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ORIGINAL RESEARCH ARTICLE

Exploring optimal land suitability for coffee production in Abaya and Gelana Districts, West Guji Zone, Oromia, Southern Ethiopia

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Abstract: Coffee production in Abaya and Gelana needs précis land mapping amid and climate issues to increase sustainable yields. This study aimed to analyze optimal land suitability for coffee production in Abaya and Gelana Districts using Geographical Information System, Remote Sensing, and Analytical Hierarchy Process-based techniques. A mixed-methods approach was adopted using an explanatory sequential research design, combining quantitative analysis of questionnaires from 398 respondents with qualitative insights from interviews. The coffee suitability map areas were classified as highly (S1), moderately (S2), or marginally suitable (S3) based on weighted factors in accordance with Food and Agriculture Organization guidelines. In the Abaya District, 19.6% of the land is highly suitable, 43% moderately suitable, and 0.49% marginally suitable for coffee production. In the Gelana District, 5.1% of land is highly suitable, 15% moderately suitable, and 71.5% marginally suitable. Cross-tabulation results indicated that climate (99.07%), soil fertility (97.5%), and infrastructure (98.59%) are the main determinants of coffee land suitability, with economic factors being secondary. The results are supported by focus group discussions and key informant interviews, which suggest that the community is concerned about inadequate roads restricting access to markets and support services, fluctuating rainfall interfering with planting, and deteriorating soil fertility affecting production. The study identified optimal coffee-suitable land in the northern, central, and southern parts of the Abaya District and in the southwest and northwest parts of the Gelana District. The Abaya District has more highly suitable land for coffee, supporting larger-scale farming, while the Gelana District offers smaller but viable areas for localized production. To enhance productivity in these areas, the study recommends advancing infrastructure, adopting sustainable practices, and addressing economic and technological challenges.

Keywords: Abaya District; Coffee production; Gelana District; Land suitability; Optimal

1. Introduction

Ethiopia is recognized as the origin of Arabica coffee and is a major supplier in the global coffee market, impacting millions of farmers' livelihoods and the country's economy.[1,2] Moreover, the country has substantial potential to increase coffee production due to its ideal growing conditions suitable altitudes, moderate temperature, fertile soil, access to high-quality native planting materials, and favorable rainfall.[3,4] However, as climate change progresses, previously unsuitable areas for coffee farming may become viable, prompting an upslope migration to cooler regions.[5] This shift will require adjustments and the development of new coffee-growing areas, with altitudes above 2000 m becoming more favorable, while lower altitudes may decline.[6]

Ethiopia's highland areas face intense population pressure, driving demand for agricultural land and causing land disputes and resource degradation.[7,8] This situation underscores the importance of land suitability evaluations for effective land management and planning.[9] Several factors, such as climate, land cover, soil characteristics, elevation, and slope, may influence crop production, including coffee.[10] Identifying suitable areas based on these factors is essential for profitable and sustainable agriculture, as improper practices and inadequate research can hinder productivity.[11] Likewise, inadequate crop handling technology, weak collaboration among producers, and reduced planting areas contribute to low coffee profitability.[12] In addition, poor crop management and planting in unsuitable places can lead to reduced productivity.[13]

The Guji coffee area, encompassing Abaya and Gelana Districts, is a significant coffee-producing area in Ethiopia.[14] It is known for its predominantly agricultural landscape and favorable elevations (1075 – 2511 m), ideal for high-quality coffee production.[15] However, coffee production is challenged by climate change, weather variability, soil degradation, water scarcity,[16] and technological limitations, such as limited modern farming techniques, poor infrastructure, and market fluctuations.

Several studies have examined the physical suitability of land for Arabica coffee production in Lembah Gumanti, Indonesia,[17] Rwanda,[18] and Kenya.[19] In several regions of Ethiopia, land suitability analyses for various cereal crops have been conducted[13,20,21] studied land suitability for Arabica coffee but overlooked factors such as climate change, socioeconomic conditions, and spatiotemporal differences. In general, previous research often omitted key factors like microclimate and proximity, and the studies varied widely in objectives, study locations, and depth of analysis.[22]

To date, no studies have been conducted in the Abaya and Gelana Districts, specifically using a Geographical information system (GIS) and multi-criteria analysis techniques to evaluate optimal land suitability for coffee production. Therefore, this study aims to analyze optimal land suitability for coffee production in the study area to support informed decision-making by farmers and policymakers. The specific study objectives are to (i) analyze the biophysical and socioeconomic factors determining optimal land suitability for coffee production; (ii) classify land areas based on their level of suitability for coffee production; and (iii) develop a spatial optimal land suitability map for coffee farming in the study area.

2. Methods

2.1. Study area

2.1.1. Location

The Abaya District is one of 10 districts in the West Guji Zone of Oromia, Ethiopia. The Abaya District is located 365 km south of Addis Ababa, between latitudes 6°10'N – 6°20'N and longitudes 38°00'E – 38°10'E (Figure 1). It is bordered by the Southern Nations to the north and east, Lake Abaya to the west, and the Gelana District to the south.[23]

The Gelana District is located in the West Guji Zone, about 470 km south of Addis Ababa, between latitudes 5°40'E – 6°20'E and longitudes 37°50'N – 38°10'N (Figure 1). It borders the Amaro District to the south, Bule Hora and Burji Districts to the southeast, the Gedio Zone to the north and northwest, the Abaya District to the northwest, Lake Abaya to the west, and the Nech Sar National Park and Gamo Gofa Zone to the southwest.[24]

2.1.2. Climate and socioeconomic characteristics

The Abaya District has two agro-climatic zones – mid-highlands (40%) and lowlands (60%) – located 1104 – 2305 m above sea level. The average annual temperature ranges from 25.1°C to 30.6°C, and annual rainfall varies between 470 and 1828.7 mm. The Gelana District consists of midlands (30%) and lowlands (70%), with elevations of 1075 – 2511 m. The average annual temperature ranges from 17°C to 23°C and rainfall from 1396 to 1710 mm.

The Abaya District has a population of 103,348,[25] with 3.42% residing in urban areas. In terms of land use, 41% is arable – 28.7% used for annual crops, 35% for pasture, and 15% for woodland. Key crops include haricot beans, maize, and coffee, cultivated on over 5000 ha. Farming depends on livestock for transport and traditional irrigation.[24]

The Gelana District has a population of 71,369,[25] with a population density of 73.60 people/km² over 135,543 km².[6] The farming system combines crops and livestock, focusing on cash crops, such as coffee, maize, sorghum, and wheat, and pulses, such as chickpeas,

