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Spatial Suitability Analysis and Mapping of Agroforestry Areas. Case study of Musanze District in Northern Province of Rwanda

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Abstract

Agroforestry has been envisioned among the possible solutions to sustainable land-use systems. Geographic Information System (GIS) is a fundamental computer based tool to examine the suitability of the study area for future agroforestry extension development. This study intends to address agroforestry suitability site selection for the future agroforestry extension in Musanze district. The biophysical criteria including land use, rainfall, temperature, soil pH, and altitude were selected. Using the Saaty's Analytic Hierarchy Process (AHP) and GIS model builder environment criteria were weighted and classified. Data analysis correlation tool in excel was used to assess the correlation between level of suitability and agroforestry survival rate in five locations of the district. The results show that regarding the district total area of 53 000 ha, only 24.3% of the study area is very suitable for agroforestry, while 56.4% is highly suitable, 17.8% is moderately suitable, and 0.5% is not suitable for agroforestry plantation. The results of trees survival rate in selected sites were found to be correlated at 0.93 to the level of suitability where the survival of trees ranging between 75% and 90% was found to be in medium to very high suitable area, respectively. The findings and the applied spatial analysis approach can assist decision-makers in finding suitable area for future agroforestry extension.

Keywords: Agroforestry suitability, Analytic Hierarchy Process, Geographic Information System, Musanze District.

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1. Introduction

A high population density and intense cultivation pressure on land are causing food insecurity in Sub-Saharan Africa (SSA) (Bucagu, 2013). According to Ahmad et al. (2018), food, fodder and fuel demand in developing countries is still a challenge due to the ever increasing population. Agroforestry was found to be one of the significant sustainable land management practices in many parts of Africa with great control on food security through increased productivity (Kiyani et al., 2017). The use of agroforestry techniques can also improve the soil and land fertility, enhance household resilience, and reduce the impacts of climate change and drought (Ganza & Katcho, 2021). It also helps in preserving biodiversity and improving air and water quality (Ahmad et al., 2017). During the 1st World Assembly of Agroforestry in 2004, the above-mentioned environmental , social and economic benefits linked to agroforestry were presented (Swamin et al., 2004). Consequently, agroforestry was considered as huge benefit for the environment and for the future generations.

The use of computers in the field of agriculture is considered as important part to lead less developed countries agricultural revolution of the 21st century. Geographical Information System (GIS) and other Computer-based Decision Support Tools (DST) have a crucial role in providing spatially explicit information that assists decision-makers in adoption, planning, and design of agroforestry systems (Ellis & Schoeneberger, 2004). As discussed by Ahmad et al. (2017), agroforestry suitability assessment is among the special form of land suitability that is very pertinent to study because of the pressure on land as a limited asset and the existence of diverse alternatives of improved agriculture practices. Agroforestry program in particular has used various kind of computer based tools such as Agroforestry Systems Inventory Database (AFSI), Multipurpose Tree and Shrub Database (MPTS), Agroforestry Modeling Environment (AME) and etc (Ellis & Schoeneberger, 2004). Geographic Information Systems (GIS) is the one widely used for the planning and management of land and particularly in Agroforestry suitability assessment. The potentiality of using Geographic Information Systems (GIS) in agroforestry suitability assessment is due to the fact that it assess accurately the natural spatial suitability of the land, by means of a set of biophysical criteria(Quinta-nova, 2018). Rwanda target to increase the use of Computer-based Decision Support Tools through digital agricultural(Balraj & Pavalam, 2012). Farmers, decision makers and planners must be able to determine the criteria and to combine them in a smart spatial decision support approach, which allow to decide where agroforestry would be the efficient agriculture practice/land use system

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(Bentrup & Leininger, 2002). Nevertheless, Rwanda policy brief on agroforestry miss the component of spatial information on land suitability toward agroforestry.

Musanze District is among the districts with high population density with 695 habitants per km2 with majority of the population doing subsistence agriculture(NISR, 2012). This situation of high population density with pressure on agricultural land has led to the continuous cultivation on fragmented plots and accelerated soil depletion. Hence, in order to improve agriculture productivity, a development plan integrating agroforestry practices to the farm system has been initiated(Eric, 2019). Currently, Musanze District has 4519 ha covered with agroforestry and targeting to increase this number to 10729 ha by 2024(R o R, 2017). Previous studies indicated that technology such as GIS can help a better planning towards agroforestry extension and sustainable land use management. However, the technology is not widely adopted in this regard, in Musanze district most of the identified sites for agroforestry extension the selection seem to be based on land availability. There is a gap in using appropriate tools to guide decision making in agroforestry site selection suitability. This situation has slowed down the agroforestry site selection which is among the preliminary activities of the agroforestry program. Also, it has affected the rate of agroforestry extension and trees survivorship. Thus, this study serves as a comprehensive spatial suitability assessment to guide decision makers and land owners in assessing various biophysical criteria that affect the development and operation of agroforestry systems on a farm. This study could also be a powerful tool to influence future agroforestry projects extension in Musanze District.

2. Materials and methods

2.1. Study area

Musanze District is located in the Northern Province of Rwanda, part of Rwandan highland zone, with steep slope, fragile soil types well-watered on a poorly covered land by vegetation due to predominating subsistence agriculture with traditional practices(NISR, 2012; Dibanga et al., 2016). The district is highly exposed to soil erosion and frequent landslides and/or floods (MIDIMAR, 2012; Nambajimana et al., 2020). Musanze district is bordered in the north by Democratic Republic of Congo and Uganda, in the south by Gakenke District, in the East by Burera District and in the west by Nyabihu District. The district is located between 1°30’06’’S to 1°30’94’’S and from 29°37’59’’E to 29°37’75’’E (Akinyemi, 2017). It has a moderate tropical climate with a temperature between 15°C and 18°C (REMA, 2011). The district has a

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total population of 368, 267 with a density of 694 habitant/Km2 with the majority of the population working in the agricultural sector (NISR, 2012).

