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GIS based suitability analysis for coffee farming in Kenya

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ABSTRACT

Coffee production in Kenya has been declining, worsening the socio-economic wellbeing of the local farmers. This study was undertaken to develop a method and design a spatial model to help in identifying sites in Elgeyo-Marakwet County in Kenya that are suitable for sustainable production of coffee. The methodology used for this study integrates GIS, remote sensing and Multi Criteria Modelling to analyze topography, soil, land cover, and climate factors by matching them with the requirements for the growth of coffee. The model used was validated based on the output results. The study results indicate that the places suitable for Arabica and Robusta coffee production cover an area of 1793.6 Km2 (58.3%) and 539.3 Km2 (17.5%) respectively. The results for Arabica suitability classes show that highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N) cover an area of 69.6 Km2 (1.2%), 1409.5 Km2 (46.6%), 314.6 Km2 (10.4%), 1231.0 Km2 and (40.7%) respectively. The results for Robusta coffee analysis indicate the classes highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N) extend to an area of 5.78 Km2 (0.2%), 507.03 Km2 (16.8%), 16.48 Km2 (0.5%), and 2495.35 Km2 (82.5%) respectively. The findings for the research imply that, for sustainable coffee economic gains in the study area, farmers need to consider growing more of Arabica coffee and less of the Robusta type. These results could be used by farmers, agricultural extension officers and the county government to devise new strategies on practical sustainable coffee farming in Kenya. The findings could be replicated in the rest of the country to boost coffee production as well as production of other crops.

Keywords: Arabica and Robusta coffee; GIS, multi criteria modelling; land suitability

1. Introduction

Global population is on the increase and is projected to hit nine billion in 2050. Appropriate decisions therefore need to be made that can help plan well for the future (World Bank, 2012). Human population in Elgeyo-Marakwet County (EMC) is increasing at the rate of 2.7% per annum (Ngugi, 2013). As a result of this upward trend, there is a corresponding upsurge in demand for agricultural produce. The main economic activity for the people inhabiting EMC is agriculture but its production is very low and less effort has been made to enhance it. Majority of the people, in the county, live in poverty and cannot meet their basic needs. The problem is that land cannot be stretched to allow for an increased space for agricultural endeavors but proper planning is required (Kamau, Kuria, & Gachari, 2015). To help address this issue, the county government of EMC has put in place priorities towards boosting food and cash-crop yields by irrigation and rain-fed farming (County Government of Elgeyo-Marakwet, 2013).

To boost food and cash crop production, it is necessary to identify suitable areas for agricultural practices. By doing so, land can be partitioned in terms of suitability for a given use so as to facilitate for efficient and effective land use management and planning systems. Suitability analysis of land based on GIS that integrate preferences of the decision makers could go a long way in proving sustainable solutions in identifying suitable areas for enhanced productivity (Malczewski, 2006).

The current methods of land suitability are mainly based on expensive and protracted methods that are not analytical. These methods utilize manual methods that use analogue maps and are inconvenient, are not precise, and the role of all effective parameters in land suitability analysis cannot be easily considered. Land use, terrain and environmental concerns are not considered as a result of these outdated methods. GIS tools bring new approaches to analyses enabling all factors affecting land suitability to be considered and weighted under one umbrella. GIS does not just carry out allocation of locations to objects and gauging their spatial relationships but possess the ability to present information in form of graphs, charts and offers immeasurable opportunity to export data to other applications (Yousefi-Sahzabi, Sasaki, Djamaluddin, Yousefi, & Sugai, 2011). GIS includes scientific tools that enable the integration of data from different sources into a centralized database from which the data is modeled and analyzed. GIS-based tools and processes addresses the challenges of suitability analysis based on the collection, processing and analysis of spatial data. The GIS approach to land suitability analysis is based multi criteria rankings and weights assigned to variables that affect coffee production. The aim of this research is to carry out GIS based land suitability analysis for coffee farming Elgeyo-Marakwet County in Kenya. The key criteria considered include soil type, soil properties, parent material, latitude, precipitation, temperature, wind, light intensity, moisture, altitude, aspect and slope (Nzeyimana, Hartemink, & Geissen, 2014; Pohlan & Janssens, 2010; Ridgman, 1989). These factors were modeled in a GIS environment using decision support.

2. Study area

The study area showing Elgeyo-Marakwet County is shown in Figure 1. The map shows county's divisions namely Kapsowar, Tirap, Tot, Kapcherop, Chebiemit, Tunyo, Kamariny, Tambach, Chepkorio, Soi and Metkei. It covers a total area of 3029 Km^2 and is located in the region bounded by latitudes $0^0\ 20'$ and $1^0\ 30'$ North and longitudes $35^0\ 0'$ and $35^0\ 45'$ East. It is inhabited by 369,998 people with population density of 122 persons per Km^2 according to 2009 census. Economic activities in the area include tourism, small business, fluorspar mining, oil prospecting by Tullow Oil Company and farming. Agriculture is the main source of food and income for the inhabitants of the county.

3. Data and Methodology

3.1. Data

Different datasets used in the study are summarized in Table 1. Landsat 8 satellite imagery and topography (GDEM) were downloaded from the US Geological Survey (USGS) website. Data on major and minor roads were acquired from the Kenya National Bureau of Statistics (KNBS). Kenya Meteorological Department (KMD) provided rainfall, temperature, and weather data. The soil characteristics which included depth, drainage, texture, pH, and cation exchange capacity (CEC) were sourced from the Kenya Soil Surveys (KSS). Administrative boundaries of the republic of Kenya and its devolved county governments and subcounties and villages were acquired from Survey of Kenya (SOK). Data on the existing coffee farms was acquired using handheld GPS receivers. Questionnaire to farmers and for expert opinion ratings were also administered during field work. The expert opinion ratings were used for determining variable weighting for multi criteria modeling. GPS data was also used to acquire training data, used in the supervised image classification.