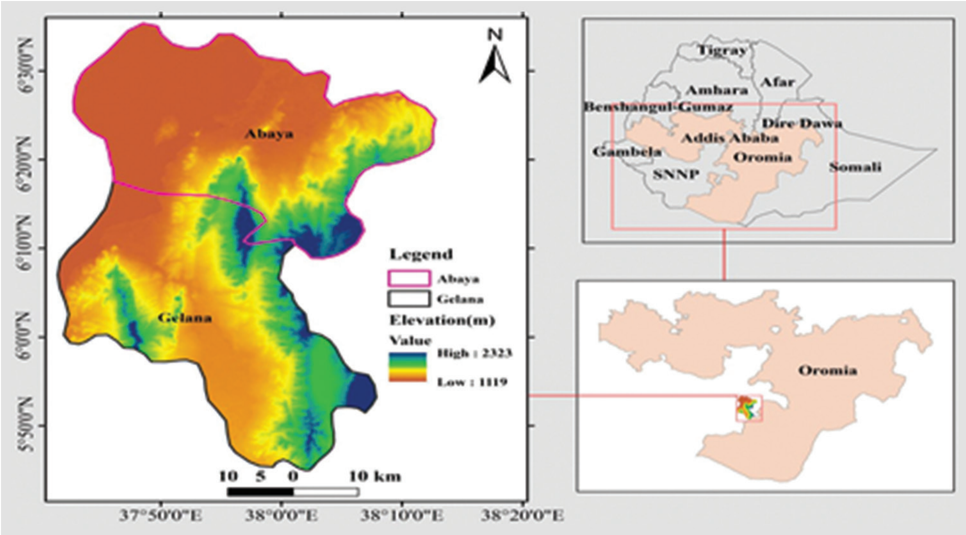

Figure 1. Map of the study area showing Abaya and Gelana Districts in the West Guji Zone, Oromia Region, Ethiopia. The map highlights the geographical boundaries of the two Districts and their surrounding areas, illustrating the spatial context for analyzing for optimal land suitability for coffee production. The coordinates of each Woreda and key neighboring regions are indicated for reference.

field peas, and fava beans. Enset serves as a staple food, with livestock supporting farming activities and some traditional small-scale irrigation.

2.1.3. Coffee production

In the Oromia region, Abaya and Gelana are prime coffee-producing areas with favorable agro-ecological conditions. Traditional agroforestry integrates coffee farming with food crops, livestock, and mixed-tree planting.[14] However, coffee production has declined due to limited adoption of improved practices, lack of sustainable agronomic management, climate change, land conversion to khat, and falling international coffee prices.

2.2. Research design

The study used a mixed-methods approach that combined quantitative and qualitative data to assess land suitability for coffee production. The approach involved satellite image analysis and household surveys in Abaya and Gelana Districts, followed by an explanatory sequential design to integrate and interpret the data.[26]

2.2.1. Household surveys

The study used probability and non-probability sampling procedures to determine the sample size. First, both Abaya and Gelana Districts were purposively selected based on their coffee-production potential. Subsequently, five kebeles were selected by simple random sampling from the two districts; two from Gelana (Giwe and Jirme) and three from Abaya (Odo Mike, Guwnagwa Badiya, and Bunata). Equation I was used to determine the sample size for the study from a total of 7553 household heads from both districts.[27]

$$n = \frac{n}{1+N(e^2)} \qquad \text{(I)}$$

= 7,553 = 7,553 = 7553
1+7,553(0.05)^2 1+7,553(0.0025) 1+18.883
n= 398

where n is the sample size, e is the level of precision, and N is the total population. The confidence level was set at 95%, with a precision level (margin of error) of 0.05.

The study evaluated coffee land suitability using primary data from 398 samples (248 from the Abaya District and 150 from the Gelana District), observations, interviews, and focus groups and secondary data from GIS and multi-criteria analysis. Primary data included input from household heads, experts, and focus groups, while secondary data covered topography, soil, meteorological information, and land use. Qualitative data were transcribed, translated, and analyzed to identify key factors.

2.2.2. Spatial datasets and sources

The study used GIS-based suitability analysis and Analytical Hierarchy Process (AHP)-based multi-criteria evaluation (MCE) to assess coffee land suitability.[28] ArcGIS 10.8 was utilized for mapping, while ERDAS Imagine 2015 was used to process the Landsat 8 images. The MCE model integrated various factors, including soil, topography, climate, proximity, and land use land cover (LULC) and assigned weights to evaluate their impact on coffee production.

2.3. Data analysis

2.3.1. Survey data analysis

Survey data were analyzed using SPSS V.26, applying descriptive statistics (frequencies and percentages) to outline socioeconomic characteristics. Cross-tabulations and Chi-square (χ^2) tests were employed to examine the impact of various factors, such as soil, topography, climate, and proximity, on coffee production in the Abaya and Gelana Districts.

2.3.2. Spatial data processing and analysis

In this study, we used MCE and GIS tools to assess land suitability for coffee production in accordance with Akpoti *et al*.[29] and Food and Agriculture Organization (FAO) guidelines,[30] evaluating factors such as topography, soil, land use, climate, and accessibility. MCE assessed both quantitative and qualitative data, providing a comprehensive overview of temperature, precipitation, soil condition (texture, depth, and pH), slope, land cover types, and infrastructural accessibility (proximity).[31] GIS enabled spatial analysis, with ArcGIS 10.8 used for mapping and ERDAS Imagine 2015 for processing Landsat 8 images.

Soil data (pH, depth, and texture) of the study area were sourced from the International Soil Reference and Information Centre (ISRIC) website (https://www.isric.org/explore/isric-soil-data-hub). Raster-formatted data were acquired, and the corresponding soil data for each study area were extracted and resampled in ArcGIS 10.8 to a resolution of 30 m. Soil maps were generated based on coffee crop requirements using land suitability categories from the Belay and Assen.[32]

Climate grid data were collected from the Hawassa Station and processed in ArcGIS 10.8 to estimate rainfall and temperature distributions. The temperature map was classified using Nagashree *et al*.,[33] and the same classification was applied to the rainfall map for assessing land suitability for coffee production. A digital elevation model (DEM) was used to analyze elevation and slope for Arabica coffee production.[34] Elevation ranged from 1104 to 2305 m in the Abaya District and 1075 to 2511 m in the Gelana District. Slope was calculated from the DEM data and reclassified according to Saleem *et al*.[35] Likewise, elevation and slope maps were also adjusted according to FAO guidelines.[36]

Landsat images (Operational Land Imager [OLI], Enhanced Thematic Map [ETM+], and Thematic Mapper [TM]) from 2023 were obtained from the United States Geological Survey (USGS; https://earthexplorer.usgs.gov/). ERDAS Imagine 2015 was used to create a LULC map through supervised classification. The maximum likelihood algorithm categorized pixels into cultivated lands, forests, grasslands, settlements, bare lands, woodlands, and water bodies[37] (Table A1). Accuracy assessments of the LULC classes were conducted following standard procedures.

Proximity is a key factor in assessing land suitability for coffee production. A close proximity to water sources ensures consistent moisture for coffee plants, reducing irrigation costs and enhancing yields.[12] Areas within 2 km of towns were excluded to prevent shadowing, as proximity to markets and transportation infrastructure reduces distribution costs and increases profitability.[38] Good road access improves transportation efficiency for both coffee and agricultural inputs and facilitates extension services, supporting better farming practices and productivity.[39]

2.3.3. Accuracy assessment

The classifications were compared with reference data to measure differences. Random pixel selection and standardized methods were used to reduce bias.[40]

The overall accuracy measures the percentage of correctly classified pixels across all classes, providing a metric for the map's overall correctness:[41]

$$Overall\ accuracy = \frac{Total\ number\ of\ correctly\ classified\ pixels}{Total\ number\ of\ reference\ pixel} \times 100\% \quad \text{(II)}$$

The Kappa coefficient evaluates classification accuracy by comparing reference data (ground truth data) and the observed classification results from classified map (e.g., coffee suitability classes derived from Landsat TM/OLI). A value > 0.8 indicates strong agreement, 0.4 – 0.8 indicates moderate agreement, and <0.4 reflects poor agreement.[42]

$$Kappa\ coeffcient = \frac{Total \times sum\ corrected - the\ sum\ of\ all\ the\ (row\ total \times column\ total)}{Total\ squared - sum\ of\ all\ the\ (column\ total)} \quad \text{(III)}$$

2.3.4. Determination of land suitability for coffee production

According to literature reviews, expert input, and local knowledge,[43] five main criteria and 11 factors were identified, including topography (elevation, slope), climate (temperature, rainfall), soil (depth, pH, texture), landscape (LULC), and proximity (to water bodies, roads, and towns) (Table 1).