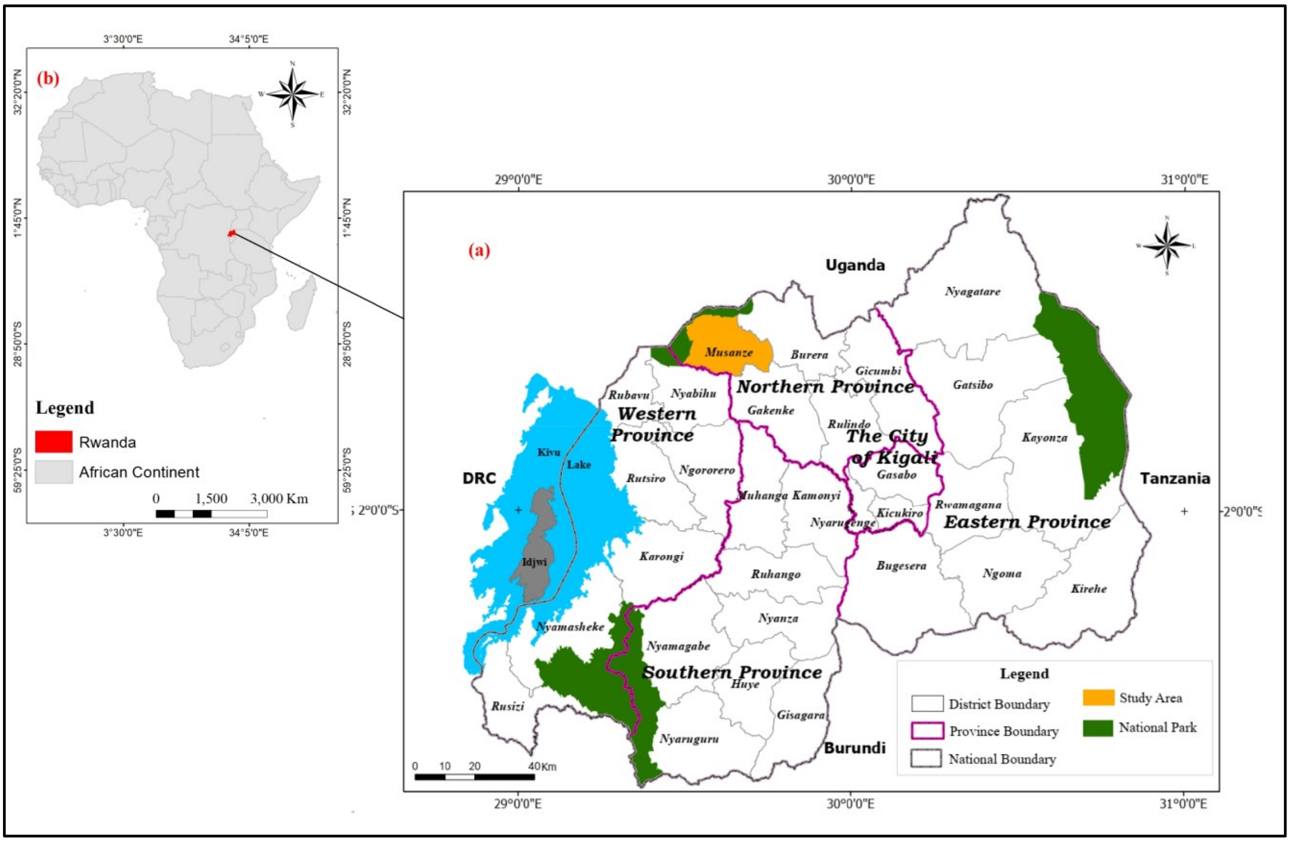

Figure 1: Administrative boundary of Musanze District and its location in Rwanda (a), with the location of Rwanda in Africa (b)

2.2. Data acquisition and processing

2.2.1. Spatial data

According to FAO (2007), the suitability of land for a given crop is influenced by biophysical, human, and economic criteria. Similarly for agroforestry, its suitability evaluation requires suitable biophysical land characteristics in terms of land use, climatic, edaphic and topographic factors (Jyoti et al., 2021). The requirements for agroforestry suitability was obtained from available literature (Yedage et al., 2013; Kihoro et al., 2013; Sarkar et al., 2014; Ahmad et al., 2017; Yohannes & Soromessa, 2018; Jyoti et al., 2021; Ganza and Katcho, 2021). The selected spatial data were land use, climatic, edaphic and topographic factors (Figure 2).

