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Multi-sensorial data-based assessment of artificial surfaces and vegetation index for the response to population expansion: A case study of Musanze Secondary City, Rwanda

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Abstract

Rapid population growth impacts land use, especially in Musanze, a secondary city. Therefore, our research aims for spatial analyses of the time series change in artificial surfaces and NDVI from 2000 to 2020. A multi-sensorial data-based analysis method assessed the changes and their effects on sustainability. Mathematical expression results reveal that (1) cultivated land increased from 64.6% to 68.9%, signifying a 4.3% rise. Conversely, forested areas decreased from 30.9% to 25.4%, reflecting a notable reduction of -5.5%. Water bodies saw a marginal uptick from 3.4% to 3.5%, a modest increase of 0.1%. Notably, artificial surfaces nearly doubled, soaring from 1.1% to 2.2%, representing an approximate 1.1% expansion in total coverage. (2) In 2000, sampled points demonstrated elevated vegetation indices, signifying that artificial areas were notably smaller than natural ones. Fast forward to 2020, after artificial surfaces had completely covered the sampled area, a significant and notable decrease in the vegetation index was observed, effectively halving the initial value recorded in 2000. In summary, urbanization can foster well-coordinated development; however, it poses a significant threat to natural areas as people migrate to urban centers. Therefore, to ensure a sustainable future for the population, we recommend enforcing zoning plans and building upward, using taller residential buildings instead of spreading out horizontally.

1. Introduction

Rapid urbanization in Africa, driven by population growth, creates complex and fragmented city landscapes, causing environmental degradation and urban poverty (Asabere et al., 2020). Primarily, People move to cities seeking better economic opportunities, improved access to services, and a higher quality of life. This rural-to-urban migration leads to urban expansion, resulting in the conversion of agricultural and forest land. As cities grow, they encroach upon surrounding rural areas, transforming once fertile agricultural land into urban developments. Additionally, the demand for resources such as timber and land for construction contributes to deforestation. This dual pressure of urban expansion and resource extraction accelerates agricultural and forest land reduction, ultimately impacting ecosystems and livelihoods dependent on these natural resources (Petrişor et al., 2020; Romano et al., 2017; Sumari et al., 2020).

Rwanda has experienced rapid urbanization driven by population growth and economic opportunities. This has led to the conversion of agricultural and forested land due to urban expansion (Aboh & Mutabazi, 2020; Gilbert & Shi, 2023; Nduwayezu et al., 2021). Remote sensing technologies, particularly GIS and NDVI analysis, have been instrumental in monitoring this transformation. GIS allows for the integration and analysis of spatial data, providing valuable insights into the spatial patterns and dynamics of urban growth. NDVI, a satellite-derived measure of vegetation health, has been crucial in assessing the impact of urban expansion on vegetation cover and health (Mugabowindekwe & Rwanyiziri, 2020; Rushema et al., 2020).

Various analyzed and cited studies have utilized Landsat data for monitoring purposes; however, it is worth noting that the outcomes can be influenced by the specific areas selected for supervised classification. To address this knowledge gap, this research has two primary objectives. First, it aims to track the two-decade

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urban expansion in Musanze City, from 2000 to 2020, using the latest classified data from Globe Land 30. Secondly, it seeks to establish a mathematical and visual correlation between urban expansion and the indices related to natural areas and vegetation cover. This comprehensive approach aims to provide a more robust understanding of urban growth dynamics and its impact on the environment in Musanze city.

2. Methods

2.1. Study area

Musanze is a phase I secondary city located in northern Rwanda, with its proximity to five dormant volcanoes. The district covers an area of 5,302 square kilometers and is divided into 15 sectors(Hirwa et al., 2023; Nzayisenga & Nzamwita, 2023). According to the detailed findings of the Fourth and Fifth Rwanda Population and Housing Census, from 2012 to 2022, its population grew from 368,267 to 476,522, increasing population density from 694 to 1,157 people per square kilometer. 68.9% of the total population are engaged in agriculture. Among them, 62.6% are engaged in crop farming, and 50.4% are engaged in Livestock husbandry (NISR, 2023; NISR & MINECOFIN, 2012).