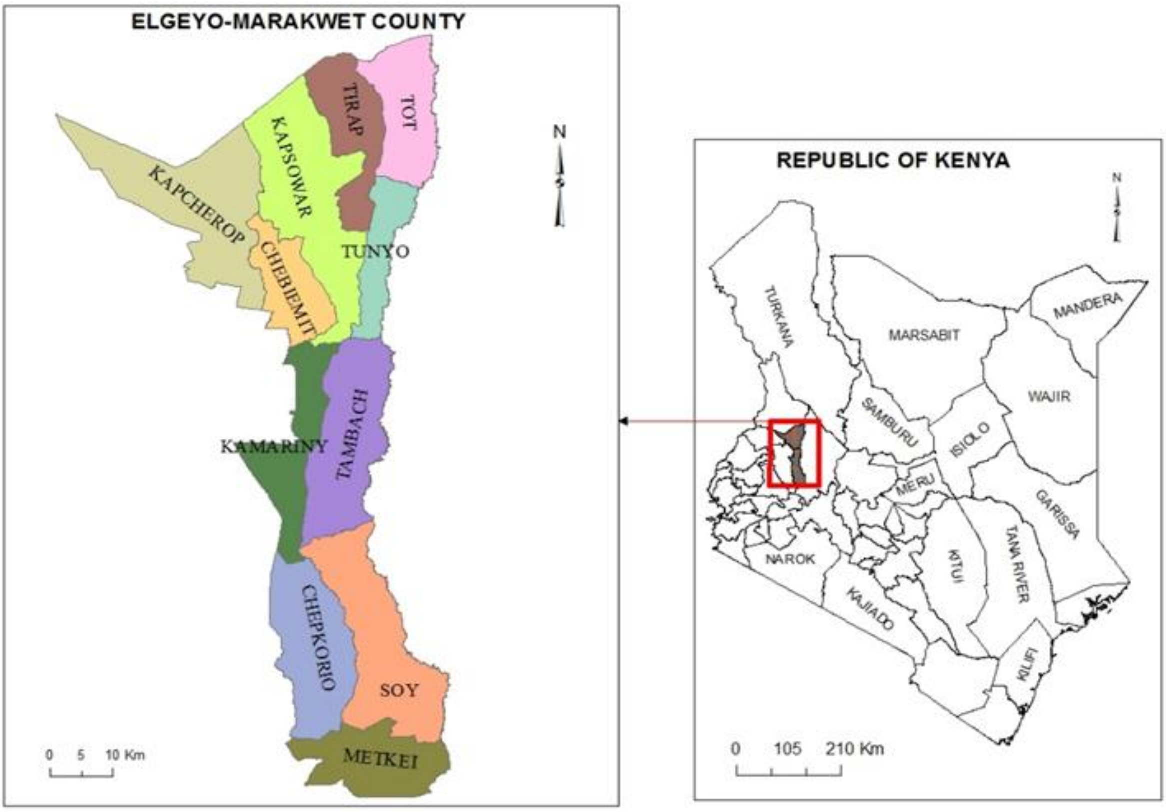


Figure 1: Study area

Table 1: Data sets used in the project

Data set	Description
Satellite image	Tiff format, USGS website, date 24th Aug 2015, resolution 1-arc-second
Roads	Shapefile format, Kenya National Bureau of Statistics (KNBS), year 2001, scale 1:50,000
Climate (rainfall, temperature) and weather stations	MS Excel, Kenya Meteorological Department (KMD), year 1980-2014,
Topography (Elevation and slope)	Tiff image, USGS website, date 17TH OCT 2011, resolution 1-arc-second
Soil depth, drainage, texture, PH, CEC	Shapefile, Kenya Soil Surveys, year 2015
Existing coffee farm	Handheld GPS, Questionnaire, date July 2015
AHP ratings	MS word, Questionnaire, June 2015
Training sites	Handheld GPS, GPS mapping, July 2015, 10m resolution
Administrative boundaries	Shapefile, Survey of Kenya, 1992, 1:250,000

3.2. Methodology

The process of carrying out a comprehensive crop-land suitability analysis requires a consideration of a number of criteria. Figure 2 below summarizes the approach followed in identifying areas for coffee farming. Multi-criteria decision making analysis was integrated with GIS, AHP and remote sensing in creating the suitability map. The process started with the acquisition and processing of data. Data preparation process included the preprocessing, classification, standardization and reclassification of various data sets.

The landsat8 satellite image tiles were downloaded and imported into ArcGIS 10.3 software then mosaicked into a continuous image, projected into UTM zone 36N and WGS84 datum, and clipped to the study area extend. In order to obtain land cover map the image was imported into envi 5.0 image processing software then layer stacked into one multiband image, after which image correction was done. Image correction for atmospheric effects was done through radiometric correction. The final task involved carrying out supervised classification comprising of five classes namely: agricultural, forest, bushland, woodland and swamp.

After processing, all data sets were imported into the geodatabase in feature class and raster formats. By using data stored in geodatabase, standardization of the various criteria into a common standard was possible. Analytical hierarchical process (AHP) was used to determine the weights of the criteria based on a common standard using Saaty scale of numbers 1 to 9 (Alexander, 2012; Saaty, 2008). The scale uses 1,2,3,4,5,6,7,8, and 9 to denote preference intensities as equal importance, equally to moderate, moderate importance, moderate to strong, strong importance, strong to very strong, very strong importance, very strong to extremely, and extreme importance respectively (Lifang, Yichuan, & Wei, 2008). Pairwise comparison matrices for the main and sub criteria were established, eigenvectors were calculated using geometric mean method, then normalized and computed as percentage weights.

Consistency was checked by calculating consistency ratio (CR). CR less than 0.1 implies the pairwise comparisons are consistent (Triantaphyllou & Mann, 1995). Having determined the weights, a GIS-based model was created and combined with the weighted overlay tool and used to link and overlay all the criteria with their respective weights to produce suitability maps. Validation, verification and comparative analysis for Arabica and Robusta coffee was thereafter undertaken to confirm the accuracy of the results. Validation involved comparisons of the existing coffee farms as mapped with the model results of coffee suitability maps.

4. Results and Discussion

4.1 Spatial distribution of coffee suitability criteria

A number of criteria were identified as essential for coffee production. Euclidean distances in meters were generated from the road networks in the study area and the results presented in Figure 3. The map demarcates regions according to how far they are from the roads. The least distant areas are shaded in yellow (0-1,284 m) and the most distant regions shown by the blue color (8,282-16,355 m). Figure 4 and Figure 5 show temperature and rainfall distributions for the years ranging from 1984 to 2014 respectively. Temperature ranges between 20 ^{0}C and 28 ^{0}C whereas rainfall varies from 1,141 to 1,845 mm. Analysis for elevation in meters was carried out and presented in Figure 6. The map indicates that the area rises from an altitude of 896 m up to 3,486 m. Slope was derived from elevation in degrees as characterized in Figure 7. The area is compost of flat and very steep slopes up to 70^{0}. Soil cation exchange capacity (CEC) spatial distribution ranging between 7 to 96 meq/100g is summarized in Figure 8. Soil pH, depth, texture, and drainage are shown in Figure 9, Figure 10, Figure 11 and Figure 12.

