*.

[55] Allouche, F. A., Delaître, E., Bousaida, D. O., and Chaari, H. 2018. "Mapping South Tunisian Landscapes Using Remote Sensing and GIS Applications." *International Journal of Environment and Geoinformatics* 5 (1): 17-28. doi:10.30897/ijegeo.

[56] Haque, M. I., and Basak, R. 2017. "Land Cover Change Detection Using GIS and Remote Sensing Techniques: A Spatio-Temporal Study on TanguarHaor, Sunamganj, Bangladesh." *Egyptian Journal of Remote Sensing and Space Science* 20 (2): 251-63. doi: 10.1016/j.ejrs.2016.12.003.

[57] Chen, Y., Wang, Q., Wang, Y., Duan, S., Xu, M., and Li, Z. 2016. "A Spectral Signature Shape-Based Algorithm for Landsat Image Classification." *ISPRS Int. J. Geo-Inf.* 5 (9): 154. doi: https://doi.org/10.3390/ijgi5090154.

[58] Senthil Lekha, S. L., and Kumar, S. S. 2018. "Selection of Suitable Supervised Classification Techniques for the Geographic Analysis of Land Using GIS Techniques." *International Journal of Engineering and Technology(UAE)* 7 (27): 82-90. doi:10.14419/ijet. v7i3.27.17661.

[59] Tilahun, A. 2015. "Accuracy Assessment of Land Use Land Cover Classification Using Google Earth." *American Journal of Environmental Protection* 4 (4): 193. doi: 10.11648/j.ajep.20150404.14.

[60] Abdelkareem, O. E. A., Elamin, H. M. A., Eltahir, M. E. S., Adam, H. E., Elhaja, M. E., Rahamtalla, A. M., Babatunde, O., and Elmar, C. 2018. "Accuracy Assessment of Land Use Land Cover in Umabdalla Natural Reserved Forest, South Kordofan, Sudan." *International Journal of Agricultural and Environmental Sciences* 3 (1): 5-9.

[61] Fichera, C. R., Modica, G., and Pollino, M. 2017. "Land Cover Classification and Change-Detection Analysis Using Multi-Temporal Remote Sensed Imagery and Landscape Metrics." *European Journal of Remote Sensing* 45 (1): 7254. doi:10.5721/EuJRS20124501.

[62] Rwanga, S. S., and Ndambuki, J. M. 2017. "Accuracy Assessment of Land Use/Land Cover Classification Using Remote Sensing and GIS." *International Journal of Geosciences* 8: 611-22. doi:10.4236/ijg.2017.84033.

[63] Allouche, F. K., Eric, D., Ouerchfen, B. D., and Chaari, H. 2018. "Mapping South Tunisian Landscapes Using Remote Sensing and GIS Applications Faiza KhebourAllouche, Eric Delaître, DalelOuerchfeniBousaida and Hanen Chaari Mapping South Tunisian Landscapes Using Remote Sensing and GIS Applications." *International Journal of Environment and Geoinformatics* 5 (1): 17-28. doi:10.30897/ijegeo.

[64] Millard, K., and Richardson, M. 2015. "On the Importance of Training Data Sample Selection in Random Forest Image Classification: A Case Study in Peatland Ecosystem Mapping." *Remote Sensing* 7: 8489-515. doi:10.3390/rs70708489.

[65] Xu, M., Ma, L., Jia, Y., and Liu, M. 2018. "Integrating the Effects of Latitude and Altitude on the Spatial Differentiation of Plant Community Diversity in a Mountainous Ecosystem in China." *PLoS ONE* 13 (4): 1-18. doi:https://doi.org/ 10.1371/journal.pone.0196653.

[66] Zhang, F., and Zhou, G. 2019. "Estimation of Vegetation Water Content Using Hyperspectral Vegetation Indices: A Comparison of Crop Water Indicators in Response to Water Stress Treatments for Summer Maize." *BMC Ecology* 19 (1): 1-12. doi:10.1186/s12898-019-0233-0.

[67] Páscoa, P., Gouveia, C. M., and Kurz-Besson, C. 2020. "A Simple Method to Identify Potential Groundwater-Dependent Vegetation Using NDVI MODIS." *Forests* 11 (2): 147. doi:10.3390/f11020147.

