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GIS-Based Multicriteria Analysis for Identifying Optimal Sites for Cassava Cultivation in Walungu, DRC

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Abstract: According to the UN's Food and Agriculture Organization (FAO) and the World Food Programme (WFP), over 27.3 million people in the Democratic Republic of Congo (DRC) suffer from acute food insecurity, with nearly seven million facing emergency hunger levels. Despite the country's immense agricultural potential, these figures highlight the challenges faced by the DRC in ensuring food security. Cassava, the staple food for about 70% of the population, holds great potential to combat hunger and improve agricultural productivity. This study aims to support ongoing efforts by developing a spatial decision-making tool for identifying optimal cassava cultivation sites in Walungu using Geographic Information Systems (GIS) and multicriteria analysis (MCA). By incorporating key biophysical factors such as water availability, temperature, slope, and soil nutrients, the results provide a valuable framework for enhancing cassava production in the region. This tool can assist farmers and policymakers in making informed decisions to address food insecurity in the DRC.

Keywords: Food insecurity, cassava, GIS, DRC, Walungu, food security, multicriteria analysis

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1 Introduction

The Democratic Republic of Congo (DRC), located at the heart of the African continent, faces a persistent food crisis that threatens the security and well-being of its population [1]. Despite its vast agricultural potential, with an estimated cultivable area of 75 million hectares, of which less than 10 million hectares are utilized [2][3], and remarkable ecological diversity, the country continues to struggle with chronic underproduction due to various socio-economic and environmental challenges.

According to the United Nations Food and Agriculture Organization (FAO) and the World Food Programme (WFP), more than 27.3 million people in the DRC—approximately one in three—are affected by acute food insecurity, with nearly seven million people suffering from emergency levels of hunger [4]. This staggering statistic positions the DRC as one of the nations with the most urgent need for food security assistance [5]. Given its substantial agricultural potential, the DRC should be able to not only feed its population but also export its surplus crops [4][6][7].

Amid this challenge, addressing the potential of key staple crops is crucial. Cassava (Manihot esculenta), a strategic staple crop in the DRC, plays a central role in the country's food security. It is consumed by around 70% of the population in various forms, such as chikwange, foufou, and porridge [8][9]. Cassava has also proven effective in stabilizing food security by filling seasonal food gaps and serving as a reserve during crop failures [10]. Despite its importance, cassava production in the DRC remains underexploited, largely due to inefficient farming practices and limited access to advanced technologies [11].

The territory of Walungu, located in the South Kivu province, reflects the broader agricultural challenges of the DRC. More than 80% of the local population depends on cassava as a staple food, yet the growing food demand coupled with declining agricultural productivity exacerbates food insecurity in the region [12]. As the population continues to grow, agricultural production declines, widening the gap between food supply and demand. Although several studies have already been conducted to increase cassava production [13][14], none have so far focused on identifying the exact locations of suitable sites for cassava cultivation in this specific territory to provide clear guidance for policymakers.

Geographic Information Systems (GIS), combined with Multi-Criteria Analysis (MCA), offer a promising solution to address this issue. While GIS is a powerful tool for spatial mapping and simple analyses, it is insufficient for making complex decisions involving multiple criteria [15]. MCA allows for the systematic structuring and evaluation of these criteria, turning GIS into an essential decision support system [16].

This study aims to identify areas within Walungu territory with the highest potential for cassava cultivation using GIS-based multi-criteria decision analysis. By combining precise spatial data with rigorous multi-criteria evaluation, this research seeks to map and assess land suitability, providing strategic recommendations for farmers and policymakers to enhance cassava production. We hypothesize that suitable areas for cassava cultivation can be identified through this approach, which could help bridge the food deficit and improve food security in the region [17].

The study area is located between latitude 2°38'S and longitude 28°40'E in the eastern Democratic Republic of Congo (DRC) [18]. Walungu territory is a decentralized entity within the South Kivu province, situated in the eastern part of the DRC. It is one of the eight territories that make up the province of South Kivu, falling within the larger geographical area known as Bushi. The landscape of Walungu is rugged and consists primarily of hills, plateaus, and lowlands, with valleys or marshes traversed by rivers. The altitude in this region ranges from 1000 meters in Kamanyola to 2400 meters at Mulumemunene [19].

