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Dynamics of land use and land cover changes and their effect on carbon stocks of Rwenzori Mountains National Park

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Abstract

This study characterized the extent of land use land cover changes in Rwenzori Mountains National Park (RMNP) and determined the effect of observed land use land cover changes on the park's carbon stocks. Landsat 5 images were obtained of 1990; Landsat 7 of 2000 and 2010 and Landsat 8 of 2020 for Rwenzori Mountains National Park and analyzed using GIS tools in ArcGIS 10.5 using supervised classification. The Landsat scenes were obtained from path and row (171, 060) and (172, 060). The effect of land use land cover changes on the park's carbon stocks was determined by estimating the amount of greenhouse gases released or sequestered following land use land cover changes using the EX-ACT tool. Results show that there were expansions and reductions in the acreages of land covers between 1990 and 2020 in Rwenzori Mountains National Park i.e. there was a 3.6% reduction in the tropical high forest well-stocked; a 59.4% increase in cultivated land; a 16.8% reduction in the tropical high forest low stocked; and a 27% increase in the grassland cover. The cultivation is mainly along the boundaries of the park. Rwenzori Mountains National Park is a net carbon sink. Land cover change has an effect on carbon stock, with a decrease in the net sequestration over the past three decades in Rwenzori Mountains National Park. Owing to the observed land cover/use changes, Uganda Wildlife Authority should tighten park boundary management by applying hybrid approaches including buffer zoning, electric fencing, and thorn and stone hedges.

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Introduction

Changes in land cover (the biophysical attributes of the earth's surface) and land use (human purpose applied to these attributes) are major environmental change concerns (Nendel *et al.*, 2018; Lahai *et al.*, 2022; Mariye *et al.*, 2022). The world is undergoing rapid land use/cover changes due to natural phenomena and various socioeconomic issues (Cheruto *et al.*, 2016). Land use land cover (LULC) changes are majorly driven by extensive agricultural practices, soil erosion, urbanization, infrastructural developments, weak policies, and high population growth rate activities (Barasa *et al.*, 2011; Hu *et al.*, 2019). LULC change has significant effects on biodiversity, resource production, soil erosion, food security and threatens public health (Sharma *et al.*, 2019; Zziwa *et al.*, 2012). Understanding the patterns of LULC of an area helps in the development of strategies to balance conservation, conflicting uses, and development pressures (Saputra and Lee, 2019).

National parks and similarly managed protected areas (PAs) play a crucial role in mitigating effects of climate change through carbon sequestration (Dimobe *et al.*, 2022). National parks protect ecosystems from the effects of land-use change, enabling trees and soil to store carbon over the long term (Dimobe *et al.*, 2022). These ecosystems' productivity is sustained by the diversity of their trees, which can also boost the ecosystem's resilience (Bengtsson *et al.*, 2000). Yet, anthropogenic disturbances and the effects of climate change also affect protected areas (Dimobe *et al.*, 2015).

Uganda has numerous National Parks which are mainly located around mountains, wetlands, Forests as well as rift valleys including the Rwenzori Mountains National Park (RMNP). The RMNP is one of western Uganda's largest and most important water catchment areas (Enyagu *et al.*, 2020). As a world heritage site, the mountain ecosystem is of global significance because it is home to several endemic, endangered, threatened, and rare Albertine rift species, some of which have limited ranges (UWA, 2004; Enyagu *et al.*, 2020). Despite the numerous advantages that protected areas can offer, there are compromised, due to various types of land-use activities inside and near protected areas. Hence, it is essential to acquire a comprehensive comprehension of the dynamics of land use and land cover changes as a foundational principle for formulating cohesive strategies that foster the sustainable stewardship and utilization of national parks.

Carbon sequestration, which involves mitigating global climate change by capturing carbon dioxide from the atmosphere and storing it in long-term mineral, organic, and oceanic reservoirs, represents a crucial ecosystem service offered by protected natural areas. Among the various forms of carbon sequestration, vegetative carbon sequestration, achieved through plant growth, has gained increasing attention in recent years. While several studies have been conducted in Uganda to assess the potential of vegetative carbon sequestration capacity (Buyinza *et al.*, 2014; Tumwebaze *et al.*, 2013), limited research has focused on national parks.

Despite national parks offering carbon sequestration services and other valuable ecosystem benefits, they are susceptible to degradation due to various land use and land cover changes occurring both within and around these areas. This study, therefore, prioritized the understanding of land cover changes and their effect on carbon stocks within the Rwenzori Mountains National Park (RMNP). The findings from this research will contribute to the sustainable management of natural resources and guide the government's efforts to align with Uganda Vision 2040, a strategic initiative aimed at strengthening the country's economic foundations to harness the abundant opportunities within the nation (Mwanjalolo *et al.*, 2018).

Materials and methods

Study area description

This study was conducted in the Rwenzori Mountains National Park (RMNP) located in Western Uganda, bordering the Democratic Republic of Congo (DRC) to the west (Fig. 1). RMNP covers the districts of Kasese, Bunyangabu, Kabarole, Ntoroko, and Bundibugyo in Uganda (Enyagu *et al.,* 2020). The RMNP is a World Heritage Site and a Ramsar Site due to its Outstanding Universal Values. Three-quarters of this range is in Uganda, where the RMNP covers 996 km² of land above 1,700 meters (WWF, 2015).