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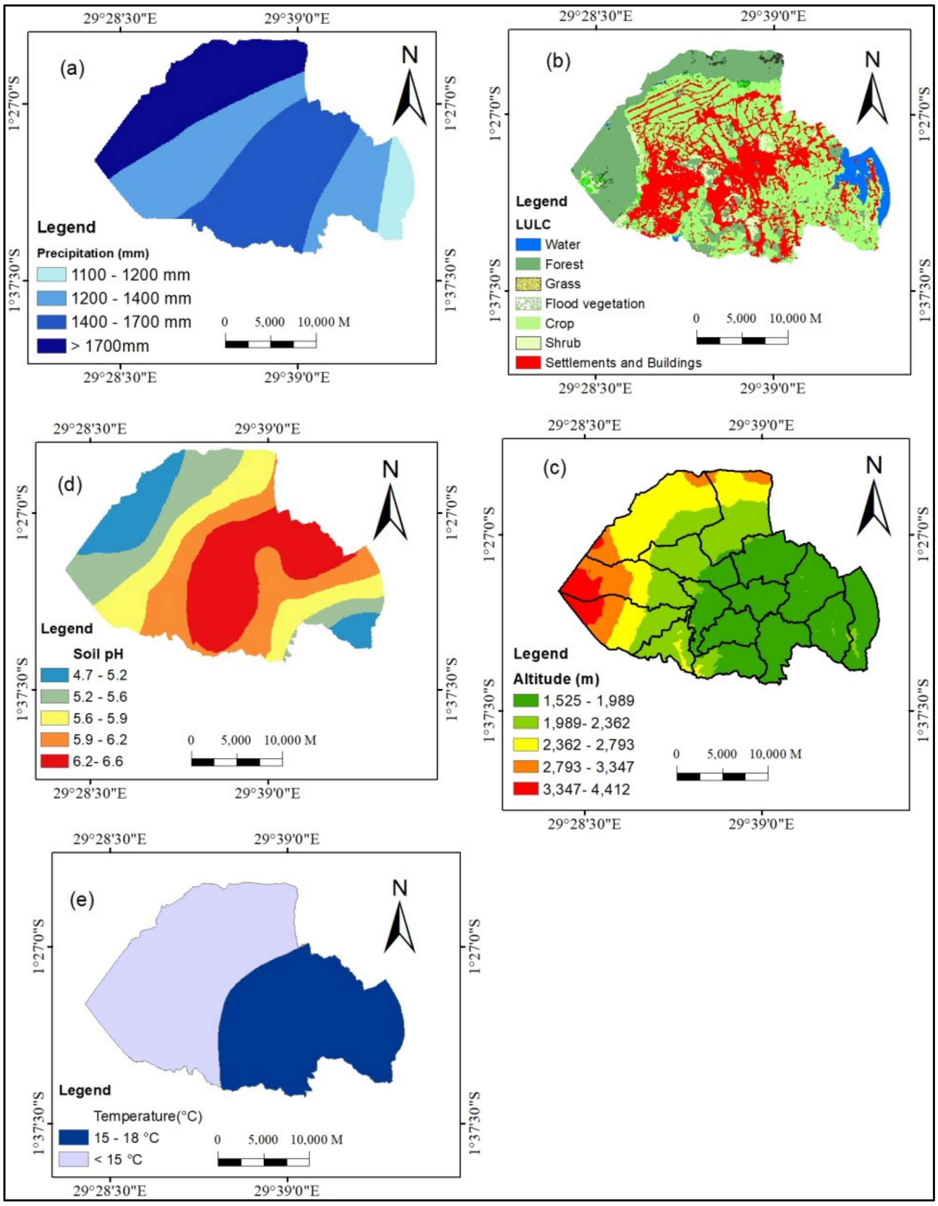

Figure 2: Biophysical criteria used in suitability analysis of agroforestry/ (a): Rainfall parameters; (b): Land use/Land cover parameters; (c): Altitude parameters; (d): Soil pH parameters; (e): Temperature parameters

Rainfall criteria on Figure 2.a is commonly used in suitability mapping of agroforestry, as it influences plant growth and crop production (Sarkar et al., 2014). Data from weather stations located in Musanze City were interpolated using Kriging Interpolation method to create a continuous raster rainfall data inside our study area. The average annual rainfall was used to generate spatial rainfall pattern (continuous surface) in ArcGIS by Kriging Interpolation method from two weather stations. When analyzing the agroforestry growth, the elevation on Figure 2.c is an important criteria as it influences the agroforestry growth to a large extent (Ahmad et al., 2017). This was also emphasized by Ritung et al. (2007), that highlighted the

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importance of topographic characteristics (elevation and slope) in any land suitability analysis. The elevation of the area influences the solar radiation and temperature and hence is associated with the plant necessities for growth. Zones with moderate elevation and gentle slope were found to be favorable for agroforestry (Jyoti et al., 2021).

Temperature on Figure 2.e is another influencing criterion, because it has a direct part to play in the photosynthesis and respiration, and it has a significant effect on plant tissue temperature. Land use land cover on Figure 2.b is an important criteria that is used to validate the suitability analysis of a given crop suitability(Sarkar et al., 2014). Soil pH on Figure 2.d is an important criteria as the soil level of acid or alkaline balance affect the growth of a given agroforestry species (Kihoro et al., 2013). According to Ritung et al. (2007), the soil pH is among soil characteristics that are important and which primarily affects the growth and development of agroforestry. The pH of our study area is moderately acidic with a range from 4.7 to 6.6. The following table 1 shows the types of data used and their sources.

Table 1: Description of data used

No	Layers	Source	Data model	Resolution
1	Administrative boundaries	Rwanda Land Management and Use Authority. Administrative boundary Updated shapefiles of 2015	Vector data: Used to extract the administrative boundary of Musanze district	1.200.000 scale
2	Precipitation	Rwanda meteorological Agency Meteorological stations data	Raster data model: Used to extract Mean annual rainfall of the study area	Mean annual rainfall for 20 years (1998–2018)
	Temperature	Rwanda meteorological Agency Meteorological stations data (2017)	Raster data model: Used to extract mean annual temperature of the meteorological stations in study area.	
3	Digital Elevation Model	United States Geological Survey Earth Explore	Raster model: Used to extract the altitude of our study area	10 X 10m
4	Land use land cover	Global Land cover produced by ESRI in 2020.https://www.arcgis.com/apps/instan	Raster model: Used to extract the land use of the study area	10 X 10m

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No	Layers	Source	Data model	Resolution
		t/media/index.html?appid=fc92d38533d440078f17678ebc20e8e2		
5	Soil pH	Rwanda Ministry of Agriculture (MINAGRI)	Vector model: Used to extrapolate soil pH of the study area	1.200.000 scale

2.2.2. Analytic Hierarchy Process (AHP) method

Analytic Hierarchy Process (AHP) is a multi-criteria decision method that is used by decision makers to easy difficult assessments of pairwise comparisons(Kirimi & Waithaka, 2014). The Analytical Hierarchy Process (AHP) was used in weighting of criteria basing on the judgment of expert and technical staffs working in the Agriculture and Natural Resources Unity of Musanze District. The expert and technical staffs involved in weighting criteria are the Director of Agriculture and Natural resources, technical staff in charge of Forestry and Natural resources, District agronomist and District Veterinary.