The study area has acidic soils with pH values in the range 5.1-8.3. It can be seen from the soil texture and soil drainage maps that the county is generally well drained, loamy and clayey. Land cover reclassification results are summarized in Figure 13 and Figure14. The major land cover classes in the map are Agriculture, Forest, bushland, and woodland. It is evident a good amount of land is available for agricultural production.

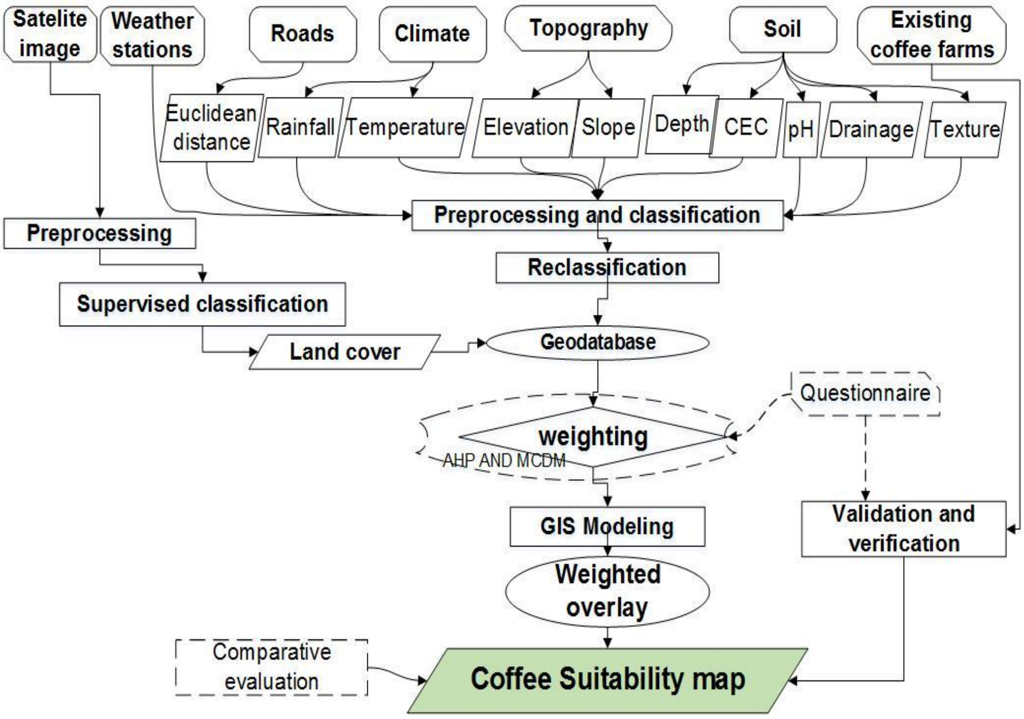
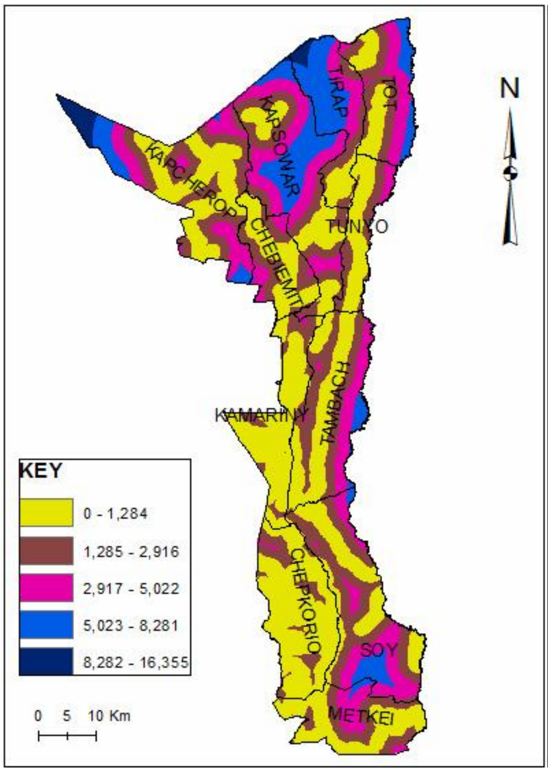


Figure 2: Methodology developed for coffee suitability analyses



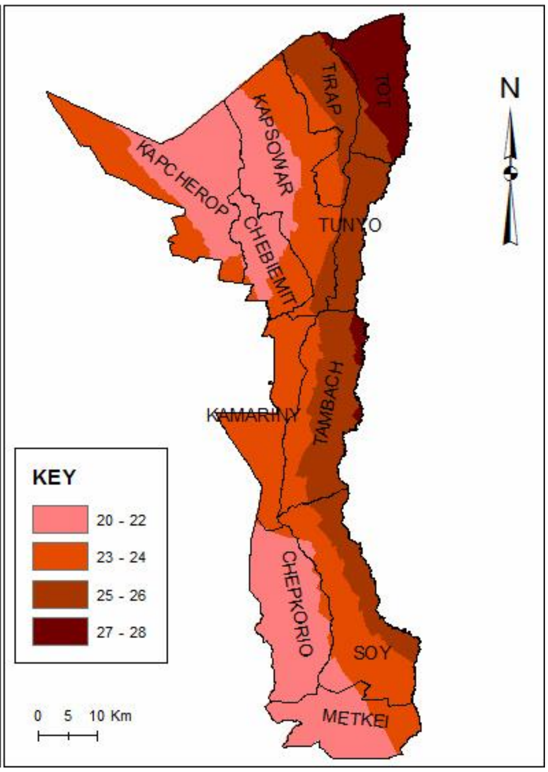


Figure 3: Euclidean distances in meters **Figure 4**: The annual mean temperature in ^{0}C

