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Original Article

Spatial and Temporal Dynamics in Vegetation Cover and Its Impact on Carbon Stock in Kicukiro District, Rwanda

Saidi Niyonizeye[1], Richard Mind'je[1], Fidele Mwizerwa[1]*

[1] University of Lay Adventists of Kigali, P. O. Box 6392, Kigali, Rwanda.
[*] Author for Correspondence ORCID ID; https://orcid.org/0009-0007-5325-6412; Email: saidiyonizeye@gmail.com

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ABSTRACT

Climate change and land use changes are significantly affecting vegetation cover and carbon storage, especially in Rwanda. This study examines how vegetation cover has changed over time and how these changes have impacted carbon stocks in Kicukiro District from 2000 to 2022. Using a combination of remote sensing, GIS, and field data, the research tracks vegetation shifts, estimates changes in carbon stocks, and explores their relationship. The results show a sharp decline in dense vegetation from 41% to 18% while sparse and moderate vegetation increased (from 5% to 12% and 6% to 17%, respectively). This led to major losses in carbon stock: 897.98 tons between 2000–2010 and 1,558.04 tons between 2010–2022. Vegetation cover also declined by 6.42 km² in the first decade and 15.45 km² in the second. Statistical analysis shows a strong negative correlation ($r = -0.9$) between vegetation cover loss and carbon stock decline, highlighting the key role of forests in climate regulation. These findings point to fast ecosystem degradation in Kicukiro and its effect on Rwanda's ability to store carbon. The study calls for urgent action to protect and restore forests, offering practical guidance for policymakers. By connecting vegetation change with carbon dynamics at the local level, the research supports informed land-use planning and climate adaptation, with lessons for similar areas in East Africa.

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INTRODUCTION

Vegetation cover plays a vital role in ecological sustainability by regulating the climate (Weiskopf, et al. 2020), preserving biodiversity, (Grimm and Wissel 2019) and supporting essential ecosystem services such as carbon sequestration (Zhang, et al. 2022). Globally, vegetation acts as a critical buffer against the adverse effects of climate change by absorbing atmospheric carbon dioxide (CO_2) (Ali, et al. 2017), (Wolfgang, et al. 2011), (Nzabarinda, et al. 2024) which accounts for about 77% of anthropogenic emissions (Kashaigili 2018). Forest ecosystems alone offset nearly 2.6 billion tons of CO_2 annually (IPCC, 2022).

However, vegetation degradation due to deforestation, urban expansion, and shifting land-use patterns is accelerating climate impacts worldwide (FAO 2021). For instance, between 2010 and 2020, the world lost forests at a net rate of 4.7 million hectares annually (Ritchie 2021), while the continent of Africa lost a total of 3.9 million hectares of forest land between 2010 and 2020 (Etahoben 2020), making it the highest level of deforestation in the world. Rwanda has also faced major vegetation loss over the past decades" (Arakwiye, John & Ronald 2021). From 1986 to 2006, the country lost 19% of its forests, around 23,412 hectares, mostly due to pasture expansion and land use changes related to conflict (Arakwiye, John and J. Ronald 2021) From 2010 to 2014, forest loss accelerated further as urban demand for land and energy resources surged (Kagabo, et al. 2024).

Presently, Rwanda's forest cover stands at 30.4%, equivalent to 724,662 hectares (Dusabemungu 2021) (MOE 2024), with over half of this consisting of plantation forests. Despite government reforestation initiatives such as "National Tree Planting Campaigns 2023", TREPA Project (Transforming Eastern Province through Adaptation (2024), Green Gicumbi Project (2019), One Shot, One Tree campaign to kick off Rwanda's annual tree planting season (2023) (REMA 2015), ongoing urban development continues to stress vegetative resources, particularly in Kigali City, urban expansion has led to substantial loss of open and green spaces, (Nshimiyimana, et al. 2023) which has implications for carbon sequestration, air quality, and urban resilience. Kicukiro District, located in Kigali, exemplifies these dynamics. It has experienced rapid land use transformation over the past three decades. Between 1990 and 2020, built-up areas expanded by 3.39 km² annually, while open land declined by 5.81 km² per year (Kagabo, et al. 2024). This trend has reduced the district's vegetative cover and carbon sequestration potential, with vegetation loss contributing to an annual reduction of 25,000 metric tons in carbon stock (Mugabowindekwe , et al. 2022).

Additionally, wetlands vital for flood control and carbon storage have decreased by nearly 30% in Kicukiro since 2010 (GGGI 2021). While existing research in Rwanda (Arakwiye, John and Ronald 2021), (Ndayisaba et al. 2016), (Kagabo et al., 2024) has focused on mapping land-use changes and identifying their drivers, there is limited understanding of how these changes specifically affect carbon stock, a critical factor in mitigating climate change. This research addresses this gap by linking spatial-temporal vegetation changes in Kicukiro to their carbon stock impacts, providing actionable data for policymakers, urban planners, and environmental stakeholders. This study was designed to achieve the following objectives: (1) to