Walungu territory is bordered by several administrative and natural boundaries: to the north, it is bordered by Kabare territory; to the south by Mwenga territory; to the east by the Bafulero Collectivity (Uvira territory), the Ruzizi River, and the countries of Rwanda and Burundi; and to the west by the territories of Shabunda and Kalehe (Figure 1).

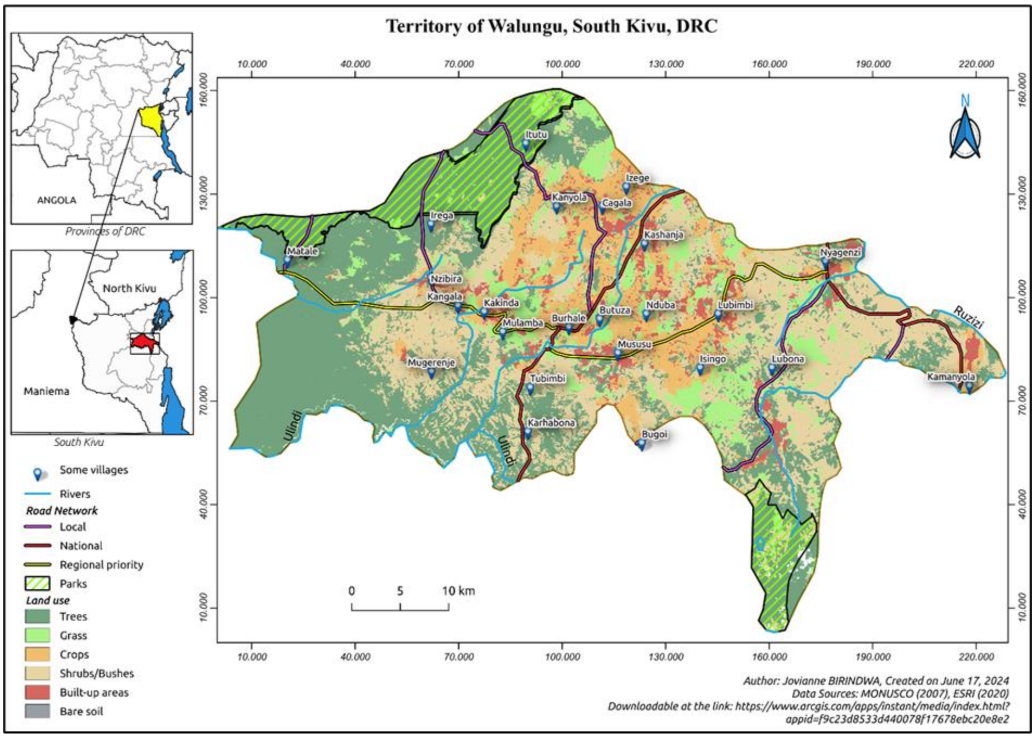

Figure 1. Map of the study area, Walungu

2 Materials and Methods

2.1 Materials

The materials used in this study consisted of both data and software. The integration of spatial data, including satellite imagery and alphanumeric data specific to cassava cultivation in the Walungu territory, was conducted following the guidelines provided by the FAO [20].

The datasets used included information on water availability, oxygen levels, nutrients, water retention capacity, soil texture, land use, annual average temperature, and topography. The processing of this data was done using QGIS, GRASS, and GDAL software. These tools facilitated data quality verification, cleaning, and reprojection into a unified coordinate system, ensuring the necessary spatial consistency for a thorough analysis [21].

Data on localities, roads, parks, and land use were obtained from MONUSCO and ESRI [22], provided in shapefile and raster formats, with updates from 2007 and 2020. These datasets were critical for generating maps to determine the suitability of land for cassava cultivation.

Annual precipitation data, sourced from the WorldClim database in raster format [23], were essential for assessing water availability for cassava cultivation. In addition, annual average temperature data from WorldClim were utilized to determine optimal temperature conditions for cassava growth. Soil properties, including organic nutrients such as nitrogen, and pH levels were obtained from the SOTERCAF database [24], with the data provided in shapefile format. Soil texture, which influences water retention capacity, and soil depth, critical for cassava root development, were also sourced from SOTERCAF.