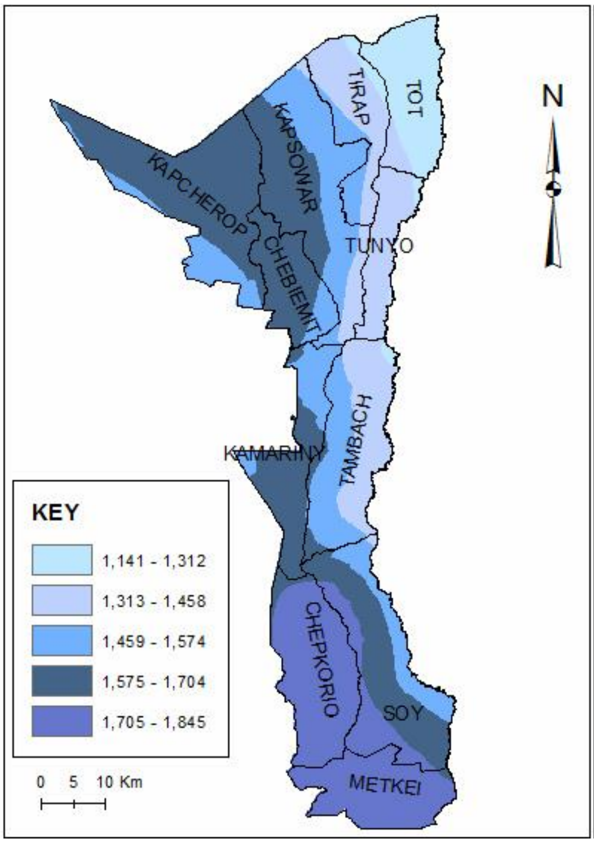


Figure 5: Annual total rainfall in mm

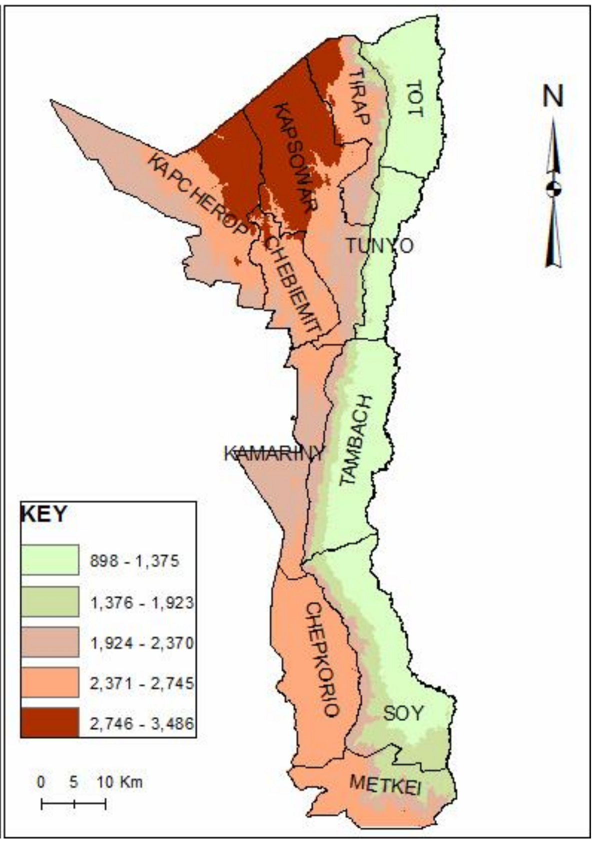


Figure 6: Elevation in meters

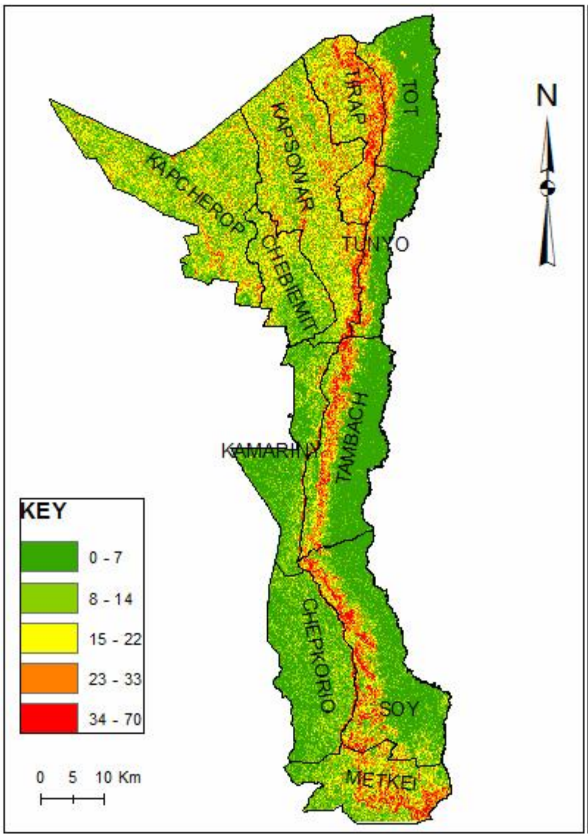


Figure 7: Slope in degrees

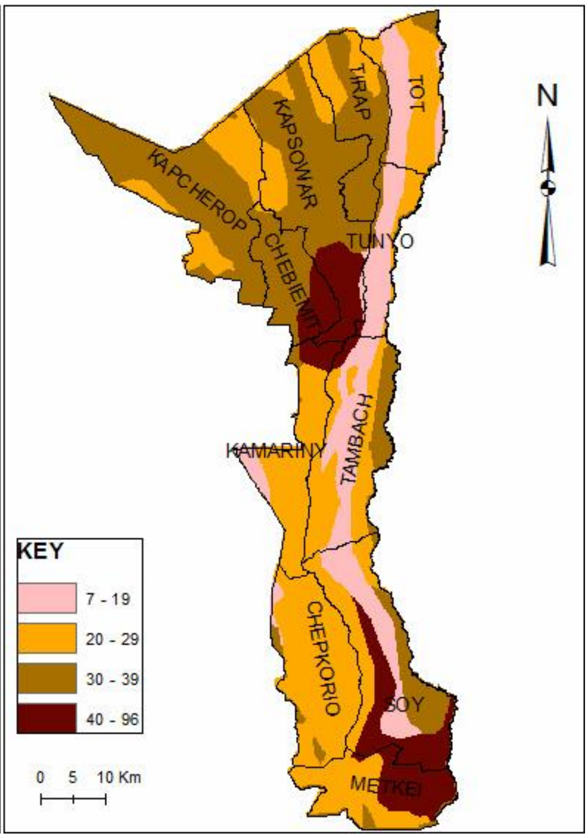


Figure 8: Soil CEC in meq/100g

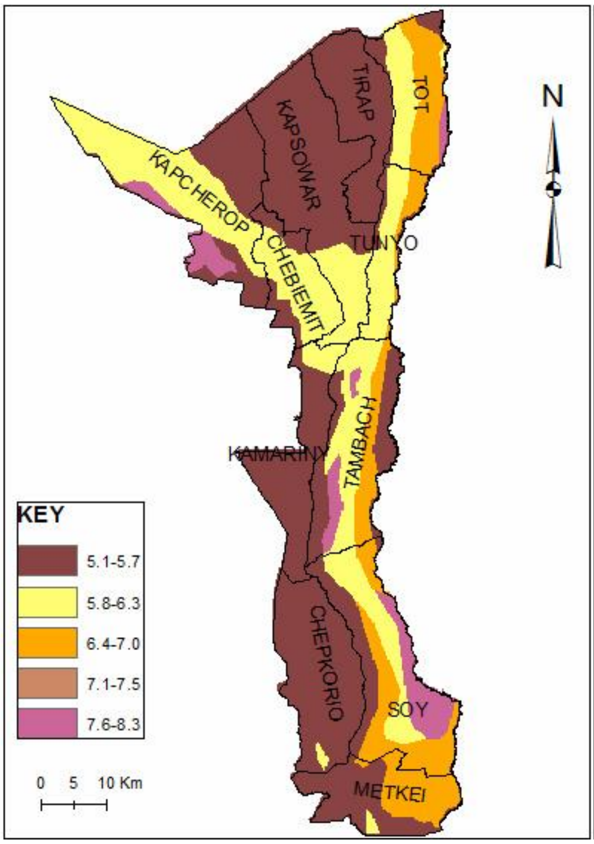


Figure 9: Soil pH

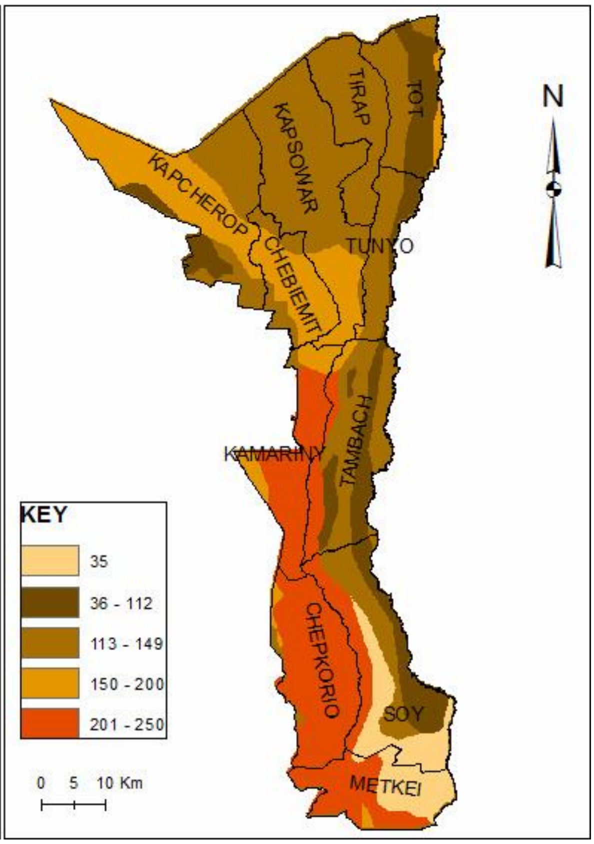


Figure 10: Soil depth in meters

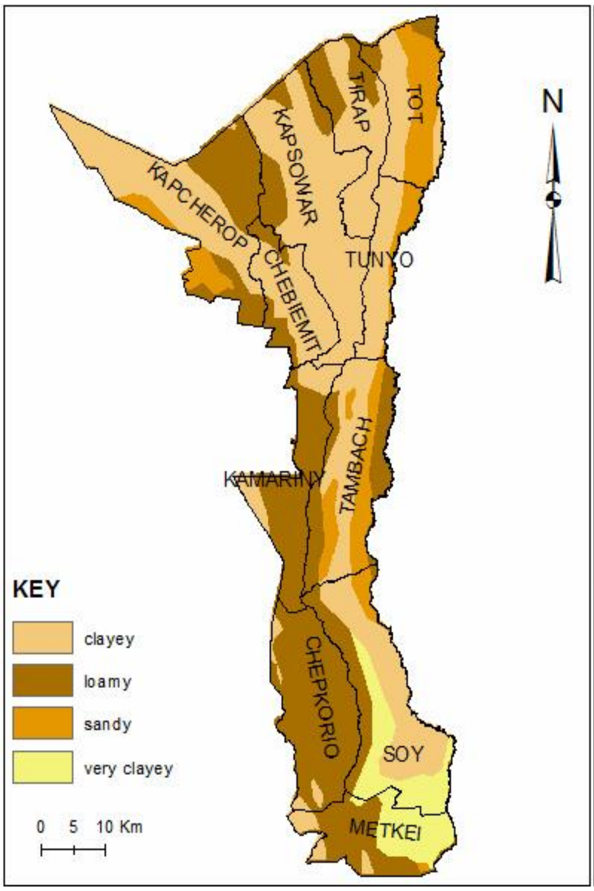


Figure 11: Soil texture

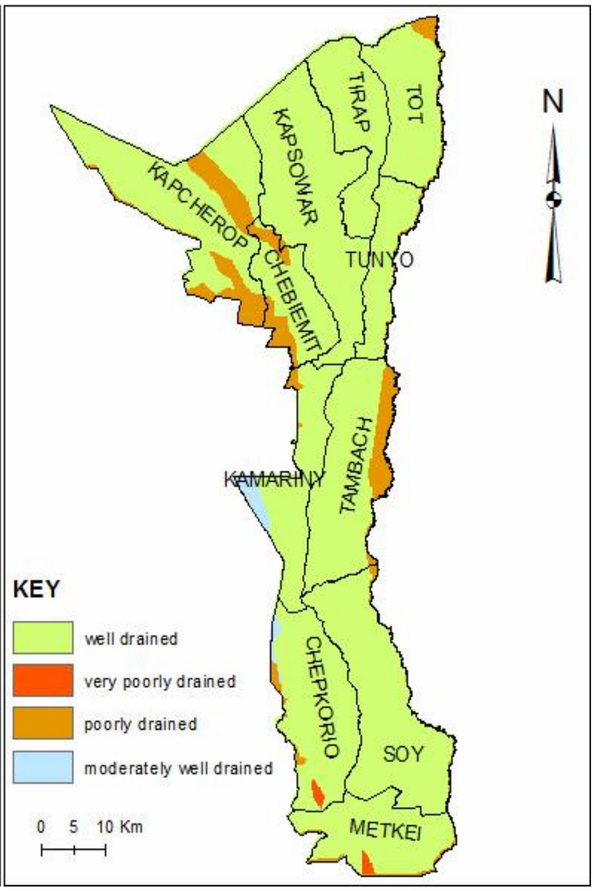


Figure 12: Soil drainage

4.2 Land cover

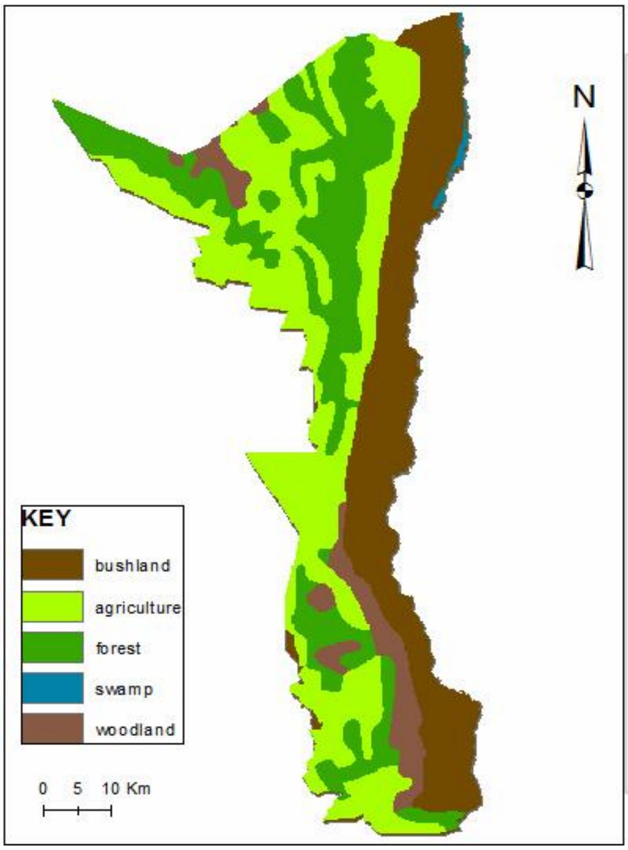


Figure 13: Land cover types

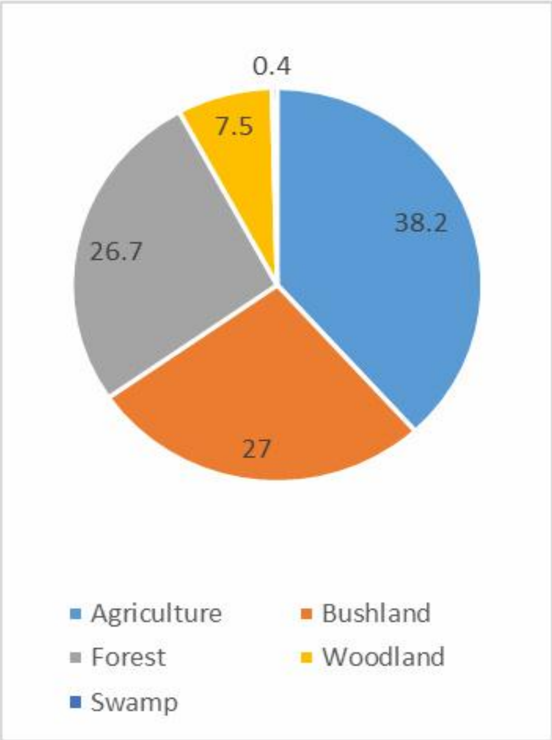


Figure 14: Land cover percentage

4.3. AHP Weighting and modeling

Analytical hierarchical process (AHP) was used to determine the weights of the criteria based on a common standard as developed by Saaty (Alexander, 2012; Saaty, 2008). The results are summarized in Tables 2, 3 and 4.