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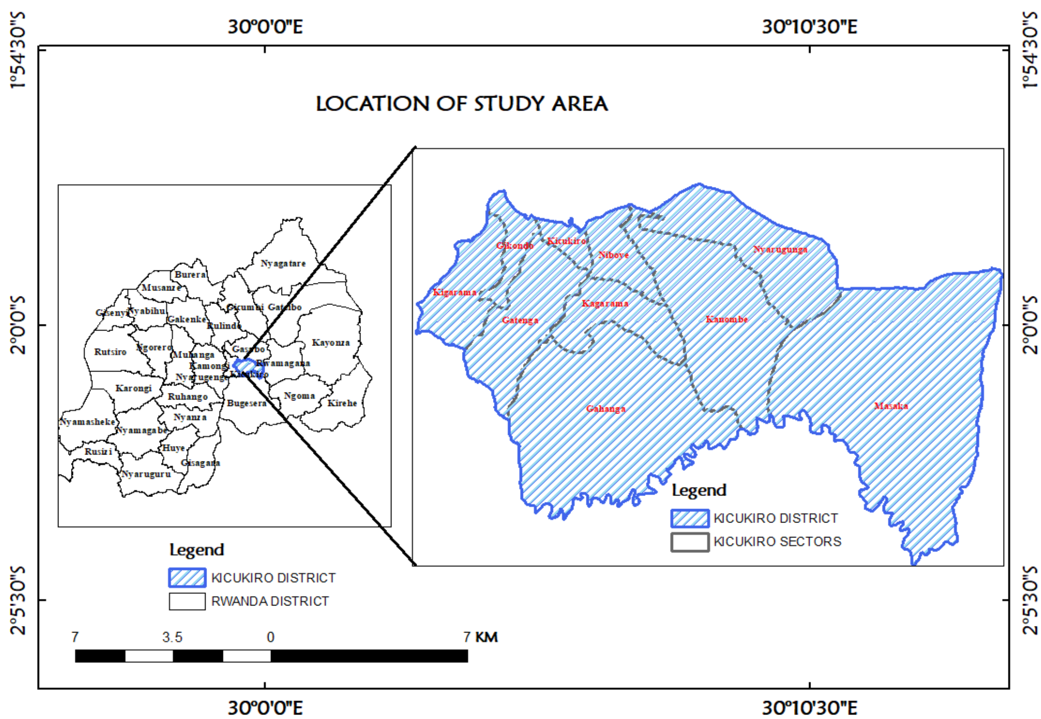
generate a spatially explicit map illustrating changes in vegetation cover between 2000 and 2022; (2) to quantify the magnitude and rate of these vegetation cover changes; (3) to assess temporal variations in carbon stock across the study period; and (4) to investigate the relationship between vegetation dynamic and carbon sequestration potential.

DATA AND METHODS

Description of the Study Area

Kicukiro District, located in the southeastern part of Kigali City, Rwanda, is one of the three administrative districts within the capital city of Kigali. The district covers an area of approximately 166.7 square kilometres (NISR 2022). The district's topography consists of a series of hills and valleys, with an elevation ranging between 1,400 to 1,800 meters above sea level (Mlotha 2018). This varied terrain contributes to diverse land use practices, including residential, commercial, agricultural, and industrial activities. The eastern parts of Kicukiro are more rural and agricultural, while the western parts are more urbanized, with significant infrastructure development. The rapid expansion of urban and suburban areas has resulted in the loss of natural vegetation, particularly in the form of forested areas and green spaces, which are essential for maintaining ecological balance and mitigating environmental issues such as soil erosion, flooding, and habitat loss (Nshimiyimana, et al. 2023).

Figure 1: Study Area Map



Data Source

The data utilized for this study encompass a diverse array of geospatial datasets, remote sensing techniques, and geospatial datasets most especially multi-spectral high-resolution satellite images of 30 m spatial resolution such as Landsat imagery from different time spans of 2000,2010 and 2022. These images were collected from the NASA-United States Geological survey (USGS) accessed from https://earthexplorer.usgs.gov/. From which the land use and land cover (LULC) change and the normalized difference vegetation index (NDVI) are processed. LULC helped to quantify and detect the dynamics in vegetation cover while NDVI helped in the quantification and analysis of carbon stock

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change. The images downloaded are Landsat-5(TM) to analyse NDVI for the year 2000, Landsat-7 (ETM+) for NDVI of 2010, Landsat-8(OLI/TIRS) for NDVI of 2022, images, with a resolution of 30m × 30m (WRS path 172 and rows 61), and 30m (WRS path 172 and rows 62). These images are pre-processed for radiometric and atmospheric rectification and then used for calculating vegetation indexes.

Data Analysis

NDVI calculations were employed to quantify vegetation density and health. This technique involves mathematical transformations of satellite band reflectance, providing a precise measure of vegetation cover and ecosystem productivity. Advanced image classification methods, including supervised classification techniques, were utilized to categorize land cover types with high accuracy. For Landsat 5TM, Landsat 7 ETM+ and Landsat 8 OLI-TIRS images, NDVI was calculated as a ratio between the red (R) and near-infrared (NIR) bands. Mathematically, calculated as follows:

$$NDVI = \frac{NIR - R}{NIR + R}$$

For Landsat-7, NIR is represented by Band 4 while R is represented by Band 3. For Landsat 8 data, NIR is represented by Band 5 while R is presented by Band 4. NDVI values range from -1 to 1, capturing a spectrum from non-vegetated areas to fully vegetated zones. The vegetation is categorized into five distinct classes: dense vegetation, Healthy/dense vegetation Moderate vegetation, Mixed vegetation, sparse vegetation, Bare soil or non-vegetated area.