The park is located between latitudes 0 06 South and 0 46 North, as well as longitudes 29 47' West and 30 11' East (Enyagu *et al.,* 2020). The mountain ranges stretch for approximately 80 kilometers north to south and 40 kilometers east to west. This study area was chosen because of a distinct pattern of events occurring in the landscape that were discovered during a reconnaissance visit in the area. The events included high encroachment on park resources by local communities living on the slopes of the park in search of fuel wood and other non-timber products.

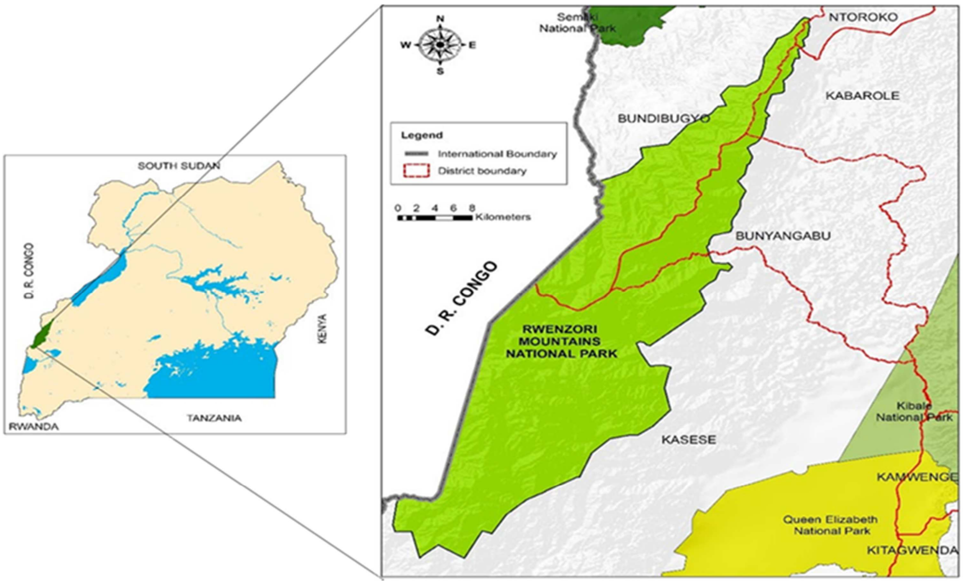

Fig. 1. Rwenzori Mountain National Park and administrative boundaries of districts in which the park is located (Source: RMNP General Management Plan 2016-2026)

The dynamics of land use land cover changes in RMNP between 1990 and 2020

The development of the land cover land use maps involved satellite image acquisition, image processing and interpretation, classification, validation, and accuracy assessment of the final map (Fig. 2).

Data acquisition

The RMNP was gazetted as a national park in 1991. Based on this knowledge, 1990 was considered for classification to determine the land use land cover changes in the park before its gazettment. The base year was also adopted from the National Biomass Study for Uganda (Kusiima *et al.*, 2022). While the thirty year period was proven sufficient to ascertain deep land use land cover changes in human dominated land mosaics (Van Eetvelde and Antrop, 2004).

Four Landsat satellite images from 1990, 2000, 2010 and 2020 were acquired from the Google Earth Engine Platform. The Landsat scenes were obtained from path and row (171, 060) and (172, 060). The area of interest boundary shape file was uploaded into Google Earth Engine cloud computing platform (GEE) and used to define the extent of the Landsat image. Landsat 5 images were obtained for 1990, Landsat 7 for 2000 and 2010 and Landsat 8 for 2020. Several factors were considered in selecting the Landsat images for the study. These included the time the images were acquired and the degree of cloud cover between 0 and 10%.

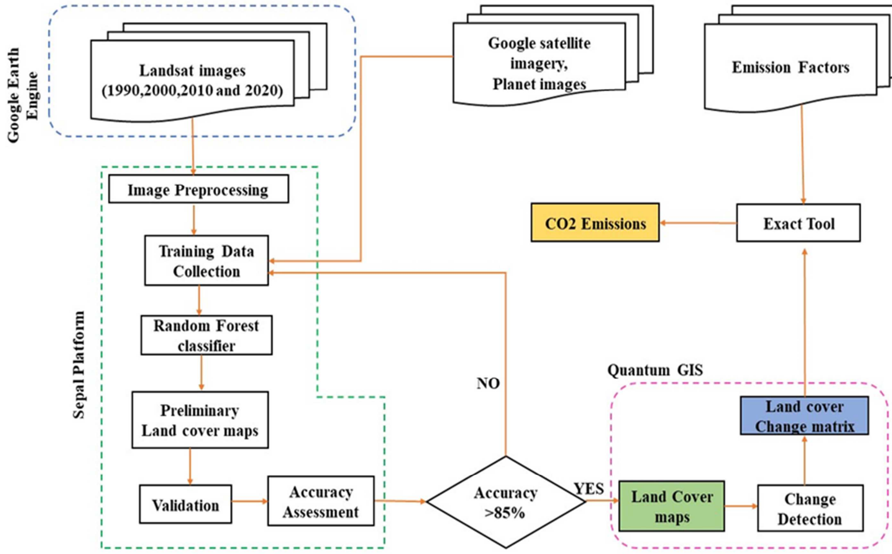

Fig. 2. Flow chart of methodology used in assessing land use land cover changes

Clear images were acquired in December, January, February, June and July, and a composite was made for the year. For those years without good images, the closest year with good images to the year of interest, either the previous or the following year, was considered.

