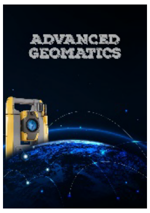
Advanced Geomatics

http://publish.mersin.edu.tr/index.php/geomatics/index

e-ISSN: 2791-8637



Evaluation of Artificial Surfaces and Vegetation Index Utilizing Multi-Sensor Data in Response to Population Growth: An Examination of Musanze Secondary City, Rwanda

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Keywords

Remote sensing,
Vegetation Index,
Population Expansion,
Forest Conservation,
Musanze City.

Research Article

Received : 28.11.2023
Revised : 29.01.2024
Accepted : 04.02.2024
Published : 31.03.2024

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Abstract

The issue of rapid population growth and its impact on land use has become a pressing concern, particularly in secondary cities such as Musanze. To address this issue, a research study was conducted with the aim of carrying out spatial analyses of time series changes in artificial surfaces and NDVI from the years 2000 to 2020. The study employed a multi-sensorial data-based analysis method to evaluate the changes and their effects on sustainability. (1) The mathematical expression results of the study reveal that during the period under consideration, 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) Furthermore, the study found that in 2000, sampled points demonstrated elevated vegetation indices, signifying that artificial areas were notably smaller than natural ones. (3) However, 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 conclusion, while urbanization can foster well-coordinated development, it poses a significant threat to natural areas as people migrate to urban centers. Therefore, to ensure a sustainable future for the population, the study recommends enforcing zoning plans and building upward, using taller residential buildings instead of spreading out horizontally.

1. Introduction

The continent of Africa has been experiencing rapid urbanization in recent years, largely driven by population growth. This trend has resulted in the creation of complex and fragmented city landscapes that pose significant challenges to sustainable development (Jiang et al., 2021; Wei et al., 2021). One of the major consequences of this urbanization is environmental degradation, which has a negative impact on the quality of life of urban dwellers and exacerbates the already fragile state of the natural environment. Additionally, rapid urbanization has contributed to the rise of urban poverty, which is a significant issue that needs to be urgently addressed (Asabere et al., 2020).

People often move to cities in search of better economic opportunities, improved access to services,

Cite this;

Gilbert, K. M., Shi, Y., & Isaac, N. (2024). Evaluation of Artificial Surfaces and Vegetation Index Utilizing Multi-Sensor Data in Response to Population Growth: An Examination of Musanze Secondary City, Rwanda. Advanced Geomatics, 4(1), 24-30.

and a higher quality of life. This rural-to-urban migration has several implications for the environment and the economy. Urban expansion leads to the conversion of agricultural and forest land, which can have a significant impact on the natural ecosystem (Radwan et al., 2019; Tilahun et al., 2022). As cities grow, they encroach upon surrounding rural areas, transforming once fertile agricultural land into urban developments. This conversion can have far-reaching effects, including loss of biodiversity, soil degradation, and water depletion. Additionally, the demand for resources such as timber and land for construction contributes to deforestation, which can have a devastating impact on the environment. Deforestation is often driven by urban expansion, as well as agricultural and industrial activities. As forests are cleared for development or agriculture, ecosystems are disrupted, and biodiversity is lost (Bonilla-Bedoya et al., 2020; McDonald et al., 2020). Deforestation can also lead to soil erosion and water pollution, impacting the livelihoods of people who depend on these natural resources. To sum it up, the dual pressure of urban expansion and resource extraction accelerates agricultural and forest land reduction, ultimately impacting ecosystems and livelihoods dependent on these natural resources. While urbanization brings many benefits, it is important to manage it in a way that minimizes its impact on the environment and the economy (Petrişor et al., 2020; Romano et al., 2017; Sumari et al., 2020).

Over the past few decades, Rwanda's population has been growing at a rapid pace. As a result, the country has experienced significant urbanization, which a combination of economic opportunities and population growth has driven. This urbanization has brought about several changes, including the conversion of agricultural and forested land into urban areas (Gasore et al., 2021; Tsinda et al., 2013). For instance, previously forested areas in and around Rwanda's cities have been cleared for the construction of roads, housing, and other infrastructure. Similarly, farmland has also been converted into residential and commercial areas to accommodate the growing population and business activities. While urbanization has brought about many benefits, such as increased economic opportunities and access to services, it has also had negative impacts on the environment (Li et al., 2017; Ramaiah & Avtar, 2019). The conversion of agricultural and forested land has resulted in deforestation and loss of biodiversity, which has had negative effects on the ecosystem and the people who depend on it. Therefore, it is important for Rwanda to balance the benefits of urbanization with the need to protect the environment and the livelihoods of rural communities. This can be achieved through sustainable land use practices and policies that promote the conservation of natural resources while also supporting economic development (Aboh & Mutabazi, 2020; Gilbert & Shi, 2023; Nduwayezu et al., 2021).