Table 1: Value Range of NDVI Classifications

No	Classification	Value Range
1	Healthy/dense vegetation	≥1
2	Moderate vegetation	0.37-0.43
3	Mixed vegetation	0.32-037
4	sparse vegetation	0.29-0.32
5	Bare soil or non-vegetated area	≤1

In order to know the area which was covered by each class of NDVI, the study applied a reclassification operation, reclassified area was provided as a counted number of pixels (CNP) as per each class following the below equation:

$$AREA = \frac{CNP \times 30 \times 30}{10000}$$

Where CNP is the counted number of pixels per class, 30*30 is the measurement of one pixel or grid in raster image in (meter) and 10000 is the conversion factor from square meter to kilometre square. The changing trend of NDVI was determined by creating a regression model using the yearly maximum values from 2000, 2010 and 2022. This approach provides a comprehensive understanding of the spatial and temporal distribution of vegetation (Shoshany M. 2000). The regression model highlights both the trend and variability of NDVI. A positive slope indicates an increasing trend, while a negative slope suggests a decrease. Additionally, the variability is positively correlated with the absolute value of the slope.

$$\text{slope} = \frac{t \cdot \sum_{i=1}^{t} i \cdot y_i - \sum_{i=1}^{t} i \cdot \sum_{i=1}^{t} y_i}{t \cdot \sum_{i=1}^{t} i^2 - \left(\sum_{i=1}^{t} i\right)^2}$$

Where t is the number of years (in this case, 3 for the years 2000, 2010, and 2022), y_i is the NDVI value for year i (yearly maximum value) and is the index for the specific year (1 for 2000, 2 for 2005, etc.). A positive slope indicates that vegetation cover (as represented by NDVI) has been increasing

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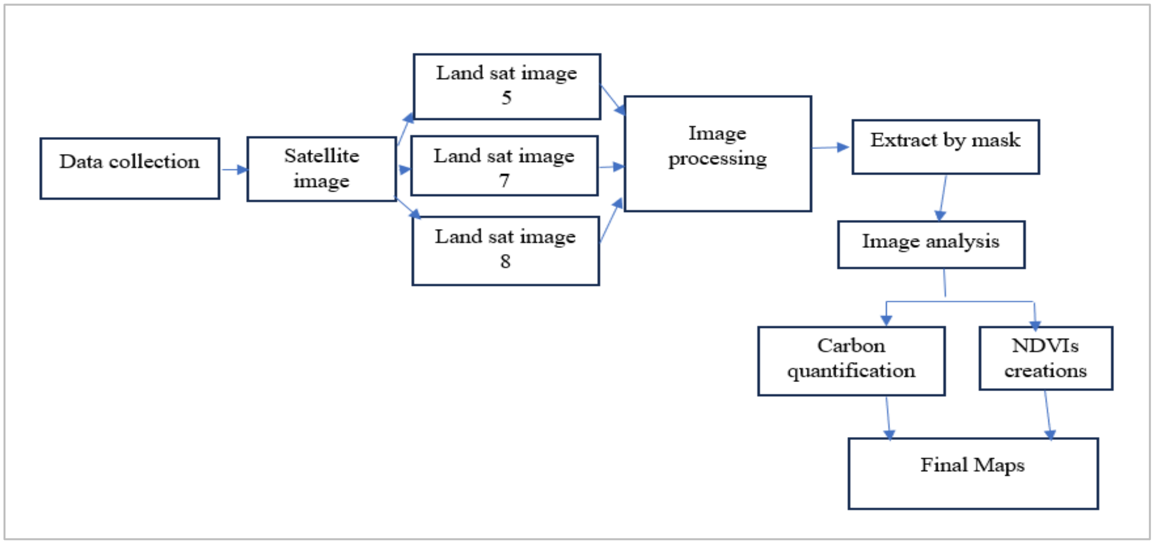
over the study period while a negative slope suggests that vegetation cover has been decreasing.

Figure 2: Methodological Flowchart Adopted for the Study



Carbon Stock Estimations

Carbon stock estimation was calculated based on the total vegetation cover data obtained from satellite imagery. It also relies on a combination of established allometric equations and field measurements. Standard methodological approaches recommended by the Intergovernmental Panel on Climate Change (IPCC) guided the carbon stock assessment. This involves analyzing vegetation biomass, calculating carbon content based on vegetation type and density, and developing comprehensive carbon stock maps. Where direct field measurements are challenging, predictive modelling techniques are employed, utilizing correlations between vegetation indices and carbon sequestration potential. Data integration and analysis was conducted using advanced geospatial and statistical software. ArcGIS and QGIS were primary platforms for spatial data manipulation. Temporal change detection algorithms were particularly crucial in tracking vegetation dynamics over the specified research period.

The conversion factors and formulas used for these calculations are derived from (Mirbach 2000) and (Sajid Ali 2017). Initially, the total wood volume, measured in cubic meters (m^3), was calculated by converting the total vegetation cover (TVC) using the following equation:

$$TWV = TFC * 1.454 * 0.396$$

Where TWV denotes the total wood volume, TFC is the total vegetation cover, *1.454 is used to modify inside bole wood volume to include non-merchantable volumes such as bark, tops and branches, *0.396 is used to estimate the below-ground volume. Moreover, the TWV is converted into total dry matter biomass (DMB) using the below equation:

$$DMB = WV * 0.43$$

Where WV is the wood volume, *0.43 is used to convert the factor from wood to dry biomass. The DMB is then converted into total carbon (TC) by using the below equation:

$$TC = DMB * 0.5$$

Finally, the TC is converted to Carbon Dioxide using the equation below:

$$CO_2 = TC * 3.6667$$

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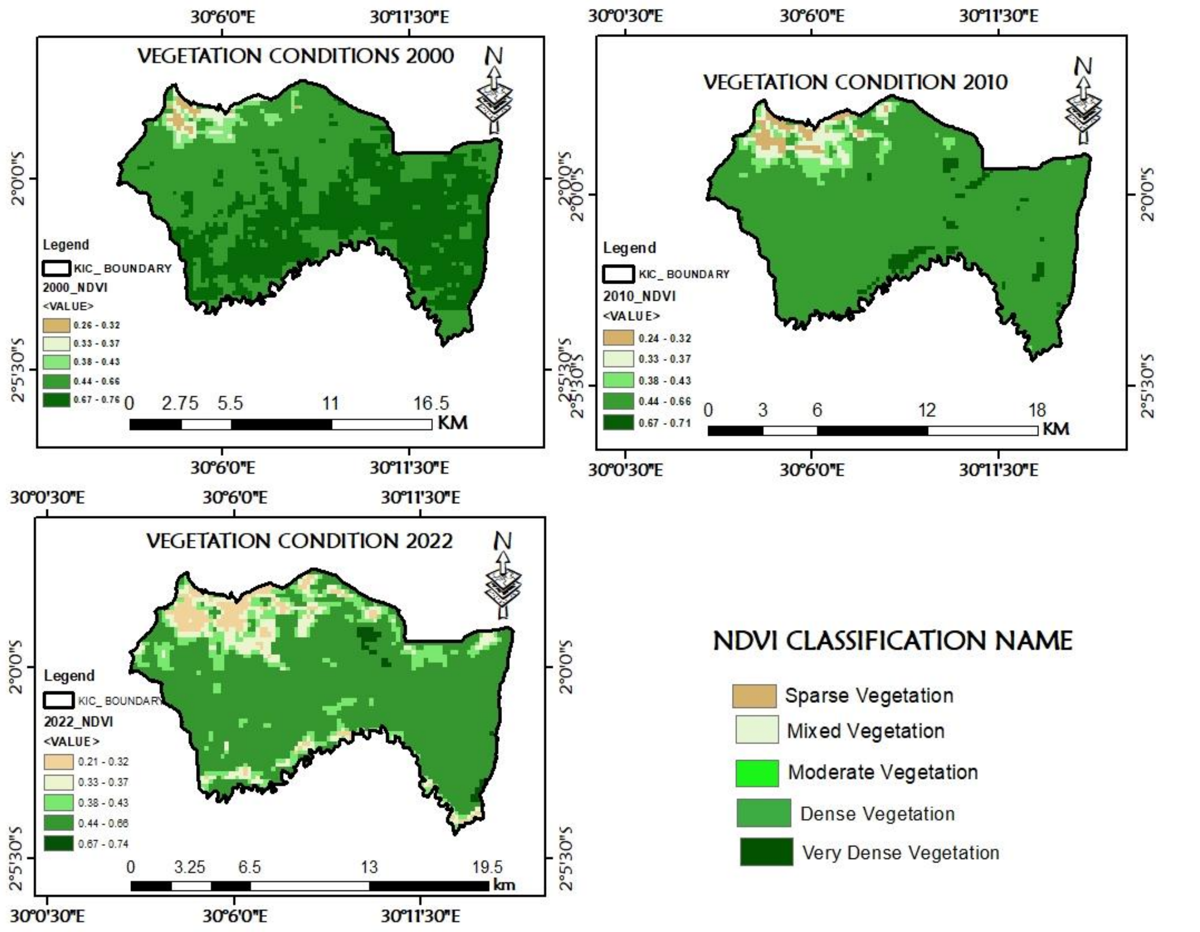
No	Description	Conversion factor
1	To modify inside bole wood volume to include non-merchantable volumes such as bark, tops and branches:	Multiply bole volume by 1.454
2	To estimate below-ground volume:	Multiply bole volume by 0.396
3	To obtain total wood volume:	Add 1 and 2
4	To convert wood volume (m3) to tonnes of dry matter biomass:	Multiply the wood volume by 0.43
5	To convert dry matter biomass to carbon	Multiply dry matter biomass by .5
6	To convert carbon to CO2 equivalent	Multiply carbon by 3.6667

RESULTS

Mapping and Quantifying Vegetation Cover Changes in Kicukiro District.

The analysis of the spatial and temporal distribution of vegetation in Kicukiro (Figure 3-6) revealed significant changes in vegetation condition trends occurring every ten years from 2000 using the Normalized Difference Vegetation Index (NDVI). The results from Figures 3-6 provide a detailed spatial-temporal analysis of vegetation conditions in Kicukiro district (2000, 2010, and 2022). The vegetation is classified using NDVI values, which are grouped into five categories: sparse vegetation (0.21–0.32), mixed vegetation (0.33–0.37), moderate vegetation (0.38–0.43), dense vegetation (0.44–0.66), and very dense vegetation (0.67–0.76). The data reveals significant changes in vegetation density over the 22-year period, reflecting broader environmental, trends in Rwanda.

Figure 3: Spatio-temporal Distribution of Vegetation Cover Status in Kicukiro District (2000 – 2022)



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In 2000, vegetation was widely distributed across the district, with a mix of all five classes. Very dense vegetation (NDVI 0.67–0.76) was concentrated in specific areas, likely in regions with minimal human disturbance, such as forests or protected zones. Moderate and dense vegetation (NDVI 0.38–0.66) covered larger areas, indicating healthy ecosystems with significant vegetation cover. Sparse and mixed vegetation (NDVI 0.21–0.37) were present but less dominant, suggesting limited areas of land degradation or agricultural activity. This period likely represents a time when traditional land use practices, such as subsistence farming and small-scale forestry, were still dominant, with less pressure from urbanization.