Suitability data must be standardized, often through linear scale transformation.[44] This study used standardization and reclassification, with suitability ratings from 1 (most suitable) to 5 (least suitable), applying a weighted overlay for comparison (Table 1). The land suitability map categorized areas into five suitability classes based on: Yalew *et al*.[45] highly suitable (S1), moderately suitable (S2), marginally suitable (S3), not suitable (N1), and permanently not suitable (N2).

A weighted overlay integrates inputs by reclassifying advantageous areas to higher values, ensuring the total influence equals 100%. Using the weighted overlay tool in ArcGIS,[46] this method mapped land suitability based on standardized criteria:

$$S = wxi \qquad \text{(IV)}$$

Where S denotes suitability, Σ denotes the sum, w denotes the weights assigned to each factor, and xi denotes the factor scores (cells).

Mapping land suitability for coffee production involved generating an optimal suitability map by filtering areas based on criteria, converting data layers, and using selection tools to refine the best locations (Figure 2). The final map highlights prime sites with ideal conditions for coffee cultivation.

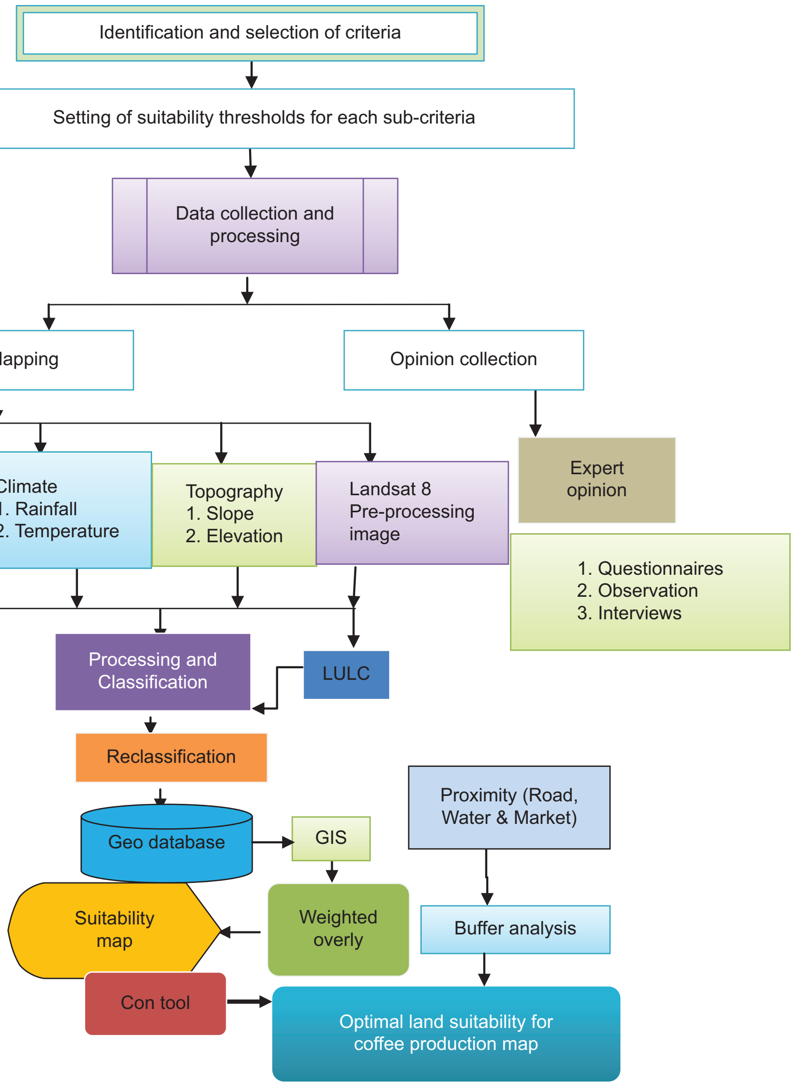

Figure 2. Method for analyzing optimal land suitability for coffee production

Abbreviations: GIS: Geographical information system; LULC: Land use land cover.

Table 1. Criteria and factors determining land suitability for coffee production

Criteria	Sub-criteria	Suitability range	Suitability class	References
Topography	Slope (%)	0 – 5	S2	2,18
		5 – 10	S1	
		10 – 20	S3	
		20 – 40	N1	
		>40	N2	
	Elevation	1100 – 1200 m	N1	
		1200 – 1600 m	S1	
		1600 – 2000 m	S2	
		2000 – 2300 m	S3	
Soil	Texture	Chromic Luvisols	S3	32
		Eutric Vertisols	S1	
		Humic Nitosols	S2	
		Lithic Leptosols	N1	
		Water bodies	N2	
		Eutric Fluvisols	N1	
		Eutric Leptosols	N1	
	pH	<3.5; >6.7	N1	21
		3.5 – 5.0	S3	
		5.0 – 5.5	S1	
		5.5 – 6.7	S2	
	Depth	>120 m	S2	
		<30 m	S3	
		30 – 90 m	S1	
Climate	Temperature	<17.5°C; >25°C	N1	29
		17.5 – 20°C	S2	
		20 – 22.5°C	S1	
		22.5 – 25°C	S3	
	Rainfall	470 – 860 mm	N1	
		860 – 1050 mm	N	
		1050 – 1200 mm	S3	
		1200 – 1400 mm	S1	
		1400 – 1900 mm	S2	
Landscape	LULC	Cultivated land	S1	47; Expert knowledge
		Forest land	S2	
		Woodland	S3	
		Settlement	S3	
		Grassland	N1	
		Bare land	N1	
		Water body	N2	
Proximity	Roads, rivers, and markets	Buffer analysis	S; N	12

Notes: Land suitability classification for this study was obtained from the FAO framework for land evaluation;[21,48] highly suitable (S1), moderately suitable (S2), marginally suitable (S3), not suitable (N1), and permanently not suitable (N2).
Abbreviation: LULC: Land use land cover.