Topographic data, particularly altitude, were obtained through the STRM Downloader plugin in QGIS, using raster data to analyse the elevation, which impacts temperature and moisture retention. A factor-weighting matrix was developed using data from previous studies, specifically referencing sources [20], [25], and [26]. This matrix was compiled in Word format and used for a multi-criteria analysis map, which combined the weighted factors. The map was generated using data on parks and land use provided by MONUSCO and ESRI.

2.2 Methods

Spatial decision-making problems inherently exhibit characteristics of multi-criteria problems, making it essential to approach them using Multi-Criteria Analysis (MCA) [27]. MCA provides a robust methodological framework by integrating multiple, often conflicting, criteria, allowing for a more holistic and evidence-based decision-making process in spatial analysis [28].

The methodology for this study was designed to leverage the capabilities of Geographic Information Systems (GIS) and MCA. Central to this analysis are the Analytic Hierarchy Process (AHP) and the Weighted Sum Method (WSM), which are widely recognized as key analytical tools for structuring and solving complex decision problems involving multiple criteria [29]. AHP, developed by Saaty in 1980 [29], enabled the calculation of the criteria weights and their hierarchical arrangement, providing critical insights into the interdependence of the factors. This method is particularly useful for structuring problems that require a breakdown into a hierarchy of criteria and sub-criteria, facilitating better prioritization based on pairwise comparisons.
Simultaneously, the Weighted Sum Method (WSM), recommended for its simplicity and effectiveness in multi-criteria evaluations by Fishburn in 1967 [30] and MacCrimmon in 1968 [31], facilitated the combination of criteria into factors and constraints to generate the final output. WSM operates by assigning weights to each criterion and summing their contributions to produce a final suitability score for each spatial unit.
In this context, the final suitability score (S) was calculated as a linear combination of the values of the factors (x_i), weighted by their respective weights (w_i), and multiplied by the product of the constraints (c_j), as shown in the following equation:

$$S = \sum_{i}^{n} w_i x_i * \prod_{j} c_j$$

where each factor is a continuous variable that either enhances or limits the suitability of a decision, while the constraints are binary variables that spatially restrict the decision-making process (e.g., avoiding protected areas). This formula enabled the model to account for both positive factors and spatial restrictions simultaneously.

In the context of this study, AHP was employed to derive weights for factors such as precipitation, temperature, soil nutrients, texture, and depth, all of which are critical for cassava cultivation. These factors were prioritized based on expert input and literature, ensuring that the most relevant conditions for cassava production were accurately represented in the model. Additionally, MCA was applied within a Spatial Decision Support System (SDSS) framework to identify the most suitable areas for cassava cultivation in Walungu, following similar approaches used in agricultural land evaluation [32].

The combined approach of GIS and MCA allowed for the integration of both spatial and non-spatial data, leading to the creation of land suitability maps. These maps are crucial for visualizing and analysing the potential agricultural zones that meet the ideal criteria for cassava production.

This methodological framework is particularly valuable because it accommodates both qualitative and quantitative data, thus enabling a comprehensive evaluation of the environmental and topographical factors that influence cassava cultivation. Furthermore, the use of AHP ensured that each criterion's contribution to the overall decision-making process was thoroughly evaluated, while the WSM enabled the seamless integration of these criteria into a coherent decision-making tool.

2.2.1 Selection and Classification of Criteria

The selection and classification of criteria is a fundamental component of the multi-criteria analysis (MCA) used to evaluate land suitability for cassava cultivation in the Walungu territory. The criteria were chosen based on both the methodological guidelines provided by the Food and Agriculture Organization (FAO) [20] and insights gathered from subject-matter experts.

Selection of Criteria

The criteria included in this study were identified for their significance in determining the suitability of land for cassava farming. Six factors were selected, each of which plays a vital role in influencing the agricultural viability of the territory. These factors are water availability, which refers to the annual precipitation levels and is critical for ensuring adequate water supply for cassava cultivation; temperature, as cassava requires specific temperature ranges for optimal growth; nutrient presence, particularly nitrogen and pH levels, as the availability of essential soil nutrients directly influences plant growth; nutrient retention capacity, which includes the soil's cation exchange capacity (CEC), determining the soil’s ability to retain and exchange essential nutrients ; water retention capacity,

determined by the soil texture, which affects the ability of the land to retain moisture; and slope, which impacts both water runoff and soil erosion.
These six factors were categorized as continuous variables that either enhance or constrain the suitability of a given location for cassava cultivation. Additionally, two binary constraints were considered: the presence of built-up areas and protected zones. These constraints were included to account for land-use restrictions, excluding areas that are unsuitable for agriculture, such as urbanized regions and national parks.