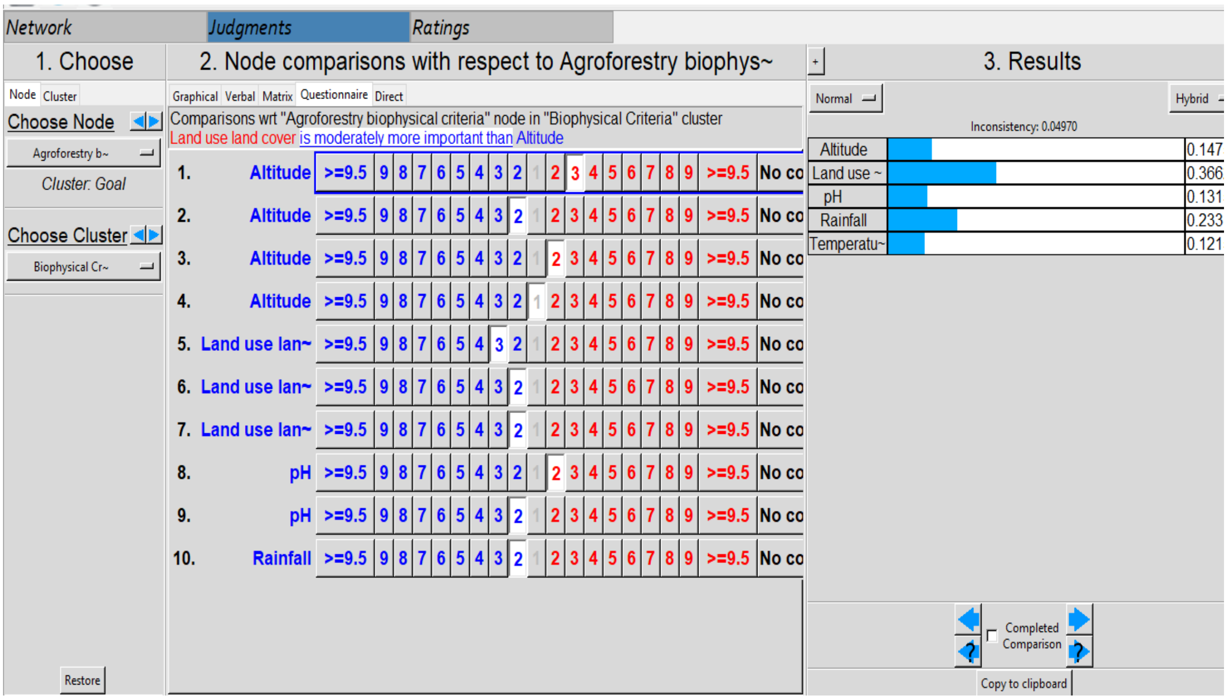

Figure 3: Questionnaire recording in in Super Decision software X 3.2.

Questionnaire comparing criteria were distributed to the expert and later recorded in Super Decision Software X 3.2 (Figure3). In table 2 criteria were compared based on Saaty's scale

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ranging from one (1) to nine (9). The comparison was done based on the criteria level of importance regarding each other.

Table 2: Saaty's judgmental scale

Scale of judgment	Definition	Explanation of Importance
1	Equal	This means that two criteria have the same level of importance
2	Between equal and moderate	One criteria is slightly important over another
3	Moderate	
4	Between moderate and strong	
5	Strong	The expert's judgment attributes a strong level of importance to one criteria over another
6	Between strong and very strong	
7	Very strong	A criteria is very strongly attributed an importance over another
8	Between very strong and extreme	
9	Extreme	This is the highest level of importance attributed to one criteria over another.

Source: Adapted from Adams and Saaty (2003)

The pairwise comparison of criteria was filled into a comparison matrix, and the matrix was populated with values from 1 to 9 and fractions from 1/9 to 1/2 representing the importance of one factor against another in the pair. Ebistu and Minale (2013), suggested that the values in the matrix need to be consistent and the rule is that the inconsistency ratio must be less than or equal to 0.10, which means that if x is compared to y, it receives a score of 5 (strong importance), y to x should score 1/5 (little importance). Something compared to itself gets the score of 1 (equal importance). In our case, the inconsistency ration is 0.0497 (Table4) since this value is less than 0.10, the expert's judgments are perfectly reliable.

Table 3: Pairwise comparison matrix

INCONSISTENCY	**0.0497**						
PAIRWISE COMPARISON	Altitude	Land use land cover	pH	Rainfall	Tempe-rature	Norma-lized	Weight %
Altitude	1	0.333333	2	0.5	1	0.15	15
Land use land cover	3.000003	1	3	2	2	0.37	37
pH	0.5	0.333333333	1	0.5	2	0.13	13
Rainfall	2	0.5	2	1	2	0.23	23
Temperature	1	0.5	0.5	0.5	1	0.12	12

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In Table 4 biophysical criteria were classified using biophysical limit and assigned weight based on Saaty's Analytic Hierarchy Process (AHP) in Table 3. Later, the results from the Table 5 were used in making agroforestry suitability maps regarding criteria.

Table 4: Weight matrix and Ranking of criteria for agroforestry suitability mapping

Agroforestry Biophysical Factors	Weight (%)	Value Ranking(1,2,3,4,5)	Suitability
Land use land cover	37	Cropland:**5** Forest:**2** Open Areas / grass/Shrub:**4** Settlements and Buildings:**2** Water:**1** Flooded vegetation:**3**	1: Very low 2: Low 3: Medium 4: High 5: Very High
Altitude	15	1525-1989m:**5** 1989-2362m:**4** 2362-2793m:**3** 2793-3347m:**2** 3347-4412m:**1**	1: Very low 2: Low 3: Medium 4: High 5: Very High
Temperature	12	15-18 °C:**4** <15 °C:**5**	1: Very low 2: Low 3: Medium 4: High 5: Very High
Rainfall	23	1100-1200mm:**3** 1200-1400mm:**4** 1400mm-1700mm:**4** >1700mm:**5**	1: Very low 2: Low 3: Medium 4: High 5: Very High
pH	13	4.7-5.2:**3** 5.2-5.6:**3** 5.9-6.2:**4** 6.2-6.6:**5**	1: Very low 2: Low 3: Medium 4: High 5: Very High

The above table introduces the weigh assigned to the criteria according to the expert's opinions. Land use criteria was assigned the highest criteria with 37% level of importance, while temperature is the assigned the less level of importance with 12%. The criteria were ranked based on the most suitable and favorable conditions for agroforestry. The results on the Table 4 were used in GIS model environment (Figure 4) to classify criteria and for the final weighted overlay.