3. Results and discussion

3.1. Factors determining optimal suitability for coffee production

3.1.1. Climate data (rainfall and temperature)

The Abaya District has an annual temperature range of 25.1 – 30.6°C and receives between 470 and 1828.7 mm of rainfall (Figure 3). Conversely, the Gelana District has an annual temperature range of 17 – 23°C and receives between 1396 and 1710 mm of rainfall (Figure 4). The analysis indicates that rainfall decreases proportionately with increasing temperatures in both districts. The differences in climate between Abaya and Gelana Districts have an impact on agricultural suitability, vegetation, and soil moisture. Rising temperature and decreasing rainfall are inversely correlated, which is

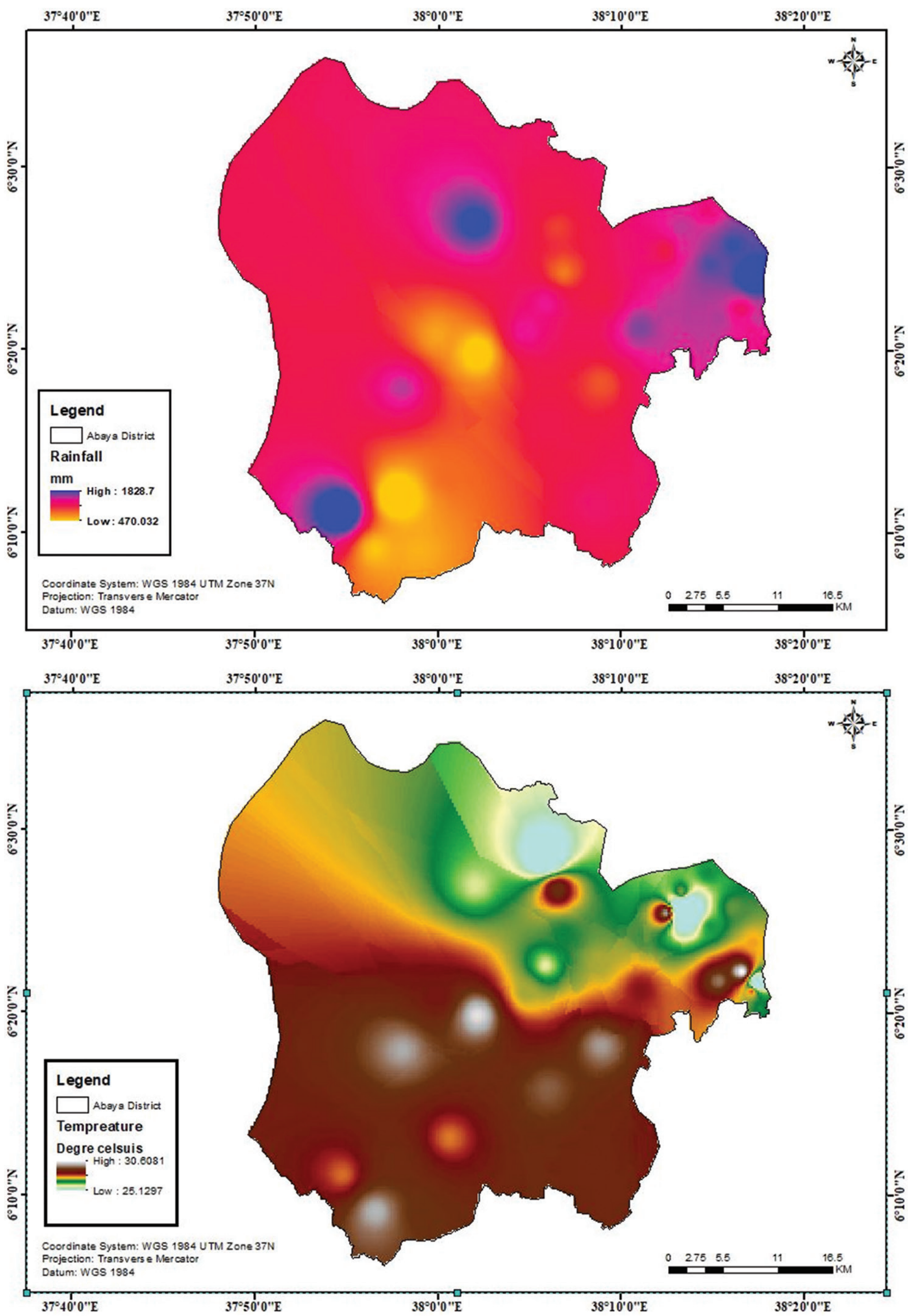

Figure 3. Mean annual rainfall (upper) and mean annual temperature maps (lower) of the Abaya District

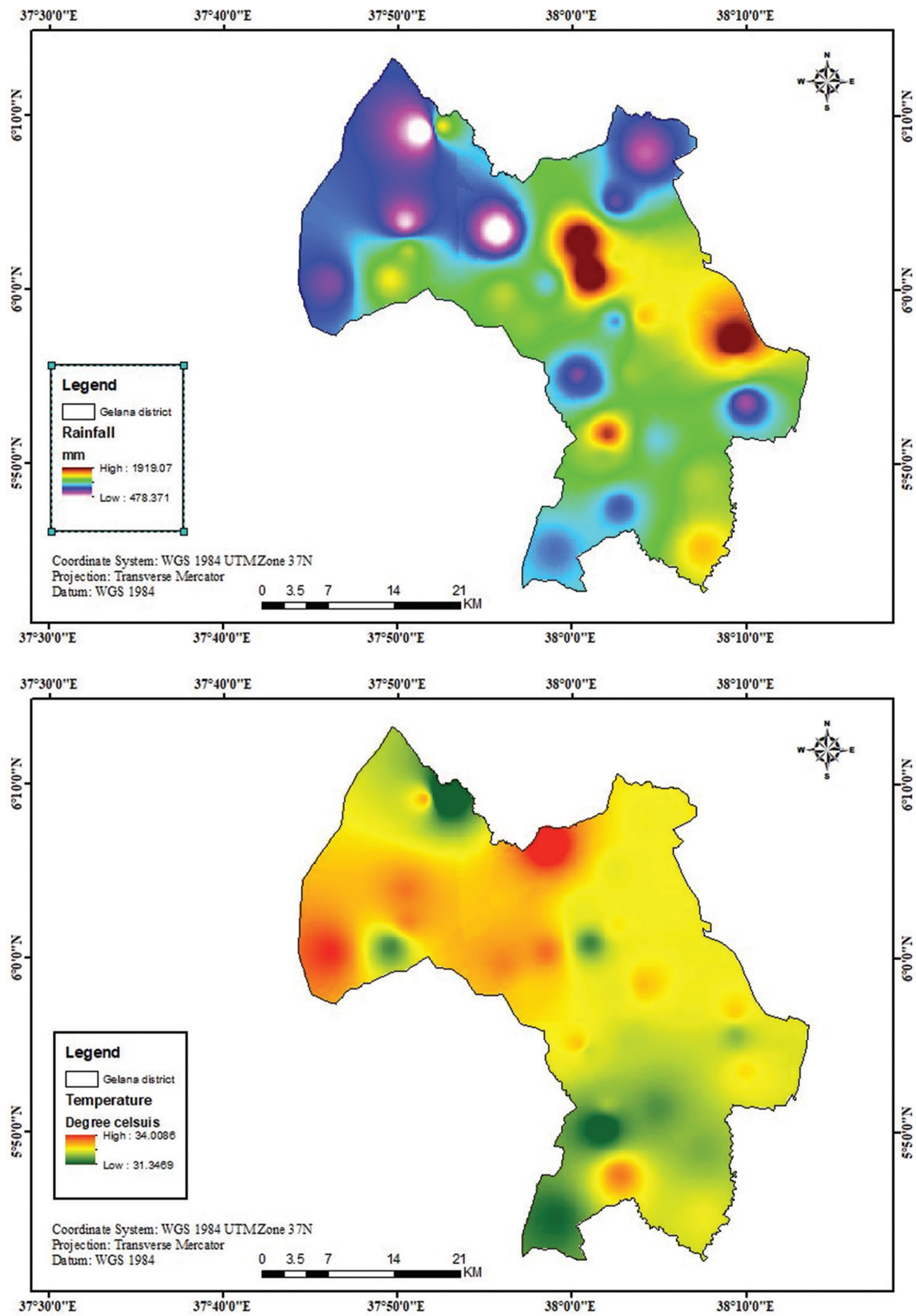

Figure 4. Mean annual rainfall (upper) and mean annual temperature maps (lower) of the Gelana District