Processing of landsat images

The processing and classification of the Landsat images were done using GIS tools in ArcGIS 10.5. First, the unprocessed image bands (blue, red, green, nir) obtained from the Landsat Satellites were imported and combined to form a single multispectral image by using the composite band tool in ArcGIS. Then, the area of interest was clipped out from the composite image and used to classify land use land covers.

Image classification

The classification scheme used for this study included 10 classes according to the Uganda National Land Cover System (NBS). Below is a description of the classes used (Table 1).

Table 1. Classification classes by Uganda national land cover system

Class Code	Land cover land use class	Description
1	Broad-leaved plantation	This consists of broad-leaved trees mainly *Eucalyptus* spp, *Maesopsis eminii*, *Acacia mearnsii* and some *Markhamia lutea*.
2	Coniferous plantation	This includes the Conifers; Pine spp. and Cypress spp.
3	Tropical high forest high stock	These are natural forests rich in species biodiversity i.e. flora and fauna. These are normally stocked with high species richness and abundance
4	Tropical high forest low stock	These are depleted or encroached with reduced species richness and composition dominated by secondary growth of bush and shrubs, in particular *Solanum gigantea*.
5	Woodland	Wooded areas are where trees and shrubs are predominant. There are wet and dry types. The wet type occurs as a zone along wetlands (riverine forest) and the dry type is found on grass-covered upland areas.
6	Bushland	This refers to vegetation dominated by bush, scrub and thicket growing together as an entity, but not exceeding an average height of 4 meters.
7	Grassland	These are rangelands, grazing grounds, improved pastures or natural savannah grassland.
8	Cultivated Farmland	Farmland areas including small holder subsistence farm units cover 50-90% of the land cover of Uganda. The cropping systems include mono-and mixed cropping.
9	Built-up	These are artificial surfaces including built up urban areas, airports, village trading centres, internally displaced peoples camps, schools, and recreational grounds.
10	Impediment	These include bare rocks, bare soil, and quarries and usually have little or no biomass.

Training data

Training data is the data you use to train a machine-learning algorithm for classification. Polygons that represented specific land cover classes were picked based on a spectral signature for the different land covers of the satellite image. However, a polygon would first be validated using more reliable high-resolution images such as Google Earth. The satellite image was visualized as a false colour composite to enhance features otherwise invisible or poorly visible to the human eye. The number of training polygons varied from one LULC class to another, depending on the ease of identification and the level of variability.

Classification process

Supervised classification was performed based on Random Forest Classifier Algorithm run using a GEE script which used Random Forests classifier to integrate the training data with the segment statistics. The model classifies satellite image pixels and assigns them land cover classes based on training data provided. Random Forest is widely popular because of their ability to classify large amounts of data with high accuracy (Breiman, 2001). It creates numerous decision trees for each pixel. Each of these decision trees votes on what the pixel should be classified as a specific land cover class. The land cover class that receives the most votes is then assigned as the map class for that pixel.

Validation

Validation of the land cover product was done to provide indications on the confidence levels that a pixel was classified correctly. This was done through visual assessment using high resolution imagery like planet images, Google earth images. The obvious misclassified areas were edited.

Change detection

Though several image change detection algorithms are currently available and are increasingly becoming a common approach in mapping land cover change, Post classification or the map subtraction method was used to generate change maps. Post-classification is the comparison of independently classified maps to identify changes in the land cover over time. This method is the most widely used, but the quality of the resulting change map depends entirely on the quality of the compared maps (Tewkesbury *et al.*, 2015).

Accuracy Assessment

Map accuracy assessment refers to evaluating the quality and accuracy of a map or geospatial data product. It involves comparing the information presented on a map with the real-world features or data it represents. This process involved deciding how many samples should be created per class and selecting the sampling scheme for generating these samples.

Since it's impossible to do an accuracy assessment for every classified pixel on the map, the sampling design dictates how the subset of the map is chosen, and this subset becomes the basis for the accuracy assessment. The stratified random sampling technique generated an error matrix indicative of the classified map. With this method, each sample unit in the area of interest has an equal probability of being chosen and includes all strata (i.e., map classes), no matter how small they are. The points sampling was designed based on pixels. The minimum number of points assessed for each land cover category was 50, and the maximum was 300.

The accuracy was assessed by determining the overall accuracy, user's accuracy, producer's accuracy, and the Kappa coefficient using the error matrix to determine the accuracy of the maps produced. The producer’s accuracy refers to the classification scheme whereas User’s accuracy refers to how accurate the actual classified map is on the ground.

Effect of land use land cover changes on the carbon fluxes of RMNP

The EX-Ante Act Carbon-balance Tool developed by FAO was used to assess the effect of land use/cover changes on RMNP carbon fluxes. The EX-ACT/Ante Carbon-balance Tool (EX-ACT) is based on the Intergovernmental Panel on Climate Change (IPCC) methodology for greenhouse gas (GHG) emissions inventories. EX-ACT gives its users a systematic approach of measuring and tracking the effects of agricultural interventions on GHG emissions.

Change detection was conducted using the post-classification method to compare independently classified maps to identify changes in the land cover over time (Tewkesbury *et al.*, 2015). Data from change detection was imported into the EX-ACT tool, and other data on management practices of the park's different land cover/use, including cropland, grassland, and forest management, over a 30-year period. The EX-ACT algorithms examined the input data to calculate net carbon fluxes following land use/cover changes in the research area. Tables and graphs were created to illustrate the gross carbon fluxes associated with different changes in land cover and land use.