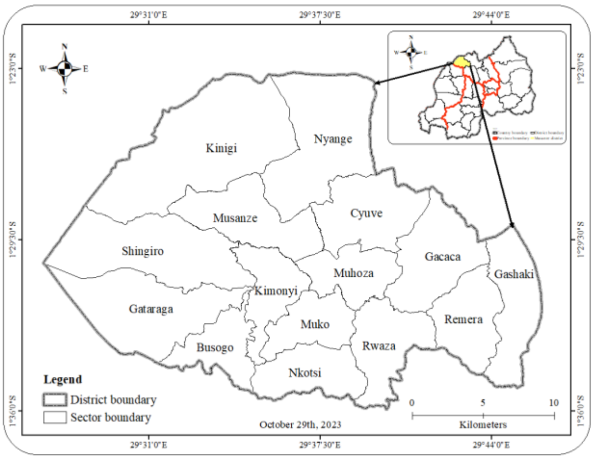

Figure 1. Administrative map of Musanze district

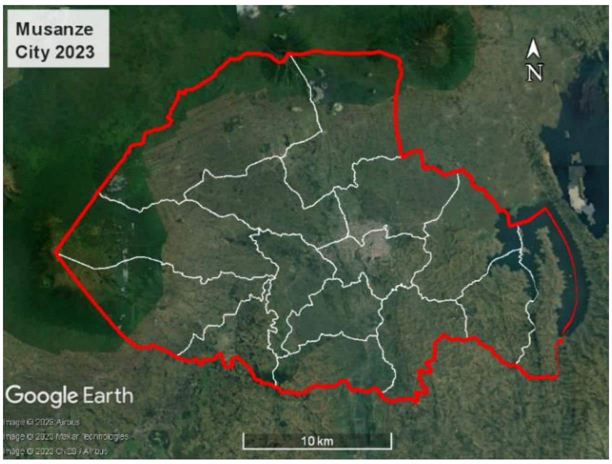

Figure 2. Google Earth image of Musanze (2023)

The topography of Musanze sets it apart from other secondary cities in Rwanda, as it is conducive to dense forests and receives higher levels of rainfall(Nakato et al., 2023; Twahirwa et al., 2023). This is attributed to its elevation range, which ranges from 4507 meters to 1535 meters above sea level. This geographical feature not only facilitates agriculture practices but also attracts a diverse range of people to the district, as it is known for its abundance of food resources compared to other areas.

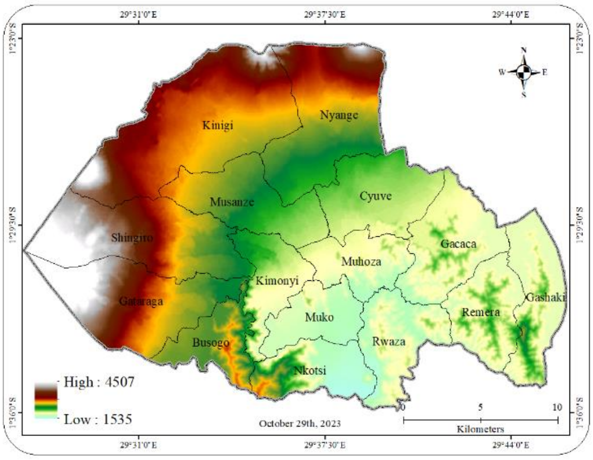

Figure 3. Elevation (meter) map of Musanze city

2.2. Data source and processing

This research has used only secondary data from different websites, as they are detailed in Table 1.

Table 1. Data source table

Data	Resolution	Source
LU/LC Data (GL30)	30 m	http://www.globalland cover.com
MOD13Q1 Vegetation Indices (NDVI)	250 m	https://ladsweb.moda ps.eosdis.nasa.gov/
SRTM Tile (DEM)	30 m	https://dwtkns.com/sr tm30m/
High-Resolution Image (2023)	-	Google Earth Pro 7.3.6.9345 (64-bit)

2.3. Data pre-processing and processing

Globeland30 is a 30-meter global land cover dataset that provides detailed and accurate information about land cover and land use on Earth(Wang et al., 2018). Regarding the nature and use of the study area, two maps of four classes (LU/LC) each were made using ArcMap 10.8 software.

The MOD13Q1 Vegetation Indices is a product of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard NASA's Terra and Aqua satellites used to generate the Normalized Difference Vegetation Index (NDVI)(Peng et al., 2021). It provides information on the density and health of vegetation across the Earth's surface by measuring the reflectance of photosynthetically active radiation. To generate NDVI maps for 2000 and 2000, using a raster calculator tool in ArcMap 10.8, an adjustment of 0.0001 was applied to each tile to standardise the values within a range of -1 to +1.

SRTM stands for Shuttle Radar Topography Mission, a space shuttle-based mission that collects topographic data on the Earth's surface(Mahmood et al., 2021). An SRTM Tile, often called a Digital Elevation Model (DEM), is a specific section of this data representing a geographical area. The tile was subject to a masking procedure specifically tailored to cover the Musanze area, and this same process was systematically implemented for all the data utilised in this research.

Under the guidance of ArcMap, a specific tool known as "Extract Multi Values to Points" was employed to gather data from 371 sample points. The attribute table subsequently established the correlation between NDVI and Globeland30 data. However, for this study, only 8 sample points representing areas converted to artificial surfaces were deliberately selected for analysis. It is worth noting that Globeland30 encompasses various land use classes, each distinguished by a unique code. For this study, the following codes were utilized: artificial surfaces (code 80), cropland (code 10), forest (code 20), and waterbodies (code 60). These codes will play a pivotal role in the subsequent analysis.

3. Results

Based on the analyzed data showing changes in land use over the past two decades, it is evident that there have been significant shifts in various land categories. Specifically, forested areas have experienced a reduction, while agricultural land and built-up areas have increased.