indicative of larger regional climatic changes.[49,50] Rain-fed agriculture is strained by elevated temperatures, which increase evapotranspiration and reduce moisture availability.[51] In Abaya, erratic rainfall and high temperatures increase the risk of drought and flooding, threatening crops like coffee and accelerating soil erosion. Although Gelana is wetter and cooler, it is also experiencing emerging drying patterns that could affect the yield of perennial crops. These trends highlight the importance of implementing local adaptation strategies to protect against increasing climate stress, such as agroforestry, water collection, and climate-resilient crops.[52]

Table 2 and Figure A1 summarize the suitability class of the Abaya and Gelana Districts based on rainfall. In Abaya, rainfall suitability for coffee is as follows: 7.6%

highly suitable (1200 – 1400 mm), 15.2% moderately suitable (1400 – 1900 mm), 55.2% marginally suitable (1050 – 1200 mm), 17.1% not suitable (860 – 1050 mm), and 3.7% permanently not suitable (470 – 860 mm). In Gelana, the classifications are 16% highly suitable, 26.6% moderately suitable, 32.4% marginally suitable, 20.5% not suitable, and 3.3% permanently not suitable. These results are consistent with recent agro-ecological research indicating that coffee grows best with 1200 – 2000 mm of evenly distributed rainfall.[15] While Abaya's challenges necessitate focused support, Gelana's higher suitability offers greater potential for adaptive investments. Permanently unsuitable areas in both districts highlight the need for alternative drought-tolerant livelihoods and climate-resilient planning.

Optimal agricultural production depends on specific rainfall and temperature conditions.[1] In the study area, rainfall was classified into highly suitable, moderately suitable, and marginally suitable categories for coffee production, emphasizing its agronomic importance.[18] In Abaya, temperatures of 25 – 27°C are considered highly suitable, 27 – 29°C moderately suitable, and > 29°C marginally suitable for coffee production, with 0.1%, 20.8%, and 79.1% of land falling in these categories, respectively. In Gelana, 31 – 32°C is considered highly suitable, 32 – 32.5°C moderately suitable, 32.5 – 33°C marginally suitable, and > 33°C unsuitable for coffee production, with 5.8%, 21.6%, 46.9%, and 25.4% of land falling in these categories, respectively (Table 3 and Figure A2).

3.1.2. Elevation and slope

Elevation influences three important variables for Arabica coffee: temperature, humidity, and rainfall.[53] According to regional standards, the study categorizes elevations of 1200 – 1600 m as highly suitable, 1600 – 2000 m as moderately suitable, and 2000 – 2300 m as marginally acceptable. Heat and low humidity make areas below 1200 m unsuitable for Arabica coffee production.[54] In Abaya, 56.1% of the area has < 5% slopes; in Gelana, it is 56.2%. Both districts have smaller proportions of areas with > 10% slopes. According to Figure A3 and Table 4, elevations of 1200 – 1600 m are highly suitable for coffee, covering 62.7% of Abaya and 47.4% of Gelana. Likewise, elevations of 1600 – 2000 m are moderately suitable, 2000 – 2300 m are marginally suitable, and < 1200 m are unsuitable for coffee production.

Table 2. Rainfall suitability class of Abaya and Gelana Districts

Rainfall (mm)	Abaya District			Gelana District		
	Suitability class	Area (ha)	Area (%)	Suitability class	Area (ha)	Area (%)
1200 – 1400	S1	162378	7.6039634	S1	257040	16.09813197
1400 – 1900	S2	326808	15.30401945	S2	425602	26.65498429
1050 – 1200	S3	1178856	55.20438655	S3	517099	32.38534058
860 – 1050	N1	366942	17.18344565	N1	327651	20.52042109
470 – 860	N2	100455	3.704184947	N2	69315	3.341122072
Total	-	2135439	100	-	1596707	100

Notes: Highly suitable (S1), moderately suitable (S2), marginally suitable (S3), not suitable (N1), and permanently not suitable (N2).

Table 3. Temperature suitability class of Abaya and Gelana Districts

District	Temperature (°C)	Suitability class	Area (ha)	Area (%)
Abaya	25 – 27	S1	2851	0.133508848
	27 – 29	S2	443,706	20.77821001
	29 – 30	S3	1,688,882	79.08828115
	Total	-	2,135,439	100
Gelana	31 – 32	S1	93,973	5.885425441
	32 – 32.5	S2	346,104	21.67611215
	32.5 – 33	S3	750,139	46.98037899
	33 – 34	N1	406,491	25.45808342
	Total	-	1,596,707	100

Notes: Highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N1).

The study classified slopes for coffee production using a previously reported framework:[18] 0 – 5% as highly suitable (S1), 5 – 10% moderately suitable (S2), 10 – 20% marginally suitable (S3), 20 – 40% not suitable (N1), and > 40% permanently unsuitable (N2) for coffee cultivation in Abaya and Gelana Districts (Table 5 and Figure A4). The findings highlight the need for soil conservation practices, including mulching, terracing, and agroforestry, to enhance marginal lands and prevent deterioration in sloped areas.[55]

3.1.3. Soil texture

According to Figure A5 and Table 6, soil suitability for coffee production in Abaya and Gelana Districts can be classified as highly suitable (Eutric Vertisols), moderately suitable (Humic Nitosols), and marginally suitable (Chromic Luvisols). In Abaya, 48.1% is highly suitable, 1.4% moderately suitable, and 0.7% marginally suitable. In Gelana, 29.1% is highly suitable, 0.006% moderately suitable, and 26.1% marginally suitable. Other soil types, including Lithic Leptosols and water bodies, are unsuitable for coffee. These findings demonstrate distinct disparities in soil suitability; Gelana's prevalence of less fertile Chromic Luvisols and inappropriate Lithic Leptosols underscores the need for better land use planning and soil management, while Abaya's rich Eutric Vertisols can sustain coffee production. According to Martinez *et al*.,[13] the significance of focused interventions for sustainable coffee development is highlighted by the restricted availability of optimal Humic Nitosols in both districts.