Classification and Normalization of Criteria

After selecting the relevant criteria, a classification process was conducted to categorize the suitability of each factor for cassava cultivation. For each factor, four suitability classes were defined: highly suitable, moderately suitable, marginally suitable and least suitable.
In contrast, the constraints (built-up areas and protected zones) were classified into two categories: Suitable and Unsuitable. This classification scheme allows for the differentiation of areas based on their degree of suitability for cassava cultivation.
Given the differences in measurement units among the selected criteria, normalization was necessary to standardize the data on a common scale. Normalization ensures that factors measured in different units (e.g., millimeters for precipitation, degrees Celsius for temperature) are made comparable. This was done using the Weighted Linear Combination (WLC) method, which involved scaling the factors on a continuous suitability scale from 0 (least suitable) to 4 (highly suitable).
The classification process is detailed in Table 1 and Table 2.

Table 1. Factors Classification for Land Suitability Analysis

Factors			**Suitability classes**			
Land quality		**Unit**	**Highly Suitable**	**Moderately Suitable**	**Marginally Suitable**	**Least Suitable**
			100 %	**80 %**	**50 %**	**20 %**
Water availability		mm	1100 - 1500	900 - 1100 1500 - 2500	500 - 900 2500 - 4000	< 500 > 4000
Temperature		°C	> 25.6	24.7- 25.6	23.5-24.7	< 23.5
Nutrient presence	N	$g\ kg^{-1}$	> 4	3.0 - 4.0	2.0 - 3.0	< 2
	pH	$g\ kg^{-1}$	6.1- 7.3	7.4 - 7.8 5.1 - 6.0	7.9 - 8.4 4.0-5.0	> 8.4 < 4.0
Nutrient retention capacity		$cmol_c\ kg^{-1}$	> 30	21 - 30	11 - 21	< 11
Water retention capacity		-	V	F, Z	M	C
Slope		%	< 5	5 - 12	12 - 20	> 20

According to the FAO standard: C-coarse, M-medium, Z-medium fine, F-fine and V-very fine.

Table 2. Factors Classification for Land Suitability Analysis

Constraint	Status	Value	Suitability Classes
Protected zones	Outside parks	1	Suitable
	Inside parks	0	Unsuitable
Built-up areas	Outside built-up areas	1	Suitable
	Inside built-up areas	0	Unsuitable

The normalized factors were then integrated into the MCA process using the Weighted Linear Combination (WLC) approach.

3.2.2. Assigning Criteria Weights

The Weighted Linear Combination (WLC) method facilitates the assignment of weights to each factor involved in the aggregation of criteria, enhancing the precision of assessing their relative importance in the decision-making process [33][34]. This is particularly useful in this land suitability analysis, where the objective is to prioritize factors that influence cassava cultivation in the Walungu region.
To determine the relative importance of each factor, expert consultations were conducted, and the Analytic Hierarchy Process (AHP) was applied to quantify these judgments. A pairwise comparison matrix AA was established based on Saaty's scale [35], which uses a nine-point scale to compare the relative importance between two factors:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}$$

Where each element a_{ij} represents the comparison between factors *i* and *j*. The values are assigned as follows:

- $a_{ij} = 1$ if factors *i* and *j* are of equal importance.
- $a_{ij} > 1$ if factor *i* is more important than *j*, with higher values indicating greater relative importance.
- $a_{ij} < 1$ if factor *i* is less important than *j*, with values closer to 1/9 indicating minimal importance.

Given that the matrix is reciprocal, $a_{ij} = 1/a_{ji}$, and all diagonal elements are $a_{ii} = 1$, ensuring consistency in the matrix.
The eigenvector *w*, which results from the matrix calculation, provides the relative weights of the factors:

$$w = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \vdots \\ w_n \end{bmatrix}$$

These normalized weights w_i are then applied to evaluate the contribution of each factor to the overall suitability for cassava cultivation.