Table 2: Pairwise comparison matrix and weights for the main criteria

	Climate	Soil	Road	Land cover	Topography	Eigenvector	Weights (%)
Climate	1	2	7	3	5	2.9137	43.4
Soil	½	1	6	3	5	1.1826	26.6
Road	1/7	1/6	1	½	1/4	0.3124	4.7
Land cover	1/3	1/3	5	1	4	1.1732	17.5
Topography	1/5	1/5	4	¼	1	0.5253	7.8

Maximum eigenvector=5.4197, CI=0.1049, n=5 CRI=1.12, CR=0.0937

Table 3: Pairwise comparison matrix and weights for Sub-criteria

	Roads	Drainage	Rainfall	Depth	Slope	Temperature	Elevation	PH	CEC	Texture	Eigenvector	Weights (%)
Roads	1	1/3	1/3	1/3	1/3	1/5	1/3	3	1/2	1/5	0.034	3.39
Drainage	3	1	1/3	1	1/3	1/3	1/2	1	3	1/2	0.061	6.06

Rainfall	3	3	1	3	3	1/3	3	3	5	5	0.186	18.57
Depth	3	1	1/3	1	1/3	1/3	1/2	1	3	3	0.073	7.25
Slope	3	3	1/3	3	1	1/5	1/3	1/2	3	2	0.082	8.24
Temp	5	3	3	3	5	1	3	5	5	5	0.270	26.97
Elevation	3	2	1/3	2	3	1/3	1	2	3	2	0.114	11.44
PH	1/3	1	1/3	1	2	1/5	1/2	1	2	1/2	0.053	5.31
CEC	2	1/3	1/5	1/3	1/3	1/5	1/3	1/2	1	1	0.036	3.63
Texture	5	2	1/5	1/3	1/2	1/5	1/2	2	1	1	0.059	5.93

Maximum eigenvector=11.1191, n=10, CRI=1.49, CI=0.1243, CR=0.08345

Table 4: Overall criteria weights

Criteria	w_1	Sub-criteria	w_2	Product weight	Normalized weight	Weight (%)
Climate	0.434	Rainfall	0.186	0.0807	0.252	25.2
		Temperature	0.270	0.1172	0.366	36.6
Topography	0.078	Elevation	0.114	0.0089	0.028	2.8
		Slope	0.082	0.0064	0.020	2.0
Soil	0.266	Depth	0.073	0.0194	0.061	6.1
		CEC	0.053	0.0141	0.044	4.4
		Drainage	0.061	0.0162	0.051	5.1
		Texture	0.059	0.0157	0.049	4.9
		pH	0.036	0.0096	0.030	3.0
Roads	0.047	Roads	0.034	0.0016	0.005	0.5
Land cover	0.175		0.175	0.0306	0.096	9.6

Table 2 and Table 3 show the pairwise comparison matrix, eigenvector and the preference weights for the main criteria and sub criteria respectively. Maximum eigenvector, consistency index (CI), order of the matrix (n), consistency random index (CRI) and the consistency ratio (CR) were computed from the two tables and placed immediately below. The overall normalized and percentage weights obtained by multiplying the main criteria weight (w_1) by the sub criteria weight (w_2) are shown in Table 4.