3.1.4. Soil depth

Soil depth has a direct impact on root growth, water retention, and nutrient availability, making it a key factor in determining land suitability for perennial crops like coffee.[56] According to Mulugeta[57] land suitability classification, soil depth in this study was categorized as follows: deep soils (30 – 90 cm) are deemed moderately suitable (S2), moderately deep soils (< 30 cm) are marginally suitable (S3), and extremely deep soils (>120 cm) are highly suitable (S1). In the Abaya District, 33.2% (730,311 ha) of the land is marginally suitable (S3), 15.3% (325,837 ha) is moderately suitable (S2), and 50.5% (1,078,663 ha) of the land is extremely suitable (S1). By comparison, the Gelana District has a higher proportion of extremely appropriate terrain, with just 3.8% (77,364 ha) designated as S3, 25.5% (407,176 ha) as S2, and 69.7% (1,111,989 ha) as S1 (Table 7). The higher percentage of extremely deep soils in Gelana indicates greater potential for sustainable coffee production compared to Abaya, where shallow soils predominate and pose challenges related to fertilizer availability and moisture retention (Figure A6). This

Table 4. Elevation suitability class of Abaya and Gelana Districts

Elevation (m)	Suitability class	Abaya District		Gelana District	
		Area (ha)	Area (%)	Area (ha)	Area (%)
1200 – 1600	S1	134,4279	62.74801678	761803	47.49383418
1600 – 2000	S2	362,851	16.93709463	405220	25.26302927
2000 – 2300	S3	284,845	13.2959444	331098	20.64196847
1100 – 1200	N1	150,370	7.018944194	105883	6.601168077
Total	-	214,2345	100	1604004	100

Notes: Highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N1).

Table 5. Slope suitability class of Abaya and Gelana Districts

Slope class	Slope range (%)	Suitability class	Abaya District		Gelana District	
			Area (ha)	Area (%)	Area (ha)	Area (%)
Nearly flat	0 – 5	S1	1,197,154	56.10163916	898,128	56.26021842
Gently undulating	5 – 10	S2	640,715	30.02551195	461,117	28.885129
Rolling to hilly	10 – 20	S3	237,720	11.14015545	184,497	11.55719621
Steep	20 – 40	N1	54,578	2.557661973	48,999	3.069378131
Very steep	> 40	N2	3735	0.175031468	3641	0.228078242
Total	-	-	2,133,902	100	1,596,382	100

Notes: Highly suitable (S1), moderately suitable (S2), marginally suitable (S3), not suitable (N1), and permanently not suitable (N2).

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Table 6. Soil texture suitability class of Abaya and Gelana Districts

Soil texture/type	Suitability class	Abaya District		Gelana District	
		Area (ha)	Area (%)	Area (ha)	Area (%)
Eutric Vertisols	S1	1,027,079	48.11100374	465,281	29.14328521
Humic Nitosols	S2	30,506	1.428978959	98	0.006138316
Chromic Luvisols	S3	15,936	0.746482944	416,870	26.11101959
Lithic Leptosols	N1	16,327	0.764798383	229,740	13.38996724
Eutric Fluvisols	N1	5142	0.240864414	407,176	25.50382737
Eutric Leptosols	N2	325,837	15.26303734	77,364	3.845762276
Water bodies	N2	713,984	33.44483423	465,281	29.14328521
Total	-	2,134,811	100	1,596,529	100

Notes: Highly suitable (S1), moderately suitable (S2), marginally suitable (S3), not suitable (N1), and permanently not suitable (N2).

Table 7. Soil depth suitability class of Abaya and Gelana Districts

Soil depth	Suitability class	Abaya District		Gelana District	
		Area (ha)	Area (%)	Area (ha)	Area (%)
Very deep (> 120 cm)	S1	1,078,663	50.52733005	1,111,989	69.65041036
Deep (30 – 90 cm)	S2	325,837	15.26303734	407,176	25.50382737
Moderately deep (< 30 cm)	S3	730,311	33.20963261	77,364	3.845762276
Total	-	2,134,811	100	1,596,529	100

Notes: Moderately suitable (S2), marginally suitable (S3), and highly suitable (S1).

highlights the need for specific interventions in Abaya such as mulching, organic amendments, and agroforestry to improve soil quality. Increased productivity and climate resistance can also result from giving extremely deep soil regions priority for growth.[58]

3.1.5. Soil pH

Soil pH data for the study area, resampled to 30 m, have a pH range of 3.8 – 8.1 in the Abaya District and 3.1 – 7.5 in the Gelana District (Figure 5). The soil pH results indicate considerable spatial variability in both Abaya and Gelana Districts, ranging from strongly acidic (pH 3.1) to slightly alkaline (pH 8.1). This wide pH range suggests heterogeneous soil conditions that can greatly influence nutrient availability and crop suitability. Areas with low pH may face challenges such as aluminum toxicity and nutrient deficiencies, potentially limiting coffee production, while near-neutral to slightly alkaline zones might be more favorable for cultivation. Understanding this variability in pH is crucial for targeted soil management and improving crop yields in the area (Figure A7).

The land suitability analysis classified soil pH for Arabica coffee into four categories based on: Juita *et al.*[59] highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N1). In both Abaya and Gelana Districts, pH 5 – 5.5 is highly suitable, 3.5 – 5 moderately suitable, 5.5 – 6.7 marginally suitable, and below 3.5 or above 6.7 unsuitable for coffee production. In Abaya, 17.4% (372,299 ha) of the land is highly suitable, 38.7% (827,722 ha) moderately suitable, 42.5% (909,201 ha) marginally suitable, and 1.1% (25,589 ha) unsuitable for coffee production. In Gelana, 27.5% (440,636 ha) of the land is highly suitable, 25.5% (407,851 ha) moderately suitable, 5.5% (88,660 ha) marginally suitable, and 41.3% (659,382 ha) unsuitable for coffee production (Table 8). Soil pH is crucial for Arabica coffee production, as it determines land suitability and helps identify optimal cultivation areas.[38]

3.1.6. Land use/cover

Land use in Abaya and Gelana Districts was classified based on 2023 Landsat 8 images, identifying seven categories: woodland, water body, settlement, grassland, forest land, cultivated land, and bare land (Table A1). In the Abaya District, water bodies cover 35.9% (760,462 ha) of the region, followed by forest land (23.1%; 510,393 ha), cultivated land (15.5%; 328,463 ha), woodland (15.2%; 328,463 ha), grassland (4%; 85,653 ha), bare land (2.7%; 58,051 ha), and settlements (2.3%; 48,985 ha). In the Gelana District, forest land dominates at 36.9% (585,634 ha), followed