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2.2.3. Model Builder

Criteria with standardized parameters in Table 5 were classified in a GIS model builder environment in ArcGIS 10.6 platform (Figure.4). Suitability maps regarding each criteria were produced, for the weighting and overlaying to produce the final suitability map.

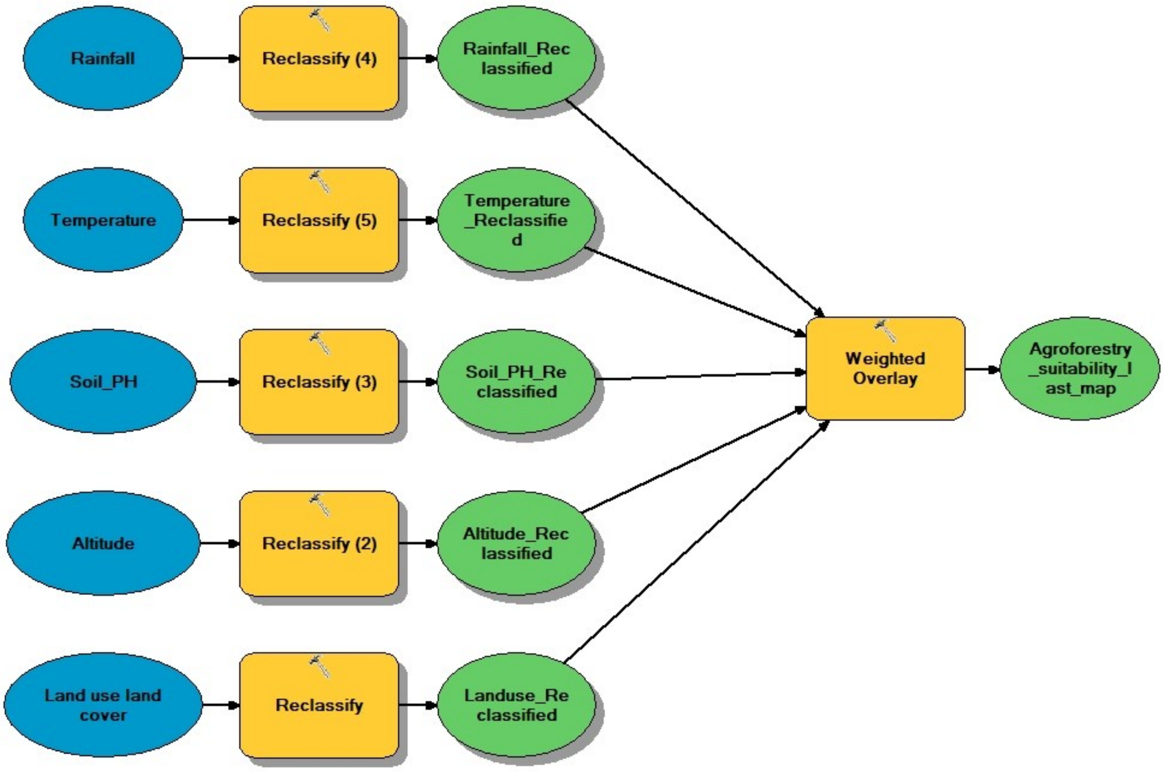

Figure 4: A model for agroforestry built in ArcGIS version 10.6

2.2.4. Validation of result

Agroforestry trees of the projects entitled "Integrated Land, Water resources and Clean Energy Management toward Poverty Reduction Project in Musanze District" were visited and the survivorship and growth data of agroforestry trees were calculated. The sites visited are located in four sectors of Musanze district: Kimonyi, Rwaza, Gataraga and Nkotsi. With Kimonyi sector located in the north-west of Musanze urban area, Gataraga sector located in the northern part of the district and bordering the Volcanoes National Park, Rwaza sector located in the southern part of Musanze city and Nkotsi sector that is located in southern–west part of the district. The following formula was used to calculate the survival rate of trees in percentage (Khopai & Elliott, 2019):

$$\boldsymbol{Survival\ rate}\ (\%) = \frac{\boldsymbol{SN}}{\boldsymbol{TN}} \times \mathbf{100}$$

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Where SN refers to the number of survived trees, and TN refers to the total number of planted trees. To validate the reliability of our final suitability map in figure (4), the finding for survival rate of trees located in sampled sites Kimonyi, Rwaza, Gataraga, and Nkotsi were digitized and overlaid to the final suitability map. The results of agroforestry survival rate were compared to the suitability classes, and data analysis correlation tool in excel was used to assess the correlation between agroforestry survival rate and the level of suitability (Table 6).

3. Results and Discussions

3.1. Agroforestry suitability analysis

Regarding the district total area of 53000Ha, the criteria land use in Figure 5.a 29441Ha (56%) is located in a very low and low agroforestry suitable area. This specific area includes land use classes covering settlements, Ruhondo Lake and the Volcanoes National Park. The remaining 23647Ha (45%) of the total area is located in Medium, High and Very High suitable, with about 19759Ha (37%) covering crop land areas. Concerning the Figure 5.b on altitude, 36929Ha (70%) is located in High and Very High suitable area, while 9601Ha (18%) is in medium suitable area and about 5595Ha (11%) of area is in low and very low suitable area. On Figure 5.c, all the areas are located in High and Very high suitable regarding temperature criteria. The soil pH on Figure 5.d, 20549Ha (39%) is moderately suitable and 32258Ha (61%) is in high and very high regarding the soil pH criteria. The rainfall criteria on Figure 5.e, indicate that 36068Ha (68%) of the total area is located in a high and very high suitable area. only 2976Ha (6%) and 13929Ha (26%) are located respectively in low and medium suitable regarding rainfall criteria. Considering the criteria parameters that have scored high and very high suitability, this kind of area would be suitable for most of the agroforestry species recommended in Rwanda Environmental Management Practical Tools on Agroforestry of 2010. Regarding the biophysical conditions of the country, Rwanda Environmental Management Practical Tools recommended the adoption of agroforestry species such as *Calliandra calothyrus*, *Cedrela serata, Grevillea robusta, Leucaena diversifolia, Mimosa scabrella, Moringa oleifera and Alnus acuminate* (REMA, 2010). Basing on Karimba and Uwanyirigira (2016), the *Alnus acuminata (Betulaceae)* specie is the most adapted to the biophysical conditions of Musanze district. This specie has origin in mountainous areas of Central and South America and grows well in 1200-3800 m of altitude, Mean annual temperature of 4 to 27oC and mean annual rainfall 1000-3000 mm (Karimba and Uwanyirigira,