Results

Dynamics of land use land cover changes in RMNP between 1990 and 2020

Landsat 5 images were obtained for 1990, Landsat 7 for 2000 and 2010 and Landsat 8 for 2020. Landsat 8 features the Operational Land Imager (OLI) sensor, which captures images in nine spectral bands, including a new coastal/aerosol band. The OLI sensor provides higher radiometric resolution and improved signal-to-noise performance compared to the Enhanced Thematic Mapper Plus (ETM+) sensor of Landsat 7. Furthermore, Landsat 8 has an improved radiometric sensitivity, allowing it to detect and differentiate subtle changes in the Earth's surface.

Spatio-temporal analysis of LULC changes

The spatial assessment of land use land cover types of RMNP between 1990 and 2000 (Fig. 3) indicated a wide unbroken coverage of tropical high forest well stocked, followed by grasslands and scattered tropical high forest low stock in 1990, with cultivated land only observed at the park boundaries. In 2000, there was a shift of cultivation from the park boundaries into the park, forming mosaic patterns of cultivated land in the forest cover.

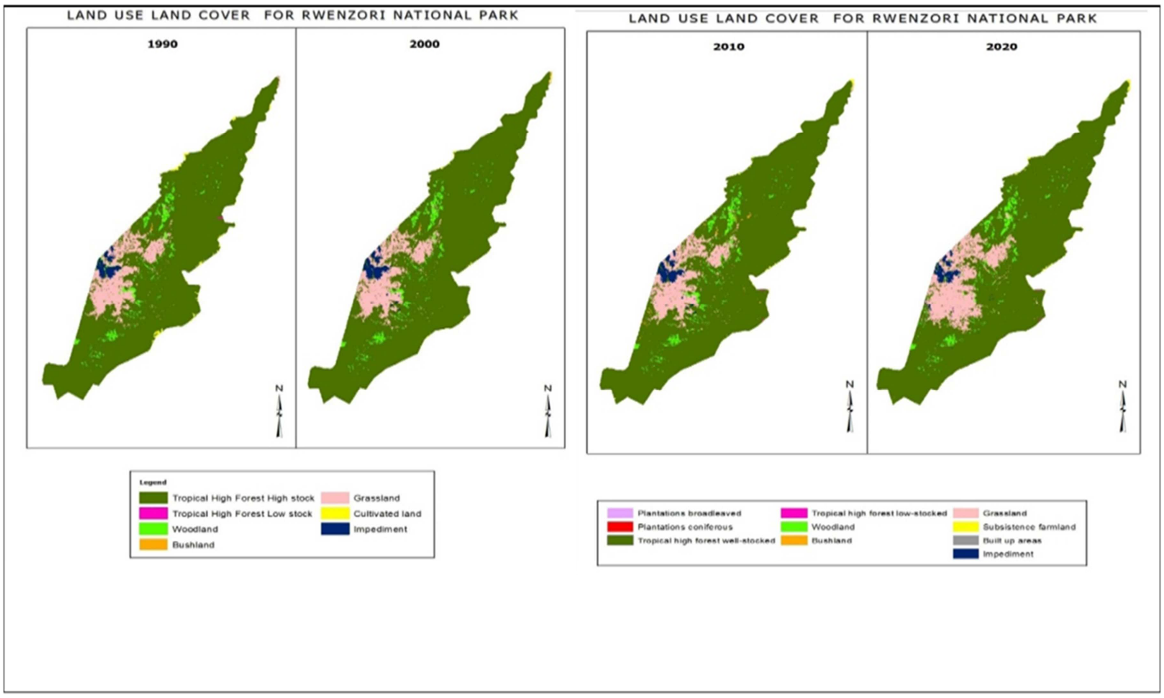

Fig. 3. Spatio-temporal LULC in RMNP 1990 to 2020

Table 2. Accuracy assessment results for the land use land cover maps produced

Land use-cover	1990		2000		2010		2020	
	Producer's accuracy (%)	User's accuracy (%)	Producer's accuracy (%)	User's accuracy (%)	Producer's accuracy (%)	User's accuracy (%)	Producer's accuracy (%)	User's accuracy (%)
Tropical high forest high stock	88.32	89.28	87.36	85.44	76.8	85.44	88.67	73.47
Tropical high forest low stock	81.6	83.52	85.44	79.68	78.72	79.68	93.75	96.23
Woodland	79.68	84.48	84.48	84.48	83.52	84.48	80.33	81.56
Bushland	74.88	74.88	72.96	74.88	72.96	74.88	73.08	75.99
Grassland	87.36	88.32	84.48	86.4	75.84	86.4	87.82	84.55
Cultivated	80.64	78.72	88.32	82.56	86.4	82.56	89.05	92.96
Impediment	99.84	97.92	96.96	96	99.84	99.84	95	98.7
Plantation							79.23	82.93
Overall accuracy (%)	84.61		85.71		82.01		85.63	85.63
Kappa coefficient	0.81		0.82		0.787		0.88	0.88

Table 3. Magnitude of land use land cover change in RMNP

	Year			
Land cover class	1990(ha)	2000(ha)	2010(ha)	2020(ha)
Broad-leaved plantation	-	-	-	49.8
Coniferous plantation	-	-	-	4.7
Tropical high forest well-stocked	84457.3	84,554.4	84,276.1	81452.7
Tropical high Forest Low stocked	42.2	0.4	48.8	35.1
Woodland	2751.0	2,653.7	2,852.6	2724.5
Bushland	36.8	59.2	249.7	24.3
Grassland	10616.4	10,434.0	10,309.3	13496.5
Cultivated land	231.5	215.6	273.9	369.1
Impediment	1307.69	1,525.9	1,432.6	1364.9