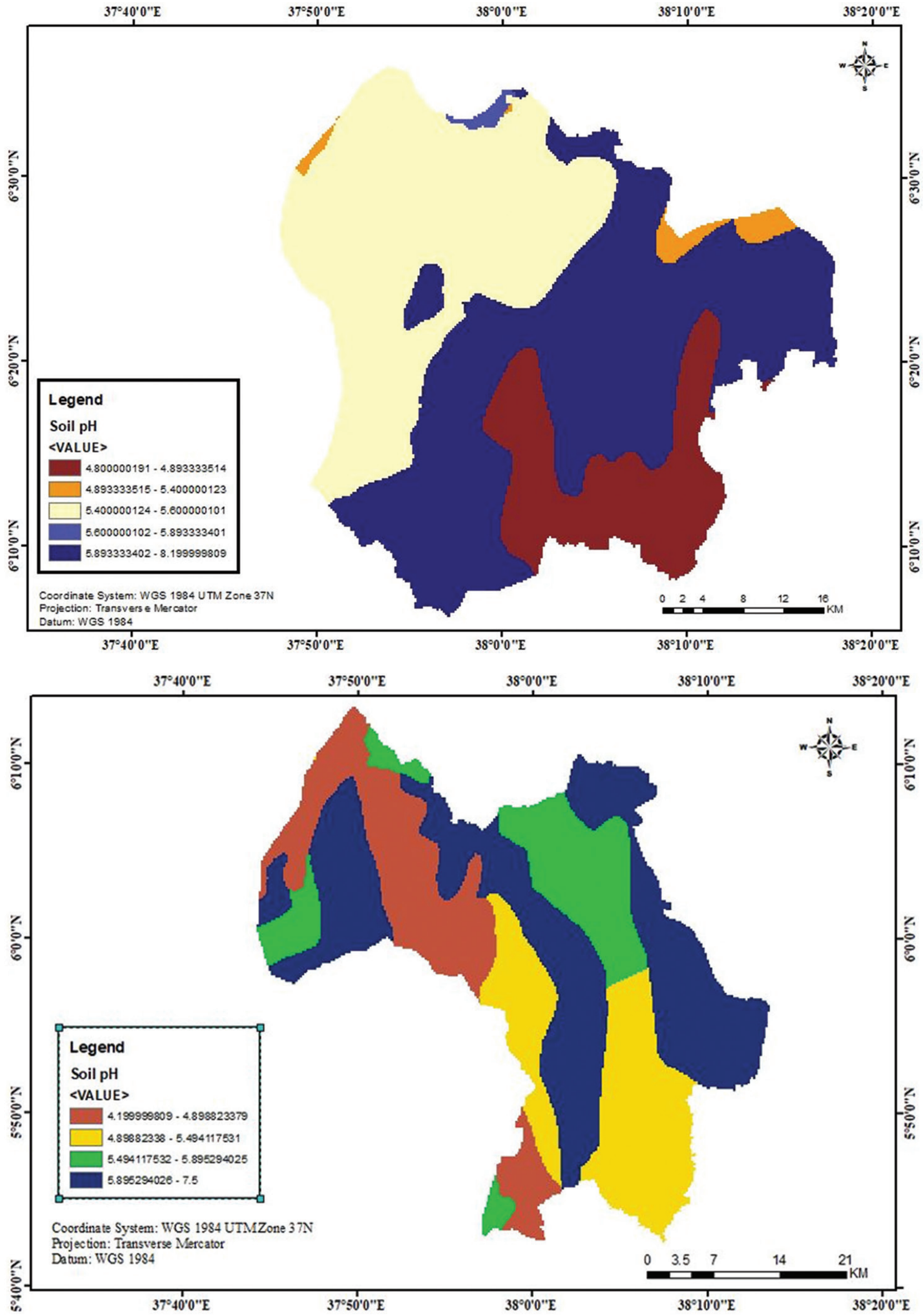

Figure 5. Soil pH map of Abaya (upper) and Gelana Districts (lower)

by cultivated land (18.2%; 289,045 ha), woodland (17.8%; 282,589 ha), grassland (11.5%; 183,494 ha), bare land (8.8%; 140,142 ha), water bodies (3.4%; 71,143 ha), and settlements (2%; 31,813 ha) (Table 9). The classification revealed significant water bodies in Abaya and dominant forest land in Gelana, emphasizing the importance of understanding land cover dynamics for sustainable management, ecosystem health, and livelihoods.[60]

The study calculated overall accuracy, user's accuracy, producer's accuracy, and the Kappa coefficient for land cover classification, with water bodies achieving 100% accuracy. The Abaya District had an overall accuracy of 88.76% and a Kappa coefficient of 0.8689, while the Gelana District had an overall accuracy of 93.82% and a Kappa coefficient of 0.9279. According to Mollick *et al*.,[61] a kappa coefficient of 0.882 indicates a strong agreement in land use/cover classification.

According to Figures 6 and A8, land use was reclassified for suitability of coffee production: forests and cultivated land were considered highly suitable; grassland was classified as marginally suitable; while settlements, water bodies, and bare land were considered unsuitable, though bare land holds potential for improvement. In the Abaya District, forest land (23.1%; 516,937 ha) is considered highly suitable, cultivated land (15.5%; 333,150 ha) is moderately suitable, and grassland (4%; 86,716 ha) is marginally suitable for coffee production. In contrast, woodland (15.2%) and bare land (2.7%) are deemed unsuitable, while settlements (2.3%) and water bodies (35.9%) are permanently unsuitable for coffee production. Overall, 43.6% of the land is suitable, 17.9% marginally suitable, and 38.1% unsuitable for coffee production (Table 10). In the Gelana District, forest land (36.9%; 592,693 ha) is highly suitable, cultivated land (18.2%; 292,820 ha) is moderately suitable, and

Table 8. Soil pH suitability class of Abaya and Gelana Districts

Soil pH	Suitability class	Abaya District		Gelana District	
		Area (ha)	Area (%)	Area (ha)	Area (%)
5 – 5.5	S1	372,299	17.43943609	440,636	27.59962393
3.5 – 5	S2	827,722	38.77261266	407,851	25.54610658
5.5 – 6.7	S3	909,201	42.58929713	88,660	5.553297184
<3.5; >6.7	N1	25,589	1.19865412	659,382	41.3009723
Total	-	2,134,811	100	1,596,529	100

Notes: Highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N1).

Table 9. Land use/cover type and area coverage of Abaya and Gelana Districts

Land use/cover type	Abaya District		Gelana District	
	Area (ha)	Area (%)	Area (ha)	Area (%)
Woodland	321,896	15.22756721	282,589	17.84179157
Water body	760,462	35.97430913	71,143	3.491748008
Settlement	48,985	2.317277567	31,813	2.00857399
Grassland	85,653	3.051888852	183,494	11.58524112
Forest land	510,393	23.14457995	585,634	36.97511144
Cultivated land	328,463	15.53822479	289,045	18.24940336
Bare land	58,051	2.746152496	140,142	8.848130517
Total	2,113,903	100	1,583,860	100

Table 10. Land use/cover suitability class of Abaya and Gelana Districts

Land use/cover type	Suitability class	Abaya District		Gelana District	
		Area (ha)	Area (%)	Area (ha)	Area (%)
Cultivated land	S1	333,150	15.55229919	592,693	36.95363066
Forest land	S2	516,937	23.13194923	292,820	18.25694268
Grassland	S3	86,716	3.048125998	286,208	17.84469316
Woodland	N1	326,038	15.22029273	186,173	11.6076422
Bare land	N1	58,783	2.744141687	141,994	8.853139537
Settlement	N2	49,520	2.311721014	32,070	1.999522409
Water body	Restrict	770,983	35.99147016	71,925	3.484429351
Total	-	2,142,127	100	1,603,883	100

Notes: Highly suitable (S1), moderately suitable (S2), marginally suitable (S3), not suitable (N1), and permanently not suitable (N2); "Restrict" indicates to water bodies that are not included (or "restricted") in suitability analyses because coffee cannot be grown in flooded or submerged areas.