Table 3. Weighting of Factors for Cassava Cultivation (1/2)

Factors	**Water Availability**	**Temperature**	**Slope**	**Nutrient Presence**	**Nutrient Retention Capacity**	**Water Retention Capacity**
Water Availability	1	5	5	7	7	9
Temperature	1/5	1	1	5	5	7
Slope	1/5	1	1	5	5	7
Présence en nutriments	1/7	1/5	1/5	1	1	3
Capacité de rétention des nutriments	1/7	1/5	1/5	1	1	3
Capacité de rétention d'eau	1/9	1/7	1/7	1/3	1/3	1

Table 3. Weighting of Factors for Cassava Cultivation (2/2)

Factors	Water Availability	Temperature	Slope	Nutrient Presence	Nutrient Retention Capacity	Water Retention Capacity	Weight
Water Availability	0,557	0,663	0,663	0,362	0,362	0,300	**0,48**
Temperature	0,111	0,133	0,133	0,259	0,259	0,233	**0,19**
Slope	0,111	0,133	0,133	0,259	0,259	0,233	**0,19**
Nutrient Presence	0,080	0,027	0,027	0,052	0,052	0,100	**0,06**
Nutrient Retention Capacity	0,080	0,027	0,027	0,052	0,052	0,100	**0,06**
Water Retention Capacity	0,062	0,019	0,019	0,017	0,017	0,033	**0,03**
Total	**1**	**1**	**1**	**1**	**1**	**1**	**1**

The pairwise comparison resulted in the following weight vector for the biophysical factors:

$$w = \begin{bmatrix} 0.48 \\ 0.19 \\ 0.19 \\ 0.06 \\ 0.06 \\ 0.03 \end{bmatrix}$$

3.2.3. Criteria combination

This phase represents the final methodological step, focusing on the aggregation of normalized factors. Conducted entirely in QGIS, the weighted sum method was applied to combine the factors and generate results. Two scenarios were created: one without constraints, and the other incorporating constraints.

In the first scenario, the factors were combined using the following mathematical expression:

$$S=(WA\times 0.48)+(T\times 0.19)+(S\times 0.19)+(N\times 0.06)+(C\times 0.06)+(WR\times 0.03)$$

Where:

- WA is Water availability,
- T is temperature,
- S is slope,
- N is nutrient presence,
- C is nutrient retention capacity,
- WR is water retention capacity.

In the second scenario (with constraints), the factors were combined with land-use and protected area constraints. The mathematical expression is as follows:

$$S=[(WA\times 0.48)+(T\times 0.19)+(S\times 0.19)+(N\times 0.06)+(C\times 0.06)+(WR\times 0.03)]\times L\times Z$$

Where:

- L represents land-use constraints,
- Z represents protected area constraints.

These combinations helped produce suitability scores, accounting for both environmental factors and land-use limitations.

3 Results and Discussion

Figures 2(a-f) highlight the biophysical factors considered crucial for cassava suitability in Walungu. These include water availability, temperature, slope, nutrient presence, and the capacity of the soil to retain both water and nutrients. The region's moderate rainfall, compatible with cassava's drought-tolerant characteristics, plays a crucial role. Other factors such as slope and temperature also have a significant influence on the overall suitability of the land. These factors collectively contribute to identifying the most suitable areas for cassava cultivation.