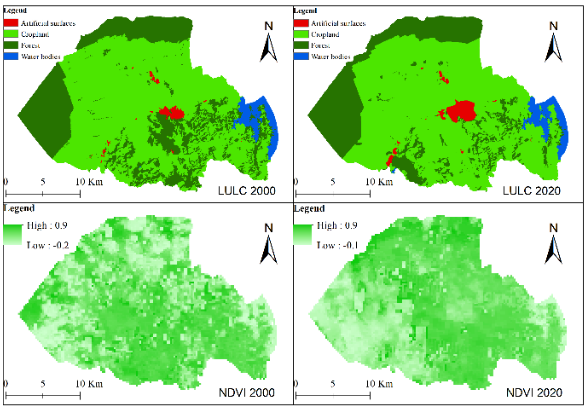

Figure 4. LULC and NDVI changes between 20 years

In terms of mathematical representation, the alterations in land use from 2000 to 2020 can be summarized as follows: The proportion of cultivated land rose from 64.6% to 68.9%, indicating a percentage increase of 4.3%. Meanwhile, forested areas experienced a decrease from 30.9% to 25.4%, accounting for a total reduction of -5.5%. Water bodies, on the other hand, exhibited a marginal increase from 3.4% to 3.5%, resulting in a slight overall uptick of 0.1%. Artificial Surfaces nearly doubled, surging from 1.1% to 2.2%. This equates to an approximate 1.1% surge in total coverage over two decades. Table 2 shows the change in square kilometers between two decades ago.

Table 2. LULC change from 2000 to 2020

Class name	2000 km²	2020 km²	Change km²
Cultivated land	341.21	363.61	22.39
Forest	163.48	134.23	-29.24
Water bodies	17.81	18.55	0.74
Artificial Surfaces	5.5	11.61	6.11

Figure 5 illustrates the percentage shift in land use within the Musanze district, presenting a comparative and visual representation of the changes over time.

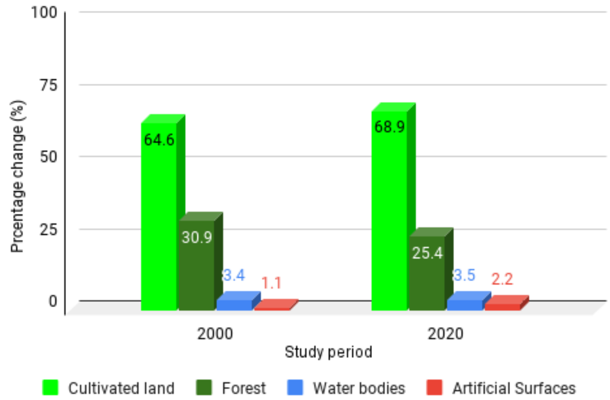

Figure 5. Comparative representation of the changes

4. Discussion

This study has revealed significant forest conversion around -29.24 km², which accounts for a total reduction of -5.5%, which is the source of increased severe effects of climate variability and climate change, specifically rising temperature and decrease of rainfall(Twahirwa et al., 2023). Therefore, 8-point samples from artificial areas were taken to increase the extraction accuracy for built-up areas and their influence on vegetation cover(Zheng et al., 2021). Half of the transitioned land to artificial surfaces (coded as 80) originated from agricultural areas (coded as 10), with 25% originating from forests (coded as 20). The remaining 25% remained consistent with its original coding (80).

Table 3. Correlation between LULC and NDVI

GL30_2000	NDVI_2000	GL30_2020	NDVI_2020
10	0.730	80	0.380
10	0.718	80	0.538
10	0.665	80	0.304
10	0.735	80	0.417
20	0.410	80	0.330
20	0.729	80	0.332
80	0.597	80	0.392
80	0.176	80	0.456

In 2000, Table 3 illustrates that most sampled points exhibited high vegetation indices, indicating that artificial areas were considerably smaller than natural ones. However, by 2020, after artificial surfaces had enveloped the entire sampled area, there was a stark and noteworthy reduction in the vegetation index, approximately halving the initial value recorded in 2000.

5. Conclusion

In summary, urbanization can foster development when well-coordinated; however, it currently poses a significant threat to natural areas as people migrate to urban centers, leading to an expansion of artificial surfaces for survival. Our study, utilizing globeland30 data spanning from 2000 to 2020, has unveiled adverse effects on forests due to the simultaneous increase in artificial surfaces and agriculture. Consequently, the region is now experiencing heightened temperatures and reduced rainfall. This alteration in land use also impacts vegetation cover, evident in the significant disparity in reflectance index between 2000 and 2020 in areas converted to artificial surfaces. To ensure sustainable livelihoods for the population, it is imperative to curtail horizontal urban sprawl. Instead, there should be a shift towards vertical housing solutions such as high-rise residential buildings. Equally important is the need for rigorous inspection and enforcement of zoning plans. Furthermore, it is crucial to provide support and incentives to encourage the adoption of sustainability measures. This multifaceted approach is essential to balance urban development and the preservation of natural ecosystems.

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