Remote sensing, Geographic Information Systems (GIS) technologies and Normalized Difference Vegetation Index (NDVI) analysis, have revolutionized the way we monitor and understand urban transformation. GIS allows for the integration and analysis of spatial data, such as land use, population density, and infrastructure, providing valuable insights into the spatial patterns and dynamics of urban growth. It helps urban planners and decision-makers to assess the impact of urbanization on the environment, identify potential areas for development, and plan for the provision of basic services. On the other hand, NDVI, a satellite-derived measure of vegetation health, has been crucial in assessing the impact of urban expansion on vegetation cover and health. By comparing the reflectance of near-infrared and visible light, NDVI can detect changes in plant health, which can indicate the effects of urbanization on vegetation (Mugabowindekwe & Rwanyiziri, 2020; Rushema et al., 2020).

It's worth noting that some studies analyzing land use changes have only utilized Landsat data for monitoring purposes. However, it's important to keep in mind that the results of these studies can be influenced by the specific areas selected and samples taken for supervised classification. To address this knowledge gap, this research has two primary objectives. First, it aims to track the two-decade urban expansion in Musanze City, from 2000 to 2020, using the freely available dataset 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. The Study Area Description

Located in Rwanda's northern province, Musanze has emerged as a thriving city center due to a combination of factors. The town is situated near the Rubavu border with the Democratic Republic of Congo, and the Cyanika border with Uganda, and is approximately 90 kilometers northwest of Rwanda's bustling capital city, Kigali. As such, Musanze serves as a crucial link between these regions, facilitating trade, commerce, and travel between these borders and the capital. Given its accessibility and central positioning, Musanze has established itself as a pivotal hub in the broader regional economic landscape, fueling its urbanization and growth. The city's proximity to the renowned Volcanoes National Park has spurred the growth of tourism-related industries, including hotels, lodges, and other tourist services (Trogisch & Fletcher, 2022). This has led to an increase in visitors, both domestic and international, and has been a catalyst for economic growth. Additionally, Musanze's position as a prominent market town for rural produce has attracted those seeking improved livelihoods, resulting in increased urbanization. The town also boasts various educational institutions and healthcare facilities, making it a desirable location for families in search of better opportunities. Musanze's allure is further enhanced by its enhanced infrastructure, government-backed urban initiatives, job prospects across diverse industries, and a vibrant social and cultural scene. These factors have collectively contributed to the town's evolution into a thriving urban hub in Rwanda. Furthermore, Musanze's pivotal geographic location plays a significant role in its importance, serving as a central point connecting various vital destinations (https://www.musanze.gov.rw/).

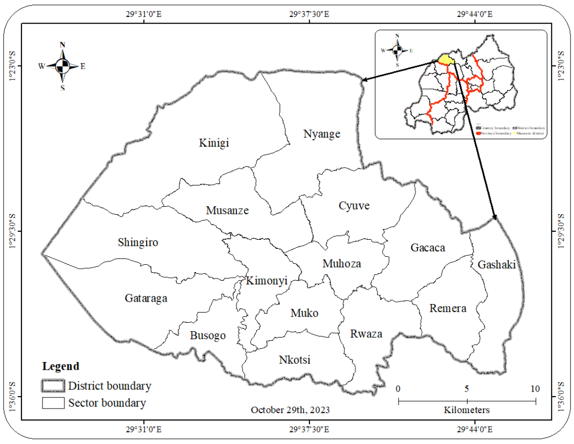

Figure 1. Administrative map of Musanze district.

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).

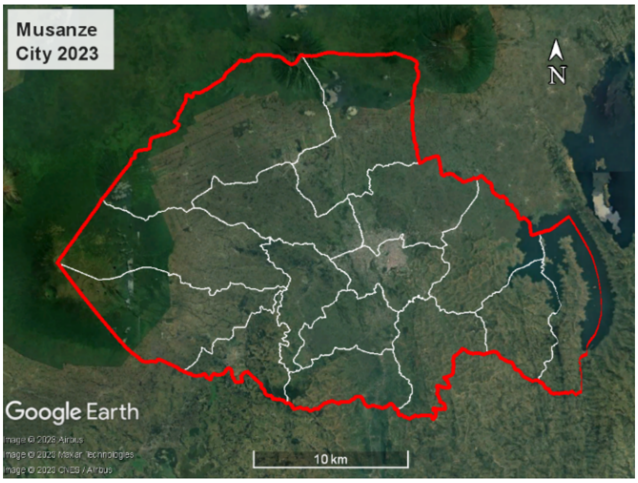

Figure 2. Google Earth image of Musanze (2023).