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2016). Therefore, Musanze district biophysical condition is ideal for this agroforestry specie as the altitude is ranging between 1525-4412m, with the temperature of 15-18oC and rainfall ranging between 1100 and >1700mm. It prefers the pH ranging between 5.5- 6.5, but could also tolerate the pH of 4-7.

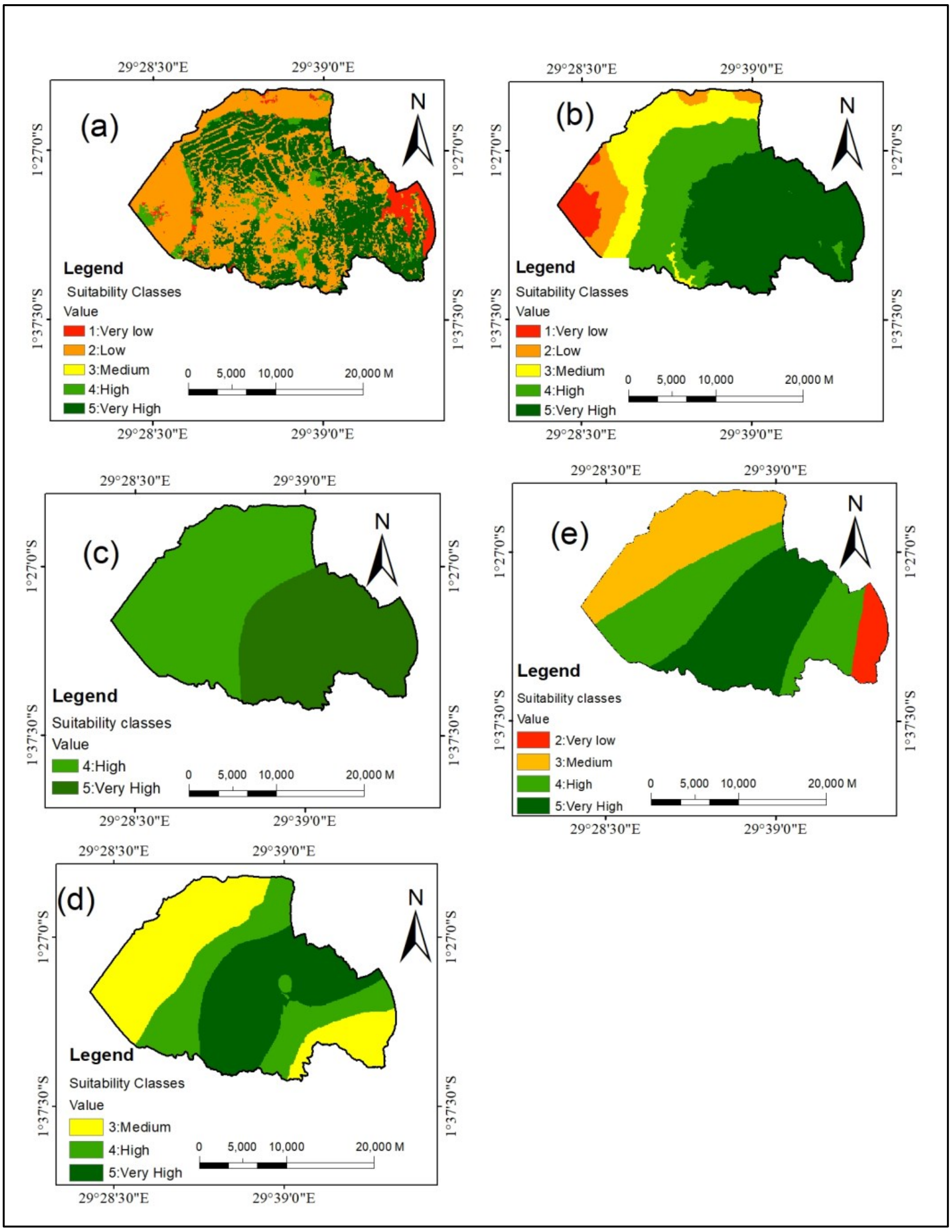

Figure 5: Standardized suitability maps for agroforestry (a): LU/LC suitability map; (b): Altitude suitability map; (c): Temperature suitability map; (d): Soil pH suitability map; (e): Rainfall suitability map

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3.2.The final agroforestry suitability map

The statistics from the final suitability map in Figure 6 shows that 24.3% (12902.4 ha) of the area as very high and 56.4% (29913.9 ha) as high suitable for agroforestry extension. While 17.8% (9434 ha) and 0.5% (272.8 ha) are located in moderate and low suitability respectively.