In 2010, the spatial distribution of vegetation cover, and classes began to shift, with a noticeable reduction in very dense vegetation. Areas previously classified as very dense vegetation transitioned to dense or moderate vegetation, indicating a loss of the highest vegetation density. Sparse and mixed vegetation expanded, particularly in areas closer to urban centres or agricultural zones, reflecting increased human activity and land use changes. The overall pattern suggests a fragmentation of previously continuous vegetation cover, with more patches of lower-density vegetation.

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Figure 4: Vegetation Conditions and Its Validation Using an Earth Observation Dataset in 2000

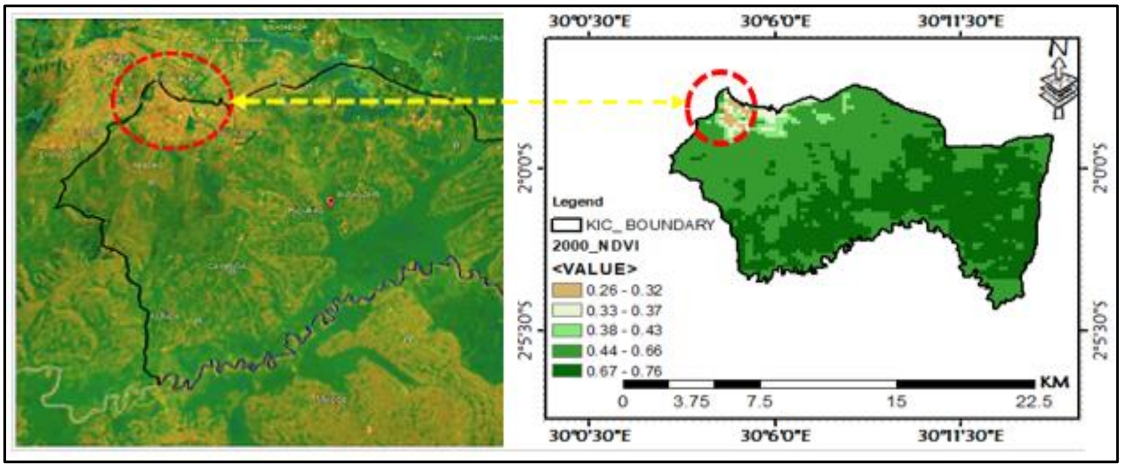

Figure 5: Vegetation Condition and Its Validation Using an Earth Observation Dataset in 2010

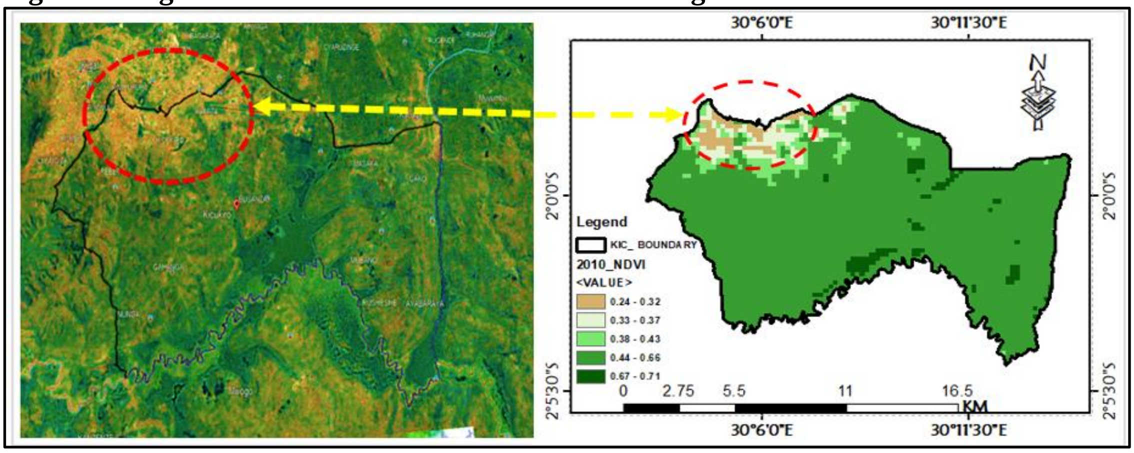

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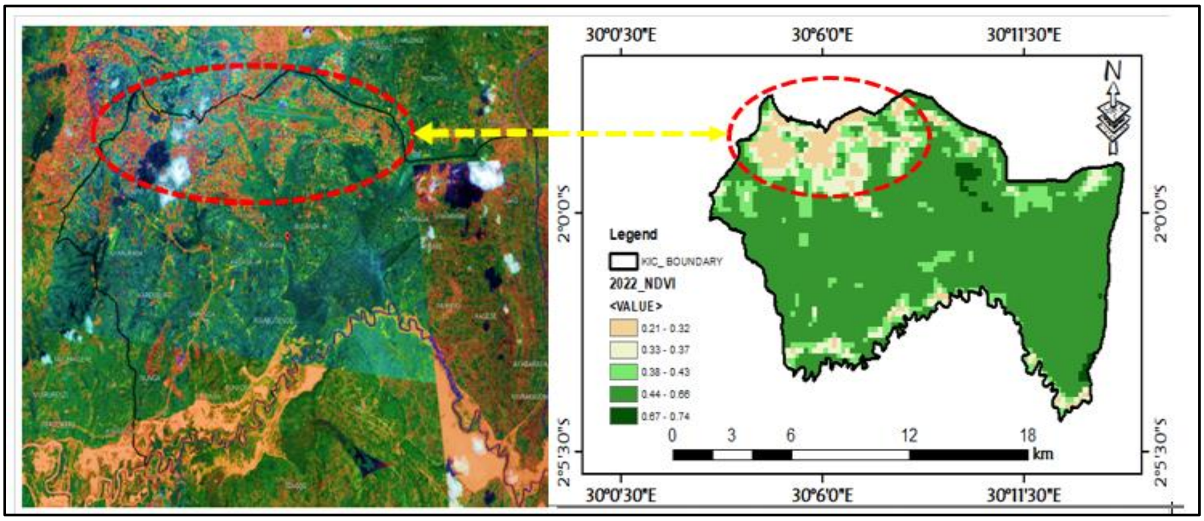
Figure 6: Vegetation Condition and Its Validation Using an Earth Observation Dataset in 2022