[68] Rousta, I., Olafsson, H., Moniruzzaman, M., Zhang, H., Liou, Y. A., Mushore, T. D., and Gupta, A. 2020. "Impacts of Drought on Vegetation Assessed by Vegetation Indices and Meteorological Factors in Afghanistan." *Remote Sensing*12 (15): 2433. doi:10.3390/RS12152433.

[69] Moura-bueno, J. M., Simão, R., Dalmolin, D., and Caten, A. 2016. "Assessment of Digital Elevation Model for Digital Soil Mapping in a Watershed with Gently Undulating Topography." *RevistaBrasileira de Ciência Do Solo* 40: 1-15. doi:10.1590/18069657rbcs20150022.

[70] Odera, P. A., and Fukuda, Y. 2015. "Recovery of Orthometric Heights from Ellipsoidal Heights Using Offsets Method over Japan." *Earth, Planets and Space* 67 (1). doi:10.1186/s40623-015-0306-z.

[71] Xiao, L., and Liu, H. 2012. "A Novel Approach for Quantitative Assessment of DEM Accuracy Using Reconstructed Contours." *Procedia Environmental Sciences* 12: 772-6. doi:10.1016/j.proenv.2012.01.346.

[72] Moura, A. C. M., and Fonseca, B. M. 2020. "ESDA (Exploratory Spatial Data Analysis) of Vegetation Cover

in Urban Areas-Recognition of Vulnerabilities for the Management of Resources in Urban Green Infrastructure." *Sustainability* 12 (5): 1-22. doi:10.3390/su12051933.

[73] Vorobevskii, I., Kronenberg, R., and Christian, B. 2020. "Global BROOK90 R Package: An Automatic Framework to Simulate the Water Balance at Any Location." *Water* 2 (12): 2037. doi:10.3390/w12072037.

[74] Sprenger, M., Leistert, H., Gimbel, K., and Weiler, M. 2018. "Illuminating Hydrological Processes at the Soil-Vegetation-Atmosphere Interface with Water Stable Isotopes." *Reviews of Geophysics* 54 (3): 674-704. doi:10.1002/2015RG000515.

[75] Koning, J. D. 1993. "Checklist of Vernacular Plant Names in Mozambique." Wageningen Agricultural University Research Papers, 93-2.

[76] Ganzin, N., Poilecot, P., and Prin, T. 2010. *Vegetation Survey of Niassa National Reserve Oriented for Vegetation Mapping and Range Resources Assessment Using Satellite Imagery* (Vol. Project re). Maputo, Mozambique.

[77] Zhao, M., Brofeldt, S., Li, Q., Xu, J., Danielsen, F., Læssøe, S. B. L., Poulsen, M. K., Gottlieb, A., Maxwell, J. F., and Theilade, I. 2016. "Can Community Members Identify Tropical Tree Species for REDD+ Carbon and Biodiversity Measurements?" *PLoS ONE* 11 (11): 1-16. doi: 10.1371/journal.pone.0152061.

[78] Ribeiro, N., Micas, C., and Faruk Mamugy, A. C. 2016. "Remote Sensing of Biomass in the Miombo Woodlands of Southern Africa: Opportunities and Limitations for Research." *Remote Sensing of Biomass—Principles and Applications* (Vol. 1), Intech, 13. doi: http://dx.doi.org/10.5772/57353.

[79] Lehto, T., and Gonçalves, R. 2008. "Mineral Resources Potential in Mozambique." *Geological Survey of Finland*, Special Paper 48, Vol. GTK Consor, 307-21.

[80] Boyd, R., Nordgulen, Ø., Thomas, R. J., Bingen, B., Bjerkgård, T., Grenne, T., Henderson, I., Melezhik, V. A., Often, M., Sandstad, J. S., Solli, A., Tveten, E., Viola, G., and Jamal, D. 2010. "The Geology and Geochemistry of East African Oregon in Nothern Mozambique." *South African Journal of Geology* 113: 87-129. doi:10.2113/gssajg.113.1.87.

[81] Ribeiro, N., Snook, L. K., Vaz, N. de C., Carla, I., and Alves, T. 2019. "Gathering Honey from Wild and Traditional Hives in the Miombo Woodlands of the Niassa National Reserve, Mozambique: What Are the Impacts on Tree Populations?" *Global Ecology and Conservation* 17: e00552. doi: 10.1016/j.gecco. 2019.e00552.