4.3. Weighted overlay analysis

The various data set layers together with their weights were overlayed using the weighted overlay tool and the suitability maps for Arabica and Robusta coffee generated. The input criteria used in the analysis process were in different dimensions and varied numbering system. It would be impracticable to have an integrated analysis involving such dissimilar criteria without a common standard of measurement. The weighted overlay analysis method demands that every criterion be reclassed into a uniform priority scale, such as 1 to 9, with 9 being the most desirable. The weighted overlay tool works only with integer input rasters. Continuous rasters must be reclassed into ranges and then integers assigned. Validation and comparative evaluation results are shown in Figure 21while the final suitability map for Arabica coffee obtained by the weighted overlay which factored in all the criteria weights are shown in Figure 15 and 17. It is observable that more than half of the area is suitable for the cultivation of Arabica coffee. Robusta coffee final map of suitability is as shown in Figure 19 and it is described by the pie chart Figure 18. About 20% of the area is suitable for the production of Robusta coffee. Validation for the suitability maps for Arabica and Robusta was done by overlaying them with the existing coffee farms as in Figure 16 and Figure 20 in that order. The areas identified as suitable coincide with most of the existing coffee farms.

The overall suitability results for Arabica and Robusta were again subjected into a comparative evaluation. The comparison results are shown in a graph in Figure 21. The bar graph shows Arabica coffee is more suited to be grown in the study area than its counterpart Robusta.