Table 4. LULC Percentage change 1990 to 2020

Land cover class	1990(ha)	2020(ha)	% Change
Broad-leaved plantation	-	49.8	
Coniferous plantation	-	4.7	
Tropical high forest well-stocked	84457.3	81452.7	-3.55754
Tropical high Forest Low stocked	42.2	35.1	-16.8246
Woodland	2751	2724.5	-0.96329
Bushland	36.8	24.3	-33.9674
Grassland	10616.4	13496.5	27.12878
Cultivated land	231.5	369.1	59.43844
Impediment	1307.69	1364.9	4.37489

In 2010 and 2020 the extent of coverage of grasslands increased as well as the mosaic patterns of tropical high forest low stocked and cultivated land within the tropical high forest well stocked forests (Fig. 5). However, there was conspicuous increase in cultivation land along the park boundaries in 2010 and 2020 as compared to 2000. Also Bushlands were more conspicuous in 2010 as compared to the year 2020, while plantations were observed in the year 2020.

The accuracy assessment results for each of the land use land cover map produced (Table 2) indicated kappa coefficients for all the four years are above 0.8 showing a good agreement between the classified pixels and the real world scenario. When kappa index of agreement is greater than or equal to 0.75, it indicates high consistency; when index is less than or equal to 0.4, it indicates poor consistency (Yuan *et al.*, 2015).

The magnitude of LULC between 1990 and 2020

There were reductions and expansions in the different land covers from 1990 to 2020 (Table 3). The LULC percentage change is given in the Table 4. There was a 3.6% reduction in the tropical high forest well-stocked. There was a 59.4% increase in cultivated land and a 27.1% increase in grassland over the study period. The least reductions were observed in woodland cover over the study period.

Table 5. Change detection matrix between 1990 and 2000

		2000 (ha)							
	Cover type	Tropical high forest well-stocked	Tropical high forest low-stock	Wood land	Bush land	Grass land	Cultivated land	Impediment	Totals 1990
1990	Tropical high forest well-stocked	84,108.4	0.4	81.8	7	93.9	71.4	94.4	84,457.30
	Tropical high forest low-stock	37.2					5		42.20
	Woodland			2,571.9		50.7		128.5	2,751.10
	Bushland				36.8				36.80
	Grassland	289.4			15.4	10,289.4	19.2	3.1	10,616.50
	Cultivated land	111.5					120		231.50
	Impediment	7.8						1,299.9	1,307.70
	Totals 2000	84,554.30	0.40	2,653.70	59.20	10,434.00	215.60	1,525.90	

Table 6. Change detection matrix between 2000 and 2010

		2010							
	Cover type	Tropical high forest well-stocked	Tropical high forest low-stock	Wood land	Bush land	Grass land	Cultivated land	Impediment	Totals 2000
2000	Tropical high forest well-stocked	84,206.80	32.7		207.1		107.9		84,554.50
	Tropical high forest low-stock						0.4		0.40
	Woodland			2,642.90	10.8				2,653.70
	Bushland			5.1	31.8		22.3		59.20
	Grassland	27.4	4.3	178.3		10,216.60	7.3		10,433.90
	Cultivated land	41.9	11.8	25.4	0.1	0.4	136		215.60
	Impediment			0.9		92.4		1,432.60	1,525.90
	Totals 2010	84,276.10	48.80	2,852.60	249.80	10,309.40	273.90	1,432.60	

Table 7. Change detection matrix between 2010 and 2020

		2020									
	Cover type	Broad-leaved plantation	Coniferous Plantation	Tropical high forest well-stocked	Tropical high forest low-stock	Wood land	Bush land	Grass land	Cultivated land	Impediment	Totals 2010
2010	Tropical high forest well-stocked	43.5	4	80,921.0	2.7	97.9	17	2847.9	152.8	130.6	84217.4
	Tropical high forest low-stock	0.1	0.3	4.6	32.2	49		4.9	0.8		91.9
	Woodland	0.9		81		2,082.40	2	666.8	12.6	6	2851.7
	Bushland			53.5	0.1	153.8		36.7		5.4	249.5
	Grassland			228		332.9	5	9,652.20	31.7	57.8	10307.6
	Cultivated land	4.4	0.3	59.3	0.1	12.0		26.8	158.9	0.7	262.5
	Impediment			12		32.7		226.4		1,161.00	1432.1
	Totals 2020	48.9	4.6	81359.4	35.1	2760.7	24	13461.7	356.8	1361.5	

Table 8. Carbon fluxes in RMNP following land cover changes

Period	Carbon dioxide equivalent emitted (+) or sequestered (-) from different sources (tCO_2-e)						
	Deforestation	Forest regeneration	Non-forest cover changes	cultivation	Grassland	Forest conservation	Net carbon fluxes
1990 – 2000	+149,269	-64,726	+1,101	+1,159	+146	-3,961,940	-3,874,991
2000 – 2010	+137,963	-14,861	+2,113	+950		-3,953,749	-3,827,584
2010 - 2020	+1,373,541	-62,522	-31,048	+1,486	+4,445	-3,953,754	-2,667,852
Total	+1,660,773	-142,109	-27,834	+3,595	+4,591	-11,869,443	-10,370,427