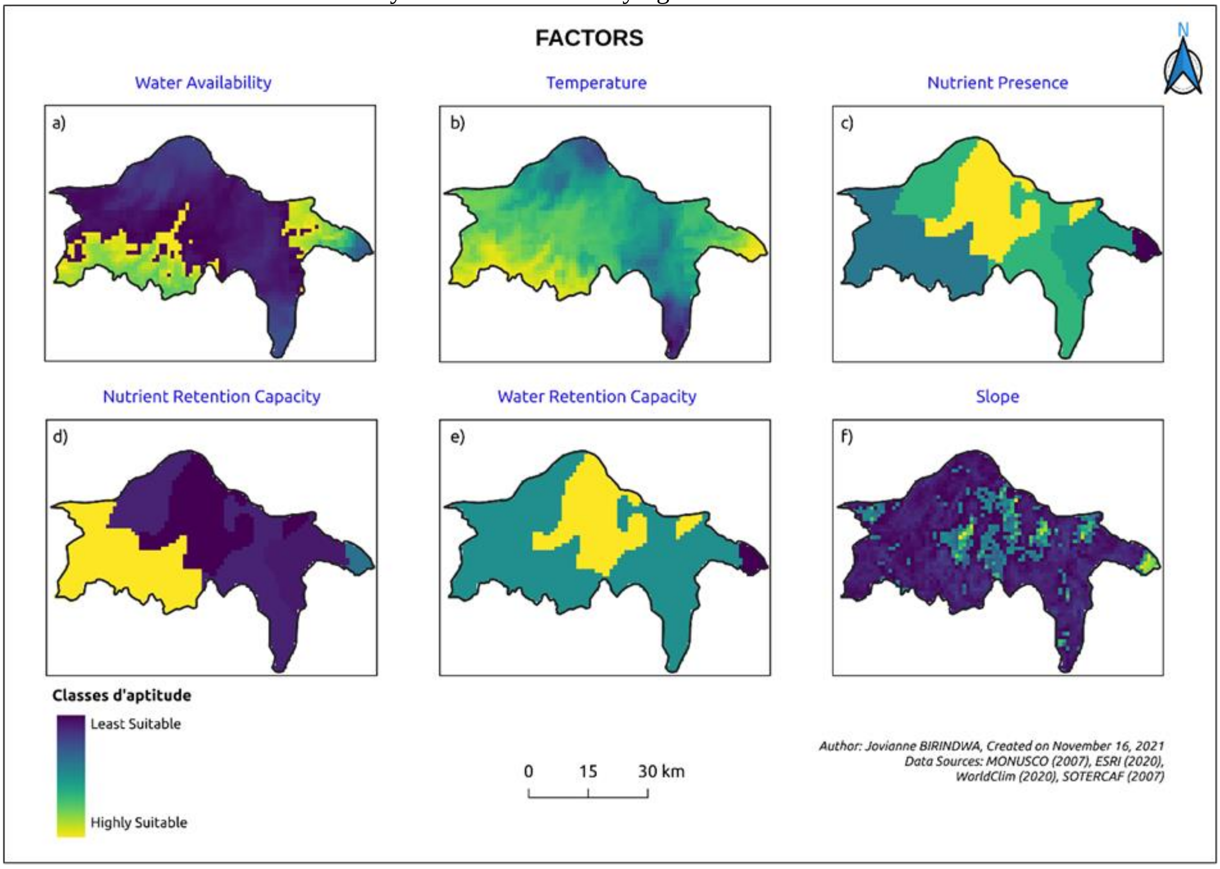

Figure 2(a-f). Biophysical factors considered for cassava suitability

Moving on to constraints, figures 3(a-b) identify areas that are restricted from agricultural use, such as built-up zones and protected areas. These constraints are essential in refining the final suitability analysis, as they rule out regions where cassava cultivation would not be viable due to legal and infrastructural limitations.