Musanze's unique topography distinguishes it from other secondary cities in Rwanda. Located in the northern province of the country, Musanze is nestled in the foothills of the Virunga Mountains, providing a perfect environment for lush and dense forests to thrive. The area also receives higher levels of rainfall compared to other regions, making it an ideal location for agriculture and biodiversity (Nakato et al., 2023; Twahirwa et al., 2023). The district's unique topography, characterized by an elevation range of 4507 meters to 1535 meters above sea level (Figure 3), plays a significant role in its popularity and prosperity. The varied altitude not only provides opportunities for agriculture practices but also creates a diverse range of habitats that support a wide range of flora and fauna. This, in turn, leads to an abundance of food resources, making the district an attractive destination for food enthusiasts and nature lovers alike. The district's distinct topography and natural resources set it apart from other areas and make it a remarkable place to visit.

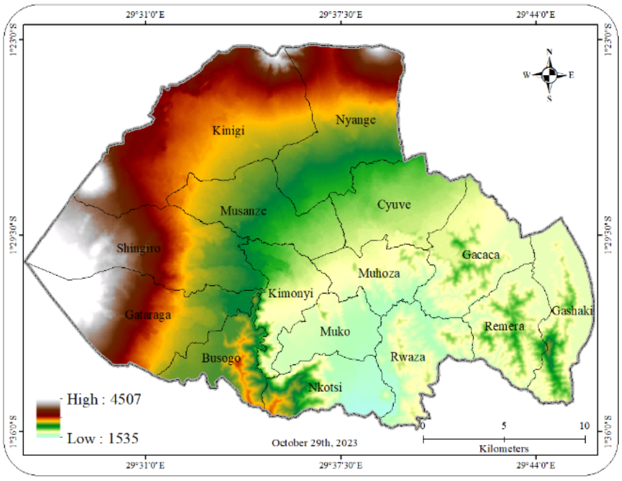

Figure 3. Elevation (meter) map of Musanze city.

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.globallandcover.com
MOD13Q1 Vegetation Indices (NDVI)	250 m	https://ladsweb.modaps.eosdis.nasa.gov/
SRTM Tile (DEM)	30 m	https://dwtkns.com/srtm30m/
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 have played a pivotal role in the subsequent analysis.

3. Results

After analyzing the data on land use changes over the past two decades, it is clear that there have been notable transformations in different land categories. The forested areas have undergone a significant reduction. This loss can be attributed to deforestation, urbanization, and expansion of agricultural land. On the other hand, agricultural land has increased, mainly due to the expansion of commercial farming and the conversion of forested areas into farmland. Additionally, built-up areas have also increased, indicating a rise in urbanization and infrastructure development. These changes in land use have significant implications for the environment, biodiversity, and human settlements, and require careful monitoring and management to ensure sustainable development.

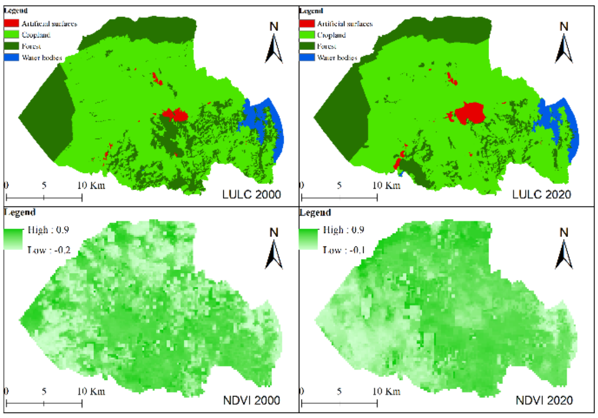

Figure 4. LULC and NDVI changes between 20 years.

A comprehensive analysis of the changes in land use from 2000 to 2020 reveals the following mathematical representation: The proportion of land under cultivation increased from 64.6% to 68.9%, indicating a percentage increase of 4.3%. This significant rise in cultivated land can be attributed to the expansion of agricultural activities in the region. On the other hand, the forested areas experienced a notable reduction, decreasing from 30.9% to 25.4%, accounting for a total reduction of -5.5%. This alarming decline in forested areas can be attributed to deforestation, wildfires, and other human activities that adversely affect the environment. Water bodies, however, experienced a marginal increase from 3.4% to 3.5%, resulting in an overall uptick of 0.1%. This slight increase in water bodies is a positive sign and indicates that the region is taking steps towards preserving its water resources. Artificial Surfaces nearly doubled from 1.1% to 2.2%, indicating an approximate 1.1% surge in total coverage over two decades. This surge in artificial surfaces is a cause for concern as it indicates urbanization, industrialization, and infrastructure development. Table 2 provides a detailed overview of the changes in square kilometers between two decades ago, thereby providing more insights into the changes in land use over the years.

Table 2. LULC change from 2000 to 2020.