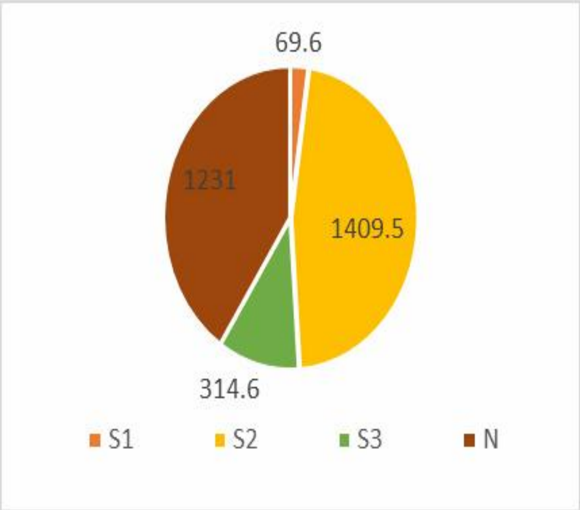


Figure 17: Arabica coffee suitability area in Km^2

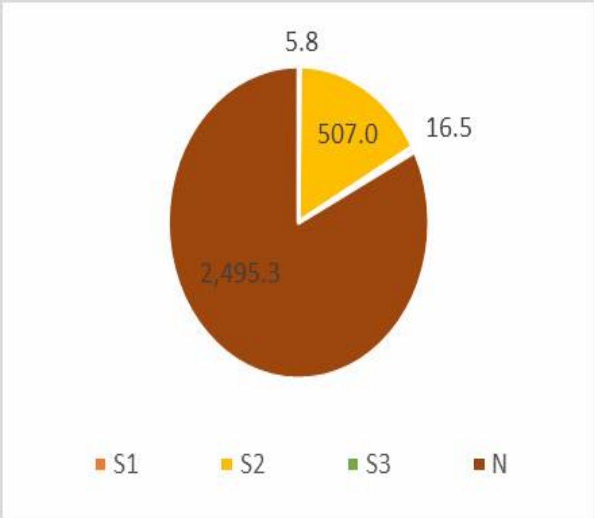


Figure 18: Robusta coffee suitability area in Km^2

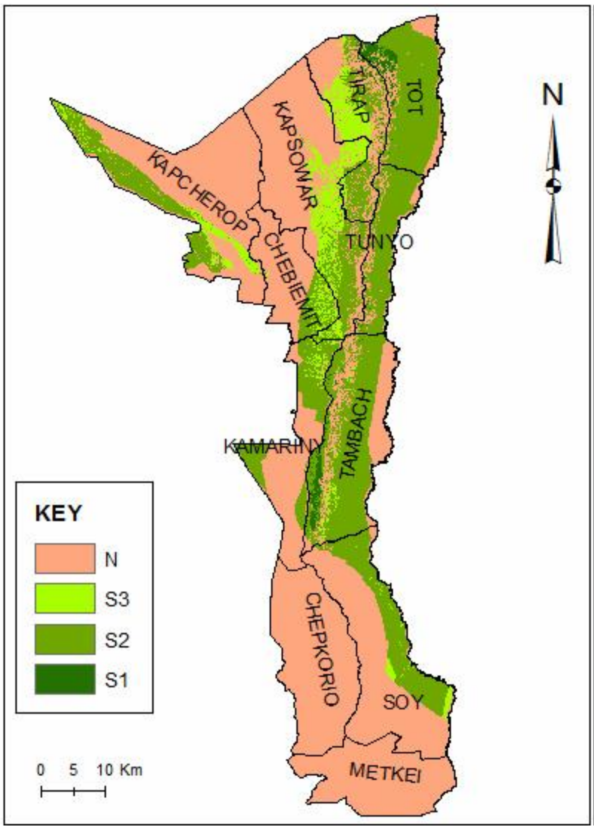


Figure 15: Suitability map for Arabica coffee

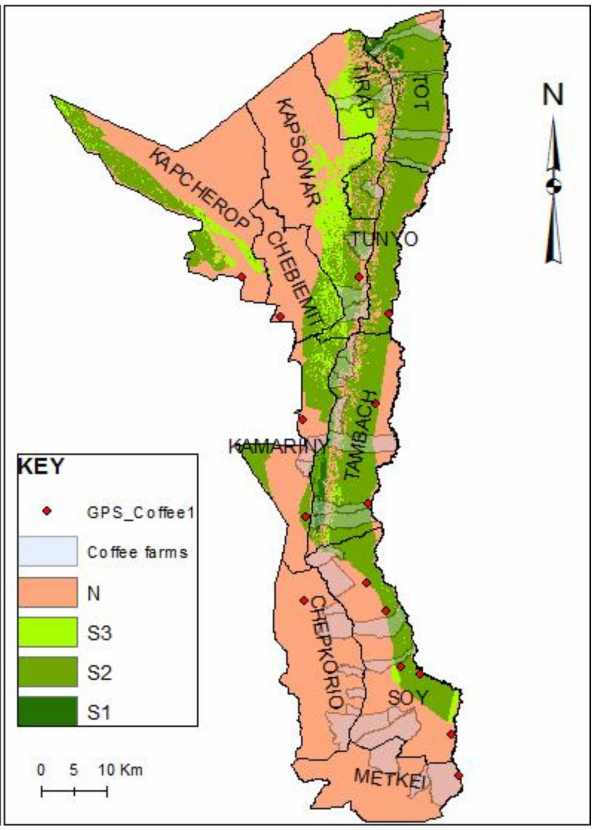
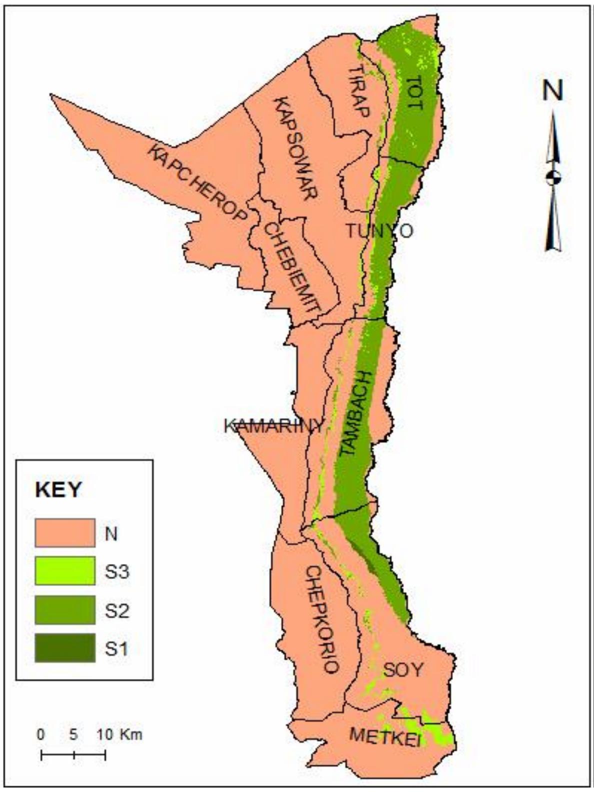


Figure 16: Validation of suitability for Arabica



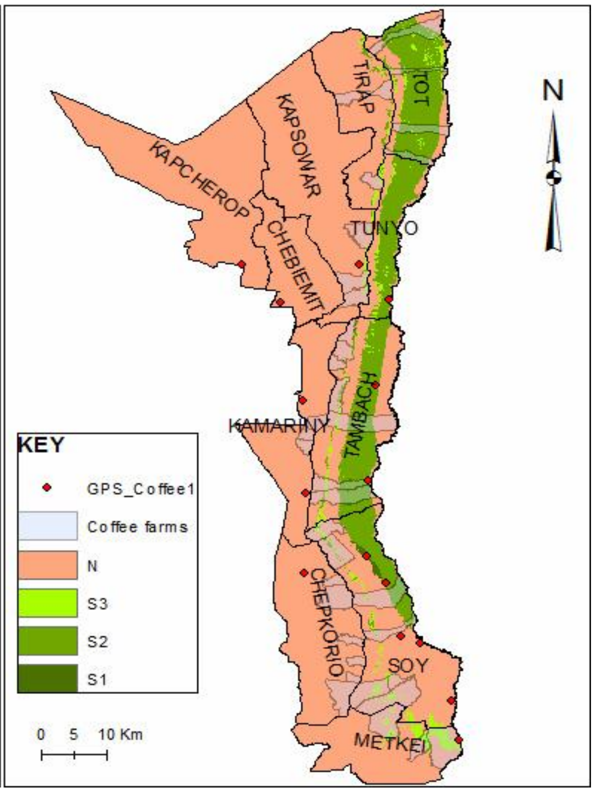


Figure 17: Robusta coffee suitability **Figure 18:** Validation suitability for Robusta

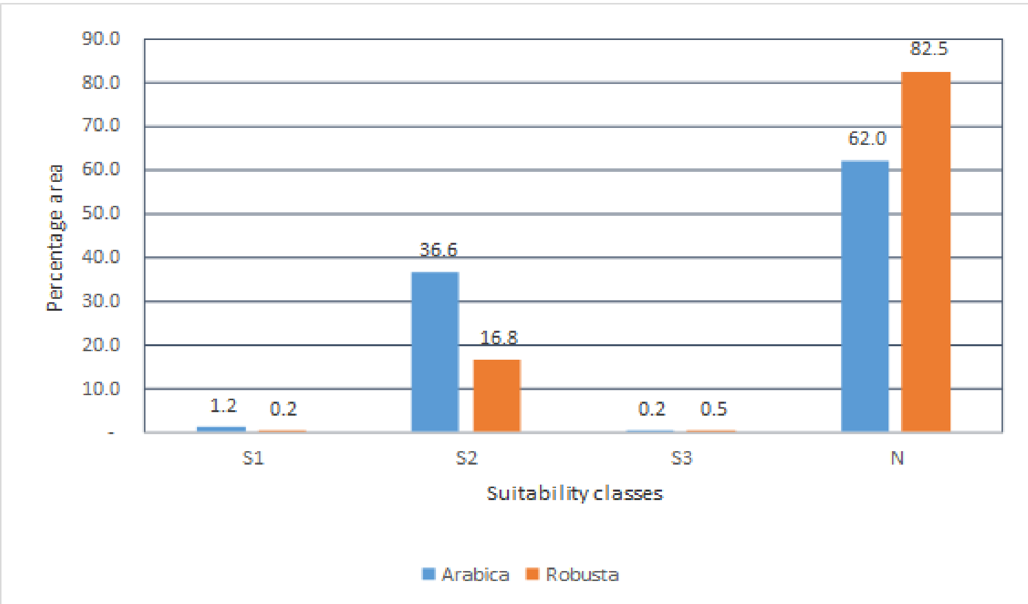


Figure 19: Comparative evaluation of suitability for coffee

5. Conclusion

Declining coffee production has resulted in increased levels of poverty in Kenya. This study was undertaken as a means of enhancing sustainable production of agricultural produce in the study area. Results show that Arabica coffee is more suited to be grown in the study area than Robusta coffee. Field work comparisons indicated that coffee is currently being produced within the spatial model results area, which indicates accuracy of the model developed. This study serves to give a comprehensive spatial information to farmers, agricultural extension officers and the county government that could guide them in selecting the best places to practice coffee farming. Similar land suitability analysis could be developed, for other crops and could be extended to cover larger areas of the country to improve food security and economic prosperity.

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