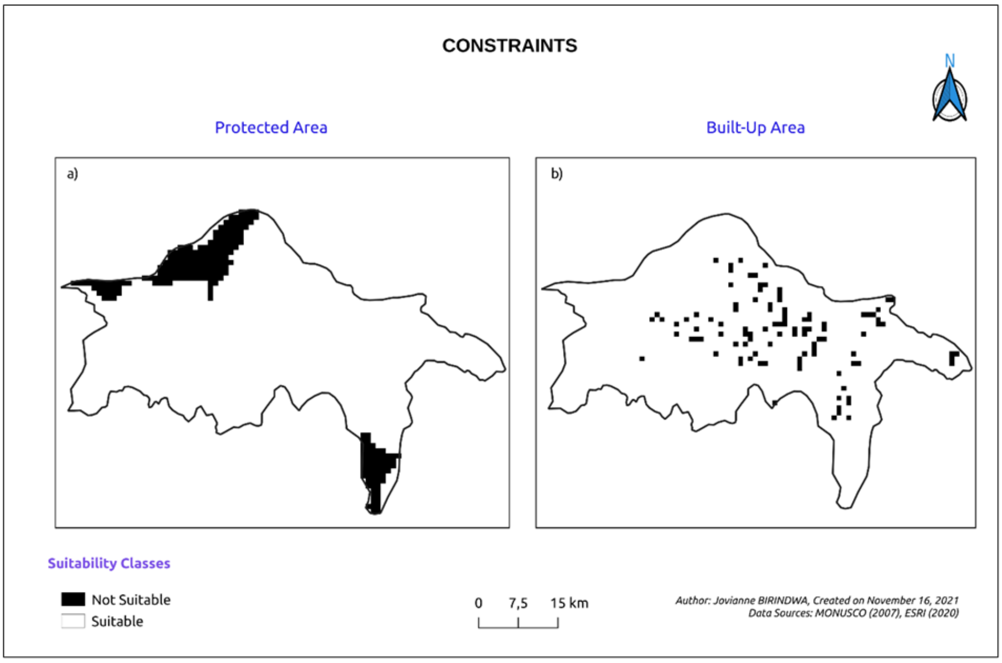

Figure 3(a-b). Constraints considered for cassava suitability.

The final decision map combines all these factors and constraints to present a clear overview of the most suitable areas for cassava cultivation in Walungu. While most of the land is moderately favourable for cassava production, certain regions are either less suitable due to nutrient deficiencies or unsuitable due to steep slopes. The decision map will serve as a practical tool for local farmers and agricultural planners to prioritize zones where cassava production can be optimized.

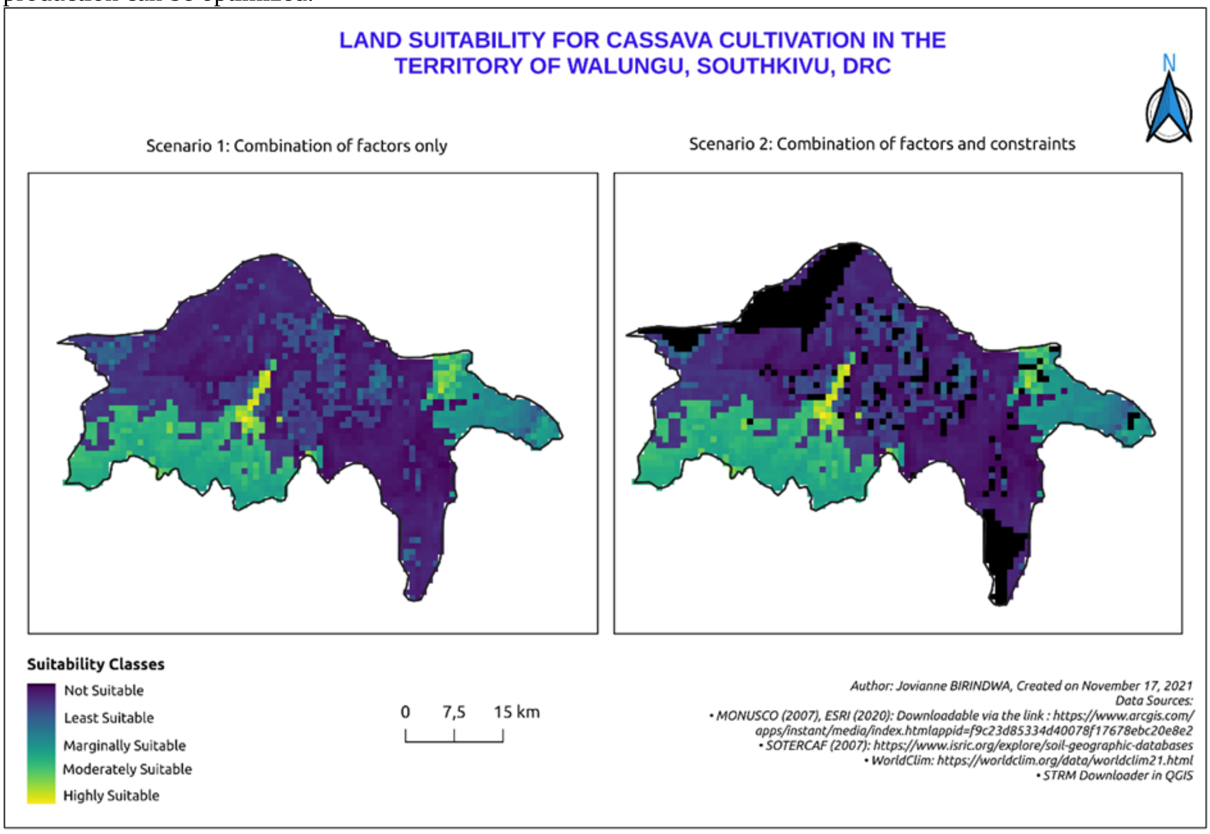

Figure 4. Land suitability for Cassava cultivation

The results of this study suggest that, although Walungu has a moderate suitability for cassava cultivation, it is not fully optimized for high-yield production. This finding aligns with previous studies conducted in other parts of