Dynamics of LULC in RMNP between 1990 and 2020

Dynamics of LULC between 1990 and 2000

The gains and losses in the different LULCs between 1990 and 2000 are given in Table 5. The total land area covered by tropical high forest well-stocked that remained unchanged between 1990 and 2000 was 84,108.4ha with a total gain of 97.1ha. Only 0.4ha of Tropical high forest low stocked remained unchanged resulting in a net loss of 41.8ha. The total unchanged land area of woodland during this period was 2,571.9ha, resulting in an overall woodland loss of 97.4ha. Bushland area that remained unaltered was 36.8ha, leading to an overall net gain of 22.4ha for bush land. The total land area of grassland that remained unchanged was 10,289.4ha in the period 1990 to 2000 resulting in a net loss of 182.5ha. The total land area of cultivated land that remained unchanged was 120ha in the period 1990 to 2000 making cultivated land to have a net loss of 15.9ha.

Dynamics of LULC between 2000 and 2010

The gains and losses in the different LULCs between 2000 and 2010 are given in Table 6. Tropical high forest well-stocked experienced a net loss of 278.4ha during the time span from 2000 to 2010. There was an overall decrease of 124.5 hectares in the grassland cover between 2000 and 2010. The total area of cultivated land that remained unchanged during the 2000 and 2010 period was 136ha. Consequently, cultivated land saw a net increase of 58.3ha during this time period. The total area covered by Tropical high forest low stocked that remained unchanged was 32.7ha resulting in an overall net gain of 48.4ha. The total expanse of unchanged woodland during this time period amounted to 2,642.9 hectares, resulting in an overall net gain of 198.9 hectares in woodland cover. Bushland area that remained unchanged was 31.8 hectares, leading to a net increase of 190.6 hectares.

Dynamics of LULC between 2010 and 2020

The gains and losses in the different LULCs between 2010 and 2020 are given in Table 7. The total area covered by tropical high forest well-stocked that remained unchanged was 80,921 hectares, resulting in an overall net loss of 2858 hectares. The total area of cultivated land that remained unchanged was 158.9 hectares, leading to a net gain of 94.3 hectares. The overall expanse of unchanged grassland during this timeframe amounted to 9652.2 hectares, resulting in a net gain of 3,154.1 hectares. The total area of woodland that remained unchanged during this period was 2082.4 hectares, resulting in an overall net loss of 135.1 hectares. The total area of tropical high forest low stocked that remained unaltered during this period was 32.2 hectares, leading to a net loss of 12.7 hectares. Coniferous plantations saw an increase of 4 hectares. Broad-leaved plantations experienced an increment of 45.5 hectares.

Effect of land use and land cover changes on the carbon fluxes of RMNP

The effect of land cover land use changes on carbon fluxes of the RMNP was determined by estimating the amount of GHGs in tonnes of CO2-equivalents released or sequestered from the different land cover land use changes in the area.

The carbon fluxes in RMNP following land cover changes are shown (Table 8). There was a high sequestration of carbon (-3,874,991 tCO2-e) in the period (1990 – 2000), followed by 2000 – 2010 (-3,827,584 tCO2-e) and lowest in 2010 – 2020 (-2,667,852 tCO2-e) (Table 6). There were high levels of deforestation between 2010 and 2020 contributing to high carbon dioxide emission (+1,373,541 tCO2-e) as compared to the emissions of 1990 – 2000 (+149,269tCO2-e) and 2000 – 2010 tCO2-e from forest conversions. The highest contributor to carbon sequestration from 1990 to 2020 is the conservation of the existing forest cover (-11,869,443 tCO2-e), which contributed 98.6% to the total carbon sequestration. The highest contributor to carbon emission is the conversion of forests to other land use/cover including cultivation, grasslands and bushlands (+1,660,773 tCO2-e), which contributed 99.5% to the total emissions from the park.

Actions taken to enforce the conservation of RMNP and protection from encroachment led to a net carbon sequestration from the park in the period 1990 – 2000 (Fig. 4), 2000 – 2010 (Fig. 5) and 2010 – 2020 (Fig. 6). The amount of carbon dioxide equivalent that is emitted without enforcement is much higher than the carbon dioxide equivalent emitted under enforcement, hence giving a net carbon dioxide sequestration.

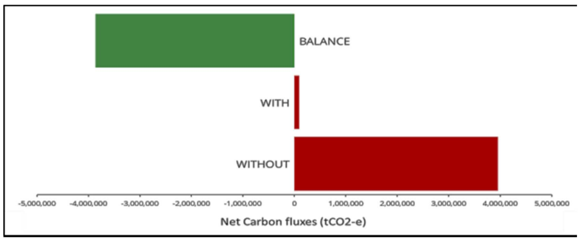

Fig. 4. Carbon fluxes following land use/cover change for the period between 1990 – 2000 without management interventions (WITHOUT) and with management interventions (WITH)

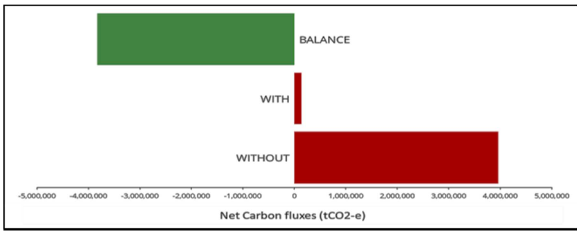

Fig. 5. Carbon fluxes following land use/cover change for the period between 2000 – 2010 without management interventions (WITHOUT) and with management interventions (WITH)