[82] Moura, I., Duvane, J. A., Silva, M. J., Ribeiro, N., and Isabel, A. 2018. "Woody Species from the Mozambican Miombo Woodlands: A Review on Their Ethnomedicinal Uses and Pharmacological Potential." *Journal of Medicinal Plants Research* 12 (2): 15-31. doi:10.5897/JMPR2017.6540.

[83] Timberlake, J., Golding, J., and Clarke, P. 2004. *Niassa Botanical Expedition—June 2003*. Bulawayo, Zimbabwe: Occasional Publications in Biodiversity No. 12.

[84] Moriarty, P., and Honnery, D. 2008. "Linking Geology with Biodiversity." *Futures* 40 (10): 865-72. doi: 10.1016/j.futures.2008.07.021.

[85] Murat Özyavuz, A. B. K., and Özyavuzen, A. 2013. "Native Vegetation." In *Advances in Landscape Architecture*. InTech., 361-84. doi: http://dx.doi.org/10.5772/55813.

[86] Fujii, K., Shibata, M., Kitajima, K., Ichie, T., Kitayama, K., and Turner, B. L. 2018. "Plant-Soil Interactions Maintain Biodiversity and Functions of Tropical Forest Ecosystems." *Ecological Research* 33 (1): 149-60. doi:10.1007/s11284-017-1511-y.

[87] Bueno, M. L., Neves, D. R. M., Souza, A. F., Oliveira Junior, E., Damasceno Junior, G. A., Pontara, V., Laura, V. A., and Ratter, J. A. 2013. "Influence of Edaphic Factors on the Floristic Composition of an Area of Cerradão in the Brazilian Central-West." *Acta Botanica Brasilica* 27 (2): 445-55. doi:10.1590/S0102-33062013000200017.

[88] De Assis, A. C. C., Coelho, R. M., da Pinheiro, E. S., and Durigan, G. 2011. "Water Availability Determines Physiognomic Gradient in an Area of Low-Fertility Soils under Cerrado Vegetation." *Plant Ecology* 212 (7): 1135-47. doi:10.1007/s11258-010-9893-8.

[89] Souirji, A. 1997. *Soil and Terrain Database of Mozambique.* Scale 1:1,000,000., Consultant Report.

[90] Zella, A. Y., Saria, J., and Law, Y. 2018. "Consequences of Climate Change and Variability in Managing Selous-Niassa Transfrontier Conservation Area." *Biodiversity International Journal* 2 (6): 500-16. doi:10.15406/bij.2018.02.00105.

[91] Purdon, A., Mole, M. A., Chase, M. J., and van Aarde, R. J. 2018. "Partial Migration in Savanna Elephant Populations Distributed across Southern Africa." *Scientific Reports* 8 (1). doi:10.1038/s41598-018-29724-9.

[92] Muller, T., Wursten, B., Chapano, C., Ballings, P., Beilfuss, R., Massungue, A., and Wild, R. 2007. "Vegetation Survey and Management Recommendation for Mount Gorongosa."

[93] Müller, T., Mapaura, A., Wursten, B., Chapano, C., Ballings, P., and Wild, R. 2012. "Vegetation Survey of Mount Gorongosa." *Occasional Publications in Biodiversity* 23 (23): 1-54.

[94] Timberlake, J., and Chidumayo, E. (2004). "Division Report." *IEEE Control Systems Magazine* 3 (2): 25. doi:10.1109/mcs.1983.1104758.

[95] Ministry for Coordination of Environmental Affairs (MICOA). 1997. *First National Report on the Conservation of Biodiversity in Mozambique.* IMPACTO

Lda Maputo, 1-63.

[96] Spalding-Fecher, R., Chapman, A., Yamba, F., Walimwipi, H., Kling, H., Tembo, B., Nyambe, I., and Cuamba, B. 2016. “The Vulnerability of Hydropower Production in the Zambezi River Basin to the Impacts of Climate Change and Irrigation Development.” *Mitigation and Adaptation Strategies for Global Change* 21 (5): 721-42. doi:10.1007/s11027-014-9619-7.

[97] Artur, L., and Hilhorst, D. 2012. “Everyday Realities of Climate Change Adaptation in Mozambique.” *Global Environmental Change* 22 (2): 52936. doi: 10.1016/j.gloenvcha.2011.11.013.

[98] Ramachandra, T. V., Setturu, B., Vinay, S., Tara, N. M., Subashchandran, M. D., and Joshi, N. V. 2018. *Conservation and Sustainable Management of Local Hotspots of Biodiversity*, pp. 365-83.