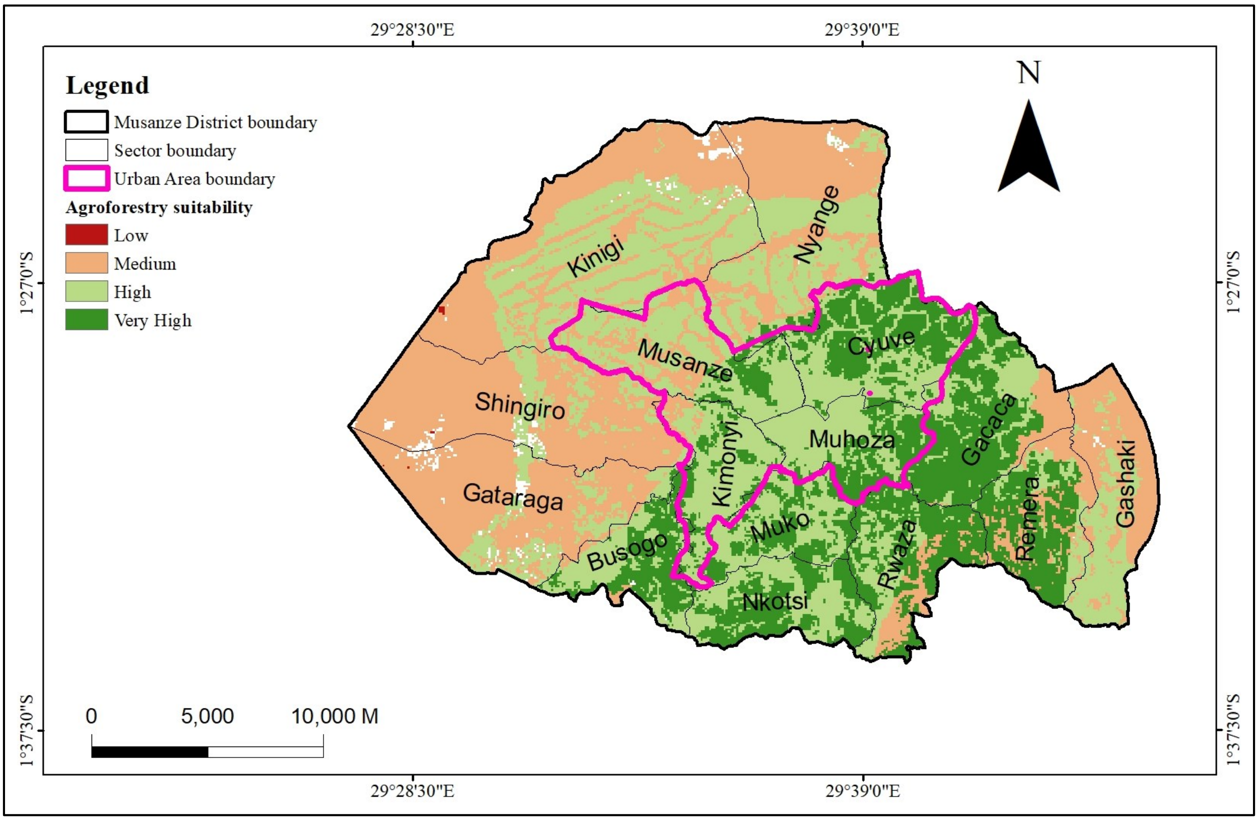

Figure 6: Composite agroforestry suitability map

Figure 6 shows that the areas identified as high and very high suitable for agroforestry are located mostly in all sectors of the District. The map on Figure 6 also displays the urban boundary that has been identified by the Global Green Growth Institute (GGGI) and the Ministry of Infrastructure (RHA, 2020). The Musanze urban boundary consists of 4 sectors (Muhoza, Cyuve, and Musanze & Kimonyi) and cover 11700 ha which is approximately 22% of the district total area. As shown by Figure 6, the high and very high suitability area is more dominating in Musanze, Muhoza, cyuve and Kimonyi that are considered urbanized. The land use master plan of the city has designed some areas that will cover urban agriculture, green space, agro-residential area and urban forests (MININFRA, 2014; RHA, 2020).Thus, Agroforestry activities are recommended in the urban agriculture system in order to assist in securing future urban food security, especially for poor citizens(Salbitano et al., 2015). In designing urban green spaces, agroforestry trees can play a huge contribution in designing

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urban aesthetics landscapes and increasing recreational access(Taylor & Lovell, 2021). Urban agroforestry was also found to be the most effective strategy to reduce climate change effects and urban heat. Therefore, the suitable areas identified in the urban boundary are also potential sites for the future agroforestry extension. The remaining sectors are generally considered rural and dominated with agriculture activities. For the finest agriculture production, the ongoing and future agroforestry projects can be diverted in areas of high and very high suitability identified in those rural sectors mainly dominated with agriculture.

3.3.Validation of the results

Agroforestry tree plantation survival rates on sampled sites were found to be 85%, 75%, 83%, and 90% respectively for Kimonyi site, Rwaza site, Gataraga site, and Nkotsi site. This is illustrated in the map in Figure 7, which presents the results from the spatial overlay analysis for agroforestry suitability with selected agroforestry sites. The results for the correlation analysis shows that the two variables grow together, the percentage of the agroforestry survivor rate increases with the suitability classes. Therefore, in Table 6 the correlation of the two variables (Agroforestry suitability classes and Rate of Survivorship and growth) was found to be positive (0.93). This is confirmed by the high percentage of agroforestry survivor rate observed in a high and very high suitable area.

Table 5: Level of correlation

	Agroforestry suitability Classes	*Rate of Survivorship and growth (%)*
Agroforestry suitability Classes	1	
Rate of Survivorship and growth (%)	**0.93**	1