Class name	2000 km^2	2020 km^2	Change km^2
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

The visual representation in Figure 5 showcases the changes in land use within the Musanze district over 2 decades from 2000 to 2020, highlighting the percentage shift in different land uses. The graph provides a comparative analysis of land use patterns, enabling a more detailed understanding of the changes that have occurred in the district.

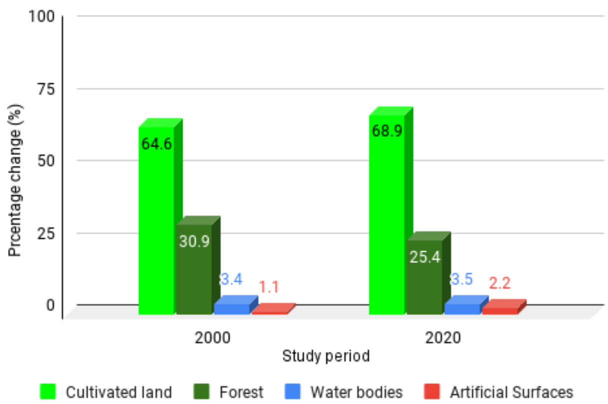

Figure 5. Comparative representation of the changes.

4. Discussion

The findings of the study indicate that there has been a significant conversion of forested areas, amounting to approximately -29.24 square kilometers. This conversion has resulted in a total reduction of forest cover by -5.5%, which has contributed to the exacerbation of the severe effects of climate variability and climate change. Specifically, the conversion of forested areas has led to an increase in temperature and a decrease in rainfall, which has had a significant impact on the local ecosystem and the communities that depend on it (Twahirwa et al., 2023). To improve the accuracy of extracting built-up areas and their impact on vegetation cover, 8-point samples were collected from artificial areas. This approach helps to ensure that the extraction process is more precise and reliable (Zheng et al., 2021). It is worth noting that 50% of the land that has been converted to artificial surfaces (coded as 80) was previously agricultural land (coded as 10), while 25% of it was originally forested areas (coded as 20). The remaining 25% of the converted land retained 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

According to the data presented in Table 3, it can be observed that in the year 2000, the majority of the sampled locations had high vegetation indices, which suggested that the artificial areas were significantly smaller in comparison to the natural ones. However, as of 2020, there has been a drastic change in the situation, with the entire sampled area now being covered by artificial surfaces, resulting in a remarkable reduction in the vegetation index. In fact, the vegetation index value has been reduced by almost half of what it was in the year 2000, indicating a significant loss of greenery in the area. This change is a clear demonstration of the impact of human activities on nature over time.

5. Conclusion

As our world continues to urbanize, it is essential to understand the impact that this process has on the environment and human well-being. While urbanization can lead to economic development and social progress, it can also pose significant threats to natural areas if not well-managed. Our study, which analyzed globeland30 data from 2000 to 2020, has revealed that urbanization in our region has resulted in the expansion of artificial surfaces and agriculture, which has had detrimental effects on forests and vegetation cover. The increase in artificial surfaces has altered the landscape and disrupted natural ecosystems, resulting in higher temperatures and reduced rainfall. The conversion of forested areas to urban landscapes has also led to a significant reduction in vegetation cover, which has negatively impacted the reflectance index in these areas. These changes have been observed over the last 20 years and are a cause for concern as they have long-term implications for the environment and human well-being.

To address these challenges, we need a multifaceted approach that balances urban development with the preservation of natural ecosystems. One of the most effective ways to achieve this is to curtail horizontal urban sprawl and instead shift towards vertical housing solutions such as high-rise residential buildings. This approach not only helps to preserve natural areas but also promotes sustainability and efficient land use. In addition to this, we need to have rigorous inspection and enforcement of zoning plans to ensure that land use is sustainable and does not negatively impact natural ecosystems. Providing support and incentives to encourage the adoption of sustainability measures will also go a long way in addressing these challenges. Overall, our study highlights the need for a coordinated and sustainable approach to urbanization. By balancing economic development with environmental conservation, we can create a better future for ourselves and the planet.

Acknowledgments

We extend our sincere gratitude to the proprietors of the data utilized, the authors referenced in this research, and lastly, the reviewers and organizers whose invaluable contributions were instrumental in facilitating the publication of our study.

Funding

This study was funded by Shenzhen Planning and Land Development Research Center. "Case Analysis of Urban Planning and Construction of Global Cities" (2021FY0001–2588).

Author contributions

Katabarwa Murenzi Gilbert: Methodology, formal analysis, visualization, and draft writing. **Yishao Shi**: Conceptualization and supervision. **Nzayisenga Isaac**: Draft review and final editing.

Conflicts of interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

Research and publication ethics were complied with in the study.

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