Africa, where similar biophysical factors such as nutrient retention and water availability significantly impact cassava yields [25][36]. For instance, research by [37] on cassava's role in food security across Africa highlights the importance of managing soil fertility and water resources to improve yields.
Cassava is known for its ability to tolerate drought conditions, which is why it performs well in areas with moderate precipitation, such as Walungu. The fact that 80% of the land is moderately suitable for cassava cultivation demonstrates the crop's resilience [38], but also underscores the need for targeted interventions in certain areas. Farmers could, for example, focus on improving nutrient availability in low-fertility zones by introducing organic fertilizers or crop rotation strategies, as suggested by [39][40].
The Factors map revealed that water availability, temperature and slope are the most influential factors in determining cassava suitability. While the temperature in Walungu is favorable for cassava growth, the steep slopes in some areas pose a challenge, particularly for large-scale or mechanized farming [38]. These slopes could increase soil erosion, thereby reducing the land's long-term productivity for cassava cultivation. Solutions such as terracing or agroforestry practices could be introduced to mitigate these effects in steeper areas.
Another critical insight from this study is the role of nutrient availability. Nitrogen was identified as a key element in supporting the vegetative growth of cassava. However, the analysis also showed that some parts of the territory have low nutrient retention capacity, which could hinder optimal cassava production. As nitrogen is the primary nutrient required for cassava growth, future research could focus on optimizing nitrogen use in these areas. For instance, the incorporation of nitrogen-fixing crops in a mixed farming system could help replenish soil fertility over time. Studies such as [41] revealed how cassava plants respond to increasing nitrate concentrations by enhancing nitrogen metabolism, which underscores the critical role of nitrogen availability in cassava production. The potential benefits of integrating nitrogen-fixing crops, such as demonstrated in intercropping systems with soybeans, further support this approach to improve soil fertility and cassava productivity [42].
This study demonstrates the effectiveness of GIS and MCA in agricultural decision-making, particularly for a staple crop like cassava. By integrating spatial data and multiple criteria, this approach provides a detailed understanding of land suitability and helps guide resource allocation for more efficient agricultural planning. Future studies could build on this research by incorporating socio-economic data, such as access to markets and farming infrastructure, to provide a more holistic view of cassava cultivation potential in Walungu.
It would have also been valuable to calculate the 'Nutrient Availability Index' rather than focusing solely on one organic element, namely nitrogen. Indeed, after nitrogen, phosphorus is the second major element in plant nutrition and is essential for healthy growth, strong roots, fruit and flower development, and greater resistance to disease, while potassium ranks third and is also considered a major plant nutrient. It helps plants resist diseases, protects them from cold, and prevents excessive water loss during dry weather [43].
A possible limitation of this study is the use of a resolution of ±1 km, which may have constrained the precision of the results.

4 Conclusion

This study highlights the value of integrating Geographic Information Systems (GIS) and Multi-Criteria Analysis (MCA) to support agricultural decision-making, particularly for identifying optimal sites for cassava cultivation in Walungu, DRC. By incorporating multiple factors—such as water availability, temperature, nutrient levels, and soil properties—the study provides a nuanced understanding of land suitability. The research demonstrates that the majority of Walungu's land is moderately suitable for cassava production, with critical biophysical factors influencing suitability, including water availability, temperature, and slope. The study suggests that further improvements in cassava productivity could be achieved by addressing low-nutrient areas, optimizing nitrogen use, and mitigating slope-induced soil erosion through terracing or agroforestry practices.
Moreover, it was noted that a more refined nutrient availability index, accounting for phosphorus and potassium in addition to nitrogen, would provide a better assessment of soil fertility. The study also recognizes that the 1 km resolution used may have been too coarse to capture the specific variations needed for more detailed site analysis. Future research should aim to incorporate socio-economic data—such as market access and infrastructure—to enhance the utility of the decision-making framework for cassava cultivation in Walungu.

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