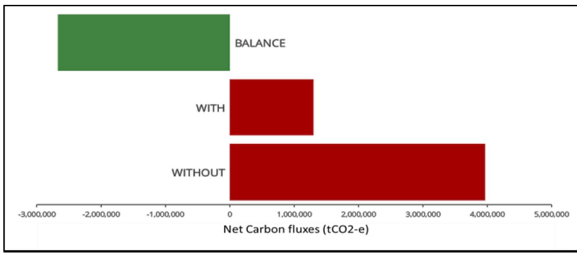

Fig. 6. Carbon fluxes following land use/cover change for the period between 2010 – 2020 without management interventions (WITHOUT) and with management interventions (WITH)

Discussion

Dynamics of LULC in the RMNP between 1990 and 2020

LULC changes in RMNP are reflected in both temporal and spatial scales as indicated by this study. Overall, there were reductions and expansions in land covers between 1990 and 2020. This increase can be ascribed to the stringent enforcement measures and conservation initiatives undertaken by park management immediately following the official gazettement of the park in 1991. These efforts led to a noticeable enhancement in the desired land covers while simultaneously causing reductions in less desirable land covers. For instance, there was a reduction in cultivated land observed in the year 2000 when contrasted with its coverage in 1990. Similarly, a substantial decrease was observed in the extent of low-stocked tropical high forest in 2000 as compared to its coverage in 1990.

Tropical high forest

Tropical high forest converted to cultivated land, grassland, and woodland over the study period. The reduction in tropical high forest both low and well-stocked in favor of woodland can be attributed to the increasing demand for wood fuel and other non-wood forest products such as medicinal herbs. The local people derive their livelihoods from natural resources in the surrounding areas where they obtain both tangible and intangible ecosystem resources (Iacopino *et al.*, 2022). Additionally, expansion of cultivated land to Tropical high forest is attributed to the encroachment of communities on the forest in search for cultivable land. These findings are consistent with Ministry of Water and Environment, (2016) which reported that Uganda lost on average 122,000ha/year of forest between 1990 and 2015, in favor of other land uses such as agricultural expansion. The loss of tropical high forest observed in this study is similar to results of other studies in national parks such as Opedes *et al.*, 2022 that focused on land cover change detection and subsistence farming dynamics in the fringes of mount Elgon national park and their study revealed a 50% loss in the tropical high forest well-stocked. Another study in protected areas of Budongo and Bugoma showed a reduction in tropical high forest well-stocked while subsistence farmlands increased over the study period (Kusiima *et al.*, 2022).

Cultivated land

There was conversion of natural vegetation (Tropical high forest, grassland, woodland, and Bushland) into cultivated land. The expansion of cultivated land can be attributed to the increasing human population and demand for food. The cultivation is however mainly along the boundaries as indicated by the findings of the study. This is due to access constraints to the park, thus locals tend to cultivate the areas closest to them, which are the boundaries. In the year 2000, an observable phenomenon occurred wherein agricultural activity transitioned from areas outside the park boundaries into the park itself, resulting in the formation of mosaic-like patterns of cultivated land, as depicted in Figure 3. This occurrence can potentially be attributed to the practice of shifting cultivation by farmers in communities adjacent to the park, possibly as a measure to avoid detection. Furthermore, it is noteworthy that the cultivated land bordering the park boundary experienced an expansion in 2010 and 2020 when compared to the situation in 2000, as evident in Figure 3. This trend can be rationalized by the initial stringent enforcement and management practices implemented right after the park's gazettement, which effectively curtailed encroachments. In subsequent years, it is plausible that enforcement capacities may have been somewhat limited, leading to the observed increase in cultivated fields in recent times (2010 and 2020). Simultaneously, this phenomenon could be attributed to the escalating population pressures stemming from communities surrounding the park. These pressures likely extend the cultivated areas right up to the park boundary, contributing to the observed expansion of cultivated lands in close proximity to the park.

Plantations

The plantation forests were observed in 2020. This is partly attributed to the quality of imagery used but also continuous efforts to restore the degraded natural forests in the area. The Landsat 5 was used to produce the 1990 and 2000; the 2010 map was produced using Landsat 7 and the Landsat 8 was used to produce the 2020 land use land cover map. Landsat 8 features the Operational Land Imager (OLI) sensor, which captures images in nine spectral bands, including a new coastal/aerosol band. The OLI sensor provides higher radiometric resolution and improved signal-to-noise performance compared to the Enhanced Thematic Mapper Plus (ETM+) sensor of Landsat 7. Furthermore, Landsat 8 has an improved radiometric sensitivity, allowing it to detect and differentiate subtle changes in the Earth's surface. According to discussions held with park management, *Eucalyptus* species are now being planted along the boundary to demarcate park boundary and adjacent private land.

Some of the unlikely changes include the conversion of impediment to tropical high forest well-stocked; and this is as a result of poor quality of the landsat 5 image.

Grassland

There was an increase in the grassland cover between 1990 and 2020; the expansions of grassland was into cultivated land, woodland and Tropical high forest. The increase in grassland can be attributed to their emergence in previously cultivated areas following the removal of encroachers. Additionally, grasslands expansion on impediments through ecological successions might have contributed to their increase over time. The conversion of grassland into woodland is a complex ecological process shaped by an intricate interplay of various factors, including management strategies, climatic conditions, and atmospheric composition (Zziwa *et al.*, 2012). These factors engage in intricate feedback mechanisms, contributing to the dynamic nature of this ecological phenomenon.