Overall, a clear spatial-temporal progression of vegetation change in the Kicukiro district has been depicted. The areas closer to Kigali and major roads experienced the most significant vegetation loss, with very dense and dense vegetation replaced by sparse and mixed classes. This reflects the impact of urban expansion and infrastructure development. However, some areas maintained moderate and dense vegetation over the 22-year period, indicating localized resilience to environmental and land use pressures. These areas may be critical for conservation efforts.

Temporal Dynamics of Vegetation Cover Changes

By 2010, sparse vegetation had begun to spread, growing from 5.63 km² (5%) in 2000 to 8.59 km² (7%). This shift seemed small at first, like weeds sprouting at the edges of a garden. But the trend was far from over. And by 2022, sparse vegetation had expanded dramatically to 14.11 km², claiming 12% of the district's area a staggering 150% increase in just 22 years. This surge was a sign of degradation. Since 2000, the mixed vegetation category was modest, covering 7.76 km² (6%). By 2010, it had swelled to 11.21 km² (9%), and by 2022, it spanned 21.15 km², making up 17% of Kicukiro's land. This increase of 13.39 km² was the largest gain among all vegetation types, suggesting a landscape in flux. Mixed vegetation, with its blend of trees and open spaces, was a sign that some degraded lands were regenerating, but it also hinted at fragmentation. Moderate vegetation increased from 16.5 km² (14%) in 2000 to 20.68 km² (17%) in 2010 and further to 31.1 km² (25%) in 2022. This represents an 88% increase over the 22-year period, the increase of moderate vegetation reflects natural regeneration in some areas or the implementation of reforestation and conservation programs.

However, it also indicates a decline in the quality of vegetation, as areas previously classified as dense or very dense transitioned to good vegetation. Dense vegetation covered 41.89km² (34%) of Kicukiro in 2000, making it one of the most important types. By 2010, it had increased slightly to 44.77 km² (37%), but by 2022, it had dropped sharply to 33.27 km² (27%) a loss of 8.62 km². However, the situation became tough on the class of very dense vegetation was the thickest and most valuable type of forest in Kicukiro. In 2000, it covered 50.33 km² (41%) almost half of the district. By 2010, it had dropped to 36.86 km² (30%) and by 2022, it had fallen further to 22.48 km² (18%) a massive loss of 27.85 km² in 22 years. The loss of very dense forests is the most serious problem. These forests store the most carbon, protect the soil, and support a wide range of animals and plants.

The detailed data on vegetation cover changes in Kicukiro District, combined with the spatial patterns observed in the maps, reveals a clear trend of degradation over the 22-year period.

Table 2: Comparison of Change in the Areal Estimates (in km^2) and Areal Share (in %) of Five Classes.

Vegetation types	2000		2010		2022	
	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Sparse vegetation	5.63	5	8.59	7	14.11	12
Mixed vegetation	7.76	6	11.21	9	21.15	17
Moderate vegetation	16.51	14	20.68	17	31.1	25
Dense vegetation	41.89	34	44.77	37	33.27	27
Very dense vegetation	50.33	41	36.86	30	22.48	18

The Carbon Stock Variations in the Kicukiro District

The assessment of carbon estimations in living vegetation cover in Kicukiro district indicated a notable decline in carbon storage trends, occurring at ten-year intervals based on an analysis of existing data. All the variables in the table TWV, DMB, TC, and CO2 are measured in tons. This consistency suggests that the analysis focuses on the mass-based assessment of vegetation and carbon stocks, which is a common approach in environmental studies and carbon accounting.

Table 3: TWV, DMB, TC, and CO2 Changes (in Tons)

Category Weight	2000	2010	2022	Change (2000–2010)	Change (2010–2022)
Total Wood Volume	8,313.53	7,174.46	5,198.10	-1,139.07	-1,976.36
Dry Matter Biomass	3,574.82	3,085.02	2,235.18	-489.8	-849.84
Total Carbon	1,787.41	1,542.51	1,117.59	-244.9	-424.92
Carbon Dioxide Storage	6,553.89	5,655.92	4,097.87	-897.97	-1,558.05

The analysis of vegetation and carbon storage in Kicukiro District from 2000 to 2022 shows a steady and worrying decline in forest resources and their ability to store carbon. The data focuses on four main categories namely Total Wood Volume (TWV), Dry Matter Biomass (DMB), Total Carbon (TC), and Carbon Dioxide Storage (CO_2). All these categories have seen significant reductions over the 22-year period.

To begin with, the Total Wood Volume (TWV), which represents the total amount of wood in the district, has decreased sharply. In 2000, TWV was 8,313.53 tons, but by 2010, it had dropped by 1,139.07 tons to reach 7,174.46 tons. The decline became even more severe in the next 12 years, with a further reduction of 1,976.36 tons, leaving only 5,198.10 tons in 2022. This trend suggests that deforestation and land-use changes have been accelerating, possibly due to changes in land use expansion. Similarly, the Dry Matter Biomass (DMB), which includes all organic matter from trees and other vegetation, also declined significantly.