Source: Data analysis

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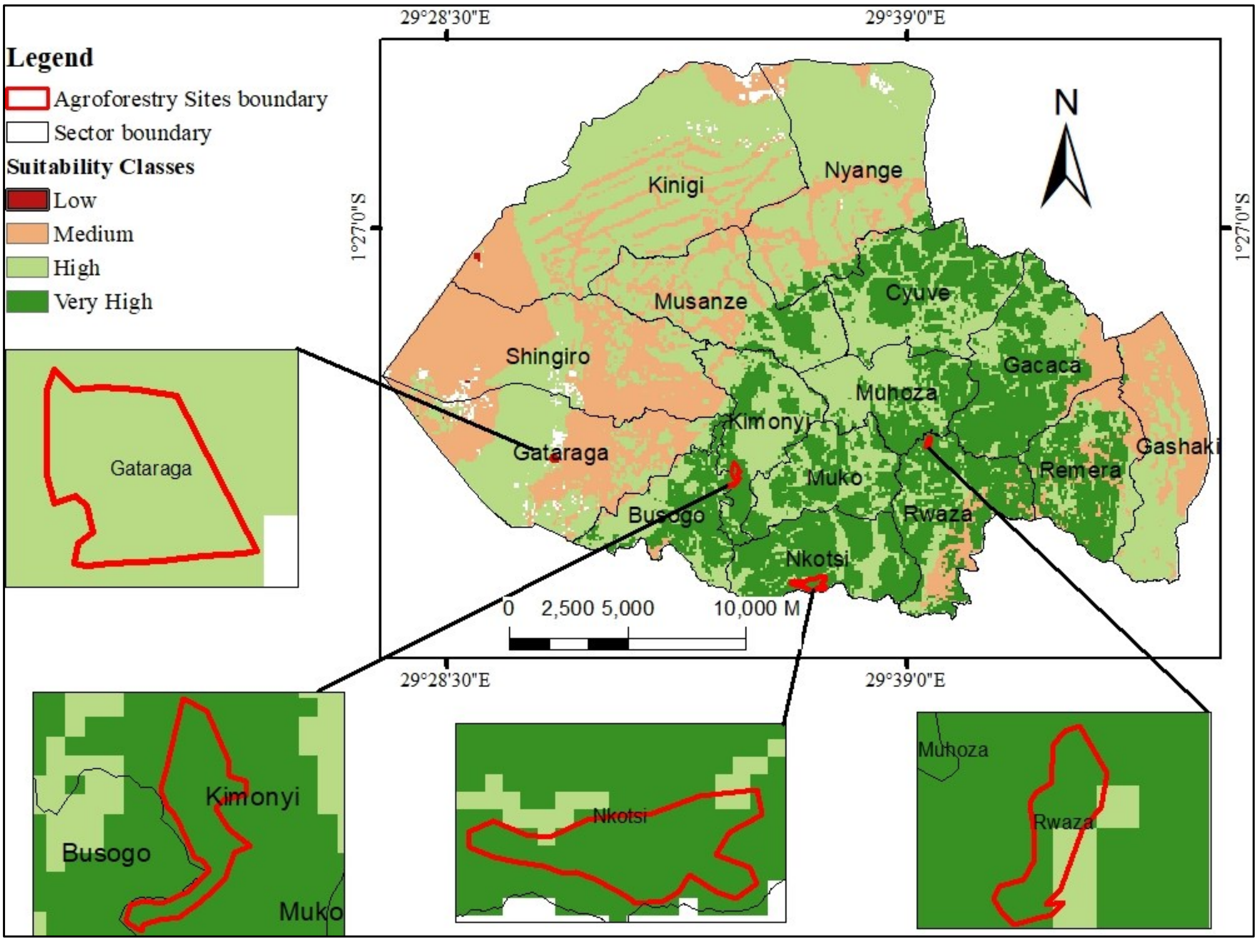

Figure 7: Location of agroforestry sites

This map on Figure 7 shows the level of agroforestry suitability for the selected sites that contain a high percentage of survivor rate. The future agroforestry project could be extended to the identified, suitable areas of high and very high suitable areas for the finest production.

3.4. Policy implications

Policymakers still miss the component of spatial information of agroforestry suitability. This is confirmed through the Rwanda policy brief on agroforestry that misses a component containing spatial information on land suitability toward agroforestry (Hassan et al., 2015). Our study findings highlight the honest approach to fulfill such an existing gap in providing spatial information of land suitability towards the best area for agroforestry options. The results of this study need to be replicated in other districts of Rwanda that still meet the challenge in finding areas suited for agroforestry plantation. This GIS model also has an advantage over the current biased traditional method of agroforestry site selection, as it will reduce the loss of money and efforts attributed to the failing of agroforestry trees planted in an unsuitable area (Ellis and

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Schoeneberger, 2004). Therefore, the policy brief needs to be revisited with some fine-tuning concerning spatial information on agroforestry suitability. Strong agroforestry policy that incorporates computer based tools would facilitate the process of agroforestry extension. This could also be an important asset to assist the current vision to increase the agroforestry program in order to reduce poverty and enhance food security in Rwanda (Bucagu, 2013).

3.5. Study limitations

In this study the biophysical factors were considered, nevertheless, factors such as soil contents were not considered since our study is located in more fertile and rich volcanic soil of the Northern Province of Rwanda (Turamyenyirijuru et al., 2019). However, for the perfection of the agroforestry suitability results, we suggest including the soil contents data. The level of agroforestry adoption is another influencing factor to study agroforestry suitability, but it was not included in our assessment. Although Conchedda et al., (2001) highlighted that high human and livestock population densities are associated with high probability for farmers to adopt agroforestry farming systems. To improve the results of future research on agroforestry suitability, we recommend researchers to conduct a survey on socioeconomic criteria such as local community adoption, gender inclusion and benefit of agroforestry regarding tree species.

4. Conclusion

This study applied the Geographical Information System (GIS) and Multicriteria Evaluation (MCE) as Computer-based Decision Support Tools (DST) to assess the agroforestry suitability in Musanze District. The result showed that over total area of 53000Ha under the study, the very suitable area for the agroforestry represents 12902.4Ha (24.3%) of the study area, while 29913.9 (56.4%) is high suitable, and 9434Ha (17.8%) is moderately suitable. Only 272.8Ha (0.5%) has been identified as not suitable. The final agroforestry suitability map was compared to the level of agroforestry planted trees survival rate ranging from 75-90% and all agroforestry sites are located in high and very high suitable area. During this study only the biophysical factors of the area were used in assessing the suitability of the area to the agroforestry expansion. This study relied on the biophysical evaluation approach to provide useful information on spatial suitability of agroforestry that could be used by the local farmers in the selection of a suitable site for agroforestry. The results can also be used by decision makers and researchers in the sake of improving and promoting the agroforestry system. Yet, further studies that integrate social economic aspects (e.g., level of agroforestry acceptability of local

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community) and agroforestry tree species information are recommended for more comprehensive understanding of the future agroforestry extension.

5. References

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