Woodland

The woodland cover experienced a minor decline between 1990 and 2020. The reduction in woodland area over this period can be attributed to heightened anthropogenic activities, which encompass practices like tree cutting for cultivation, establishment of plantation forests, creation of grasslands, and charcoal production. This trend aligns with observations made in various parts of the world (Lambin *et al.*, 2001; Mwavu and Witkowski, 2008; Maitima *et al.*, 2010).

Nevertheless, the augmentation of woodland within grassland environments as indicated by the study is a more intricate process influenced by numerous contributing factors. Some of the driving forces behind reductions in woodland area exhibit a positive feedback mechanism, resulting in heightened woody growth in the same region. For instance, the indiscriminate removal of trees, particularly for wood and charcoal production, often leads to the proliferation of dense woodland stands due to the elimination of intra-species competition among trees (Zziwa *et al.*, 2012). This phenomenon fosters equal opportunities for tree saplings to mature into fully grown trees. As a result, these forces play a role in generating temporal and spatial fluctuations in the extent of woodland coverage.

Effect of land use land cover changes on the carbon fluxes of RMNP

Understanding the dynamics of net carbon changes after land cover changes provides a clear and comprehensive understanding of land cover changes' impact on the carbon cycle. The study estimated the carbon fluxes in RMNP following land cover changes to investigate the effect of land use and land cover changes on RMNP carbon stocks over a 30-year period. The results indicate a decline in net carbon sequestration during the last three decades. This trend could be attributed to a gradual rise in anthropogenic pressures over time, as well as the constrained ability of management to effectively enforce their regulatory measures. These factors have contributed to shifts in land cover, which subsequently lead to reductions in carbon sequestration capacity. Furthermore, the carbon fluxes observed over the last three decades could be attributed to changes in management approaches and strategies in RMNP. These management approaches might have caused improvements especially after immediate gazettement of the park in 1991 resulting in more sequestration that has been observed between 1990 and 2000. Land use activities that increase vegetation cover, for example, increase the potential of the vegetation to produce biomass. The carbon dioxide emitted overtime reported in the study can be attributed to encroachment of communities on the park to get wood for fuel, construction materials, and more arable land. Land use activities such as farming and urbanization reduce vegetation cover and, as a result, the capacity of vegetation to create biomass, resulting in a drop in carbon dioxide sequestered.

The highest contributor to carbon sequestration from over the study period was the conservation of the existing forest cover which contributed 98.6% to the total carbon sequestration. When forests are removed for other land uses, such as agriculture, the carbon stored in the trees and flora is released into the atmosphere as carbon dioxide. As a result, carbon stocks are reduced. Even if forests are not completely removed, actions like selective logging can cause forest degradation. As damaged trees and vegetation degrade or burn, carbon is released from the ecosystem. In contrast, the formation of new forests or the recovery of previously deforested areas can enhance carbon stocks. Previous studies, in agreement with the current study, have shown that land cover change is a key factor in carbon stock changes. For example, Shrestha *et al.*, (2010) observed a net gain in carbon stock in the larger parts of the mountain watershed in Nepal from 1976 to 1989, while a net loss was recorded between 1989 and 2003. Kashaigili and Majaliwa, (2010) also realized a reduction in carbon stock in two Tanzanian forests from 1980 to 2010. Similarly, Gond *et al.*, (2016) observed a 30% reduction in carbon stock from 1984 to 2012 in Kinshasa's wood-fuel supply basin. Furthermore, Gaston *et al.*, (1998) demonstrated a 6.6 Pg loss in aboveground carbon stock due to forest degradation in tropical Africa between 1980 and 1990. According to Zhang *et al.*, (2015), land cover change reduced carbon stock by 60 Tg between 1995 and 2010.

The generated results demonstrate the potential for RMNP to generate carbon credits through averted deforestation and degradation, as well as the park's ability to mitigate effects of climate change through sequestration of carbon dioxide. Yet, to fully harness these capabilities, increased enforcement efforts are needed to oversee the areas of deforestation that contribute to carbon emissions within the park. Specifically this enforcement should aim to reduce carbon dioxide emissions and should be complemented by initiatives to restore degraded areas.

Conclusion

There were both spatial and temporal changes in land use and land cover within RMNP, with conversions from one land use land cover type to another over time in mosaic patterns. There were overall decline in forest and woodland cover and expansion of cultivated, grasslands and impediments between 1990 and 2020, with cultivation being more conspicuous along park boundaries.

The highest contributor to carbon emission is deforestation (the conversion of forests to other land use land cover including cultivation, grasslands and bushlands) while the highest contributor to sequestration is forest management practices that maintained intact forests over the 30 year period. Overall, RMNP is a net carbon sink with more carbon sequestered than emitted between 1990 and 2020.

Owing to the observed land cover/use changes, UWA should tighten park boundary management by applying hybrid approaches including buffer zoning, electric fencing, thorn and stone hedges, etc. More enforcement by various strategies such as regular patrols and monitoring, law enforcement along with penalties for offenders to minimize deforestation so as to increase carbon sequestration potential of RMNP is recommended.

It is also recommended that the implication of observed LULC changes on other ecosystem service potential and their socio-economic effects on livelihoods of communities in the RMNP region be determined.

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