In 2000, DMB was at 3,574.82 tons. By 2010, it had decreased by 489.8 tons, and by 2022, it had lost an additional 849.84 tons, leaving just 2,235.18 tons. This continuous drop reflects not only tree loss but also a reduction in shrubs and smaller plants, which could affect soil health and biodiversity. The Total Carbon (TC) stored in vegetation wood also showed a concerning trend. It was 1,787.41 tons in 2000 but dropped by 244.9 tons by 2010. By 2022, it had decreased further by 424.92 tons, ending at 1,117.59 tons. This reduction in carbon storage means that the district's vegetation is less capable of absorbing

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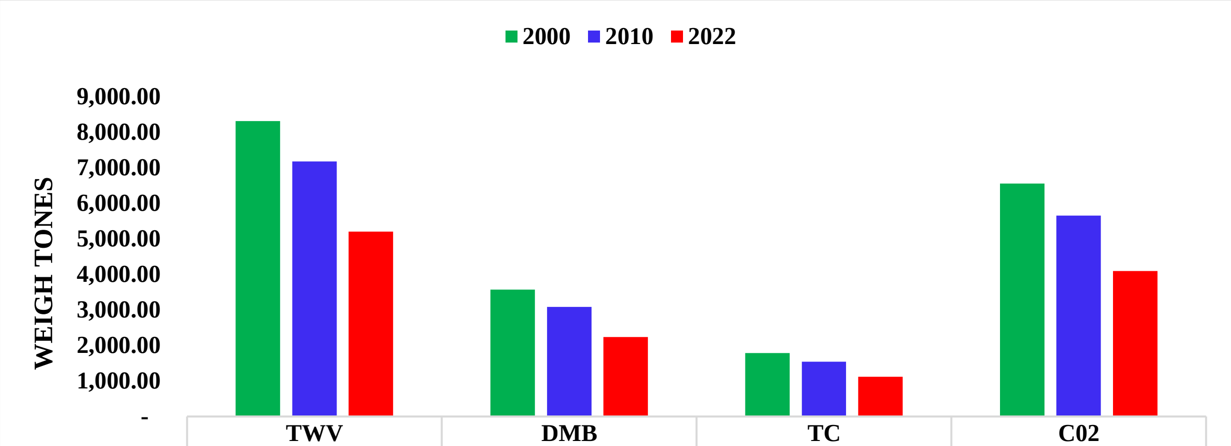
carbon dioxide from the atmosphere, potentially worsening local climate conditions. The most alarming decline was observed in Carbon Dioxide Storage (CO_2), which reflects how much CO_2 the vegetation can absorb and store. In 2000, the CO2 storage capacity was 6,553.89 tons. It fell by 897.97 tons by 2010 and dropped even more sharply by 1,558.05 tons by 2022, leaving just 4,097.87 tons. This loss of carbon storage capacity highlights the impact of deforestation and vegetation degradation on climate regulation. Less carbon storage means higher levels of CO_2 remain in the atmosphere, which could contribute to increased temperatures and altered rainfall patterns in the district.

Figure 7: Temporal Changes in TWV, DMB, TC and CO2 (2000-2022).



	TWV	DMB	TC	C02
2000	8,313.53	3,574.82	1,787.41	6,553.89
2010	7,174.46	3,085.02	1,542.51	5,655.92
2022	5,198.10	2,235.18	1,117.59	4,097.87

Figure 7 shows how Total Wood Volume (TWV), Dry Matter Biomass (DMB), Total Carbon (TC), and Carbon Dioxide Storage (CO2) have declined significantly from 2000 to 2022 in Kicukiro District. The bars for each category illustrate a steady decrease over the three time points: 2000 (green), 2010 (blue), and 2022 (red). This trend suggests a continuous loss of vegetation and carbon storage capacity and supports the previous analysis of significant environmental degradation in Kicukiro District

The Correlation between Vegetation Cover Dynamics and the Carbon Stock Variations in Kicukiro District.

Table 4.3 presents a comparative analysis of vegetation cover area and carbon stocks in Kicukiro District from 2000 to 2022. It highlights the changes (Quantity Loss) and decline percentages over two intervals: 2000–2010 and 2010–2022. The data shows a clear relationship between declining vegetation cover and reduced carbon stocks.

Table 4.3: Temporal Changes in Vegetation Cover and Carbon Stocks in Kicukiro District, Rwanda (2000–2022)

Category Weight	2000	2010	2022	Change (2000 - 2010)		Change (2010 - 2022)	
				Difference	% change	difference	% change
Vegetation cover area (km^2)	108.729	102.312	86.859	-6.42	-6%	-15.45	-15%
Carbon stocks (Tons)	6553.8934	5655.9161	4097.8714	-897.98	-14%	-1,558.04	-28%

Between 2000 and 2010, Kicukiro District experienced a 6% decline in vegetation cover, with the area shrinking from 108.729 square kilometres to 102.312 square kilometres. This loss of 6.42 square kilometres of green space was accompanied by a 14% decline in carbon stocks,

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which fell from 6,553.89 tons to 5,655.92 tons. Accelerated loss appeared in the period from 2010 to 2022 saw an even steeper decline in both vegetation cover and carbon stocks. The vegetation cover area decreased by 15.45 square kilometres, a 15% decline, while carbon stocks fell by 1,558.04 tons, a 28% decline. By 2022, the vegetation cover area had shrunk to 86.859 square kilometres, and carbon stocks had dropped to 4,097.87 tons. The decline in vegetation cover and carbon stocks in Kicukiro District has far-reaching implications for both the local environment and the global climate. Vegetation loss leads to reduced biodiversity, soil erosion, and disrupted water cycles, while the decline in carbon stocks exacerbates climate change by releasing stored carbon into the atmosphere.

Table 4. 4: The Correlation between Vegetation Cover Area and Carbon Stocks

Correlation between Vegetation cover change and carbon stock		
variables	**vegetation cover area**	**carbon stocks**
vegetation cover area	1	-0.9
carbon stocks	-0.9	1
	R = -0.9	

The correlation between vegetation cover and carbon stocks in Kicukiro District is striking. Statistical analysis reveals a strong negative correlation, with a coefficient of -0.9. This indicates that as vegetation cover decreases, carbon stocks also decline significantly. The strong correlation between vegetation cover and carbon stocks underscores the importance of addressing these issues together. Restoring vegetation cover can simultaneously enhance carbon sequestration, improve ecosystem health, and support sustainable development.

DISCUSSION

The findings from this study revealed significant changes in vegetation cover and carbon stocks, emphasizing a crucial trajectory in ecosystem dynamics and climate regulation. Notably, the transition from dense to less dense vegetation types indicates a critical deterioration of forest quality, which may not only signify underlying environmental stressors but also reflect ongoing anthropogenic influences such as land-use change, logging activities, and climate change impacts (D'Amato 2011), (Laurance 2014). The marked increase in sparse and moderate vegetation types for sparse and moderate vegetation highlights a worrying trend towards forest degradation, which directly correlates with increased vulnerability of ecosystems and declines in associated biodiversity (Newman 2019).

The implications of this study are profound. The decline in dense and very dense vegetation threatens essential ecosystem services that forests provide, such as biodiversity habitat, water regulation, and carbon sequestration (Murray 2017). (Schwartz 2019) documented similar findings in their analysis of forest fragmentation, indicating that dense canopy cover is integral to maintaining both ecological integrity and carbon storage capability. However, while this study noted a notable increase in good vegetation, earlier studies primarily focused on trends of forest loss without accounting for potential improvements in less dense but healthier forest types (Zhang 2020)

Comparatively, the decline in carbon stocks across different indicators such as wood volume, dry mass biomass, and total carbon further illustrates the critical relationship between vegetation density and carbon sequestration capacity. The strong correlation reinforces findings from earlier studies that connected forest density to carbon dynamics (Houghton 2005); (Ahrends 2010). The comprehensive scope of this research, particularly concerning the rapid decline in very dense vegetation, adds to the body of literature highlighting forest degradation's

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complex interplay with climate change adaptation and mitigation.

Possible reasons for observed similarities with previous studies may include consistent factors such as climate stressors, land utilization practices, and socio-economic developments that affect forest health globally. However, differences could stem from regional variances in ecological conditions, differences in measurement techniques, or contrasts in the timeframe of data collection. For instance, while some studies may have focused on longer-term trends, our short-term analysis underscores rapid changes that may not be captured in broader regional assessments. Regional factors such as local policies, community engagement in conservation efforts, and landscape management practices may also play a role in the differing outcomes between studies (Ahrends, 2010)

Uncertainties surrounding the implications of these findings arise from multiple dimensions, including limitations in remote sensing resolution, potential sampling biases, and the influence of data collection methodologies employed across different studies. These factors can yield variations in the extent to which vegetation and carbon dynamics are accurately represented. Additionally, climate variability and its indirect effects on local ecological systems can complicate the prediction of future trends. This study presents the pressing need for immediate conservation actions and policy interventions aimed at protecting remaining dense forest areas. The findings serve as a critical indicator of the potential for increased vulnerability to climate change impacts alongside diminished ecosystem services, necessitating integrated land management strategies that prioritize biodiversity, carbon storage, and resilience against ongoing environmental changes.

CONCLUSION

This study investigated vegetation cover changes, carbon stock variations, and their correlation in Kicukiro district over a 22-year period. The findings reveal significant ecological changes, with a notable decline in very dense and dense vegetation, which originally covered a large portion of the district but has now significantly reduced. Sparse and mixed vegetation, on the other hand, have expanded, indicating forest degradation driven by urbanization, agriculture, and infrastructure expansion. The spatial-temporal analysis showed that vegetation fragmentation occurred more frequently in areas closer to urban centres and major roads, highlighting the pressure exerted by human activities on natural ecosystems. Carbon stocks, including forest biomass and carbon storage capacity, have also declined substantially. The district's ability to store carbon has diminished in parallel with vegetation loss, with a notable reduction observed over the study period. This decline in carbon storage is a direct consequence of decreasing forest cover, as dense vegetation plays a crucial role in absorbing and storing carbon. The increasing dominance of sparse vegetation reduces the ability of the ecosystem to sequester carbon, thereby worsening climate change challenges in the region.

A strong negative correlation was observed between vegetation cover and carbon stocks, showing that as forested areas declined, carbon storage capacity also diminished. For instance, during the first decade of the study, a moderate loss of vegetation resulted in a measurable decrease in carbon stocks, while the more significant vegetation loss in the later years led to an even steeper decline. This trend highlights the accelerating impact of deforestation on carbon sequestration.

These findings emphasize the alarming trend of forest loss and its direct impact on climate regulation. The disappearance of dense forests not only affects biodiversity and ecosystem resilience but also weakens the district's ability to combat climate change. The study highlights the necessity of implementing reforestation programs, enforcing land-use policies, and promoting sustainable urban planning to mitigate the negative effects of vegetation loss.

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