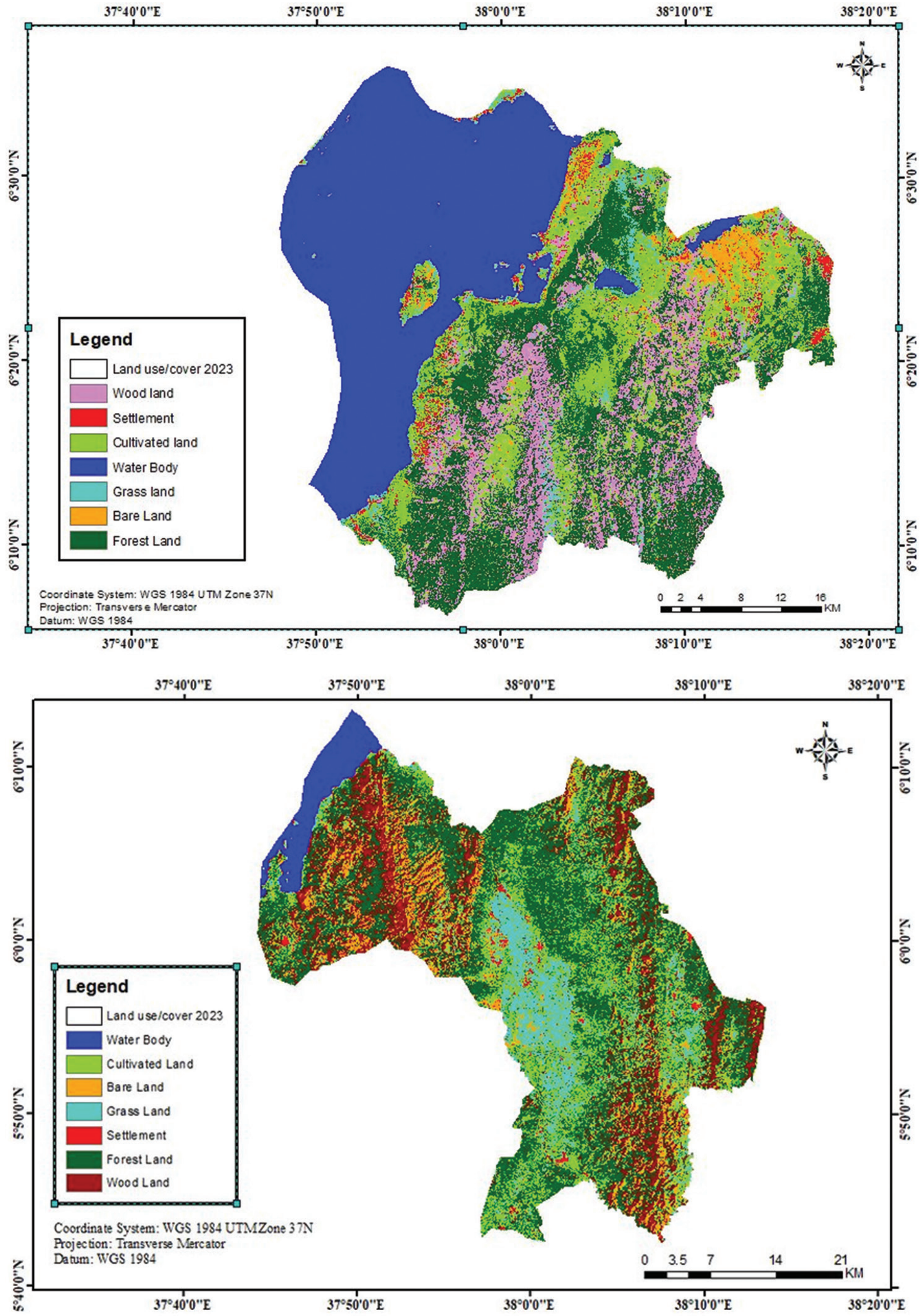

Figure 6. Current land use/cover map of the Abaya (upper) and Gelana Districts (lower).

woodland (17.8%; 286,208 ha) is marginally suitable. Conversely, grassland (11.6%) and bare land (8.8%) are unsuitable, while settlements (1.9%) and water bodies (3.4%) are permanently unsuitable. Overall, 72.9% is suitable, 20.4% marginally suitable, and 6.3% unsuitable for coffee production (Table 10).

The final suitability map indicates varying land suitability for coffee production in Abaya and Gelana Districts (Figure 10). In the Abaya District, 19.6% (417,671 ha) of the land is highly suitable, 43% (91,605 ha) is moderately suitable, 0.49% (10,557 ha) is marginally suitable, and 36.8% (783,241 ha) is not suitable for coffee production. In the Gelana District, 5.1% (81,677 ha) of the land is highly suitable, 15% (239,017 ha) is moderately suitable, 71.5% (1,137,589 ha) is marginally suitable, and 8.2% (131,455 ha) is not suitable for coffee production (Table 11).

3.1.7. Proximity

Buffer analysis was used to identify optimal land for coffee farming by creating buffer zones around constraints such as towns, water bodies, and roads. Areas within 2 km of towns, 10 m of main roads, and 5 m of rivers were excluded to avoid shading, disturbances, and waterlogging issues. The details for each analysis are as follows:

i. Road buffer analysis was conducted to assess constraints on coffee farming areas. Proximity to roads is a key factor in land suitability, as it reduces transport costs and enhances profitability by improving access to markets and processing facilities.[62] Road proximity affects coffee production suitability. To minimize disturbances including dust, runoff, vibrations, and vehicular emissions that could adversely affect growth and quality of Arabica coffee, areas within 10 meters of roads were excluded from consideration.[63] In accordance with environmental planning guidelines, this buffer zone also improves worker safety and avoids land-use conflicts.[64] The sustainability and dependability of coffee cultivation near roads are improved by this barrier. In Abaya, suitable areas are located in the northern, northwestern, southern, and eastern regions; while in Gelana, they are located in the southwestern, northern, and central regions (Figure 7).

ii. River buffer analysis was conducted to assess constraints on coffee farming areas. Proximity to water sources is vital for coffee growth, as it reduces irrigation costs and improves overall yield.[12] Figure 8 indicates that areas within 5 m of rivers are unsuitable for coffee production due to risks of toxic gases and waterlogging. In the Abaya District, suitable areas are located in the northern, central, southern, and eastern regions; while in the Gelana District, suitable areas are located in the southwestern, eastern, northeastern, and central regions.

iii. Town proximity analysis was conducted for constraints in coffee farming areas. Proximity to markets and transportation infrastructure enhances coffee farming efficiency and profitability by lowering transport costs.[36] In this study, areas within 2 km of towns were excluded from suitability analysis to avoid shading effects that can limit sunlight availability for coffee plants (Figure 9). In Abaya, suitable areas are located in the northeastern, central, southern, and eastern regions; while in Gelana, they are located in the northeastern, eastern, southwestern, and central regions.

3.1.8. Overlaying and suitable sites

The AHP-weighted coffee suitability criteria were integrated into ArcGIS to generate the final coffee suitability map (Figure 10). In the Abaya District, the northwestern, central, and southern regions are deemed highly suitable, while the eastern and southwestern regions are marginally suitable, and the western region is not suitable for coffee production. In the Gelana District, the southwestern region is highly suitable, the central and southeastern regions are moderately suitable, the northern and eastern regions are marginally suitable, and the northwestern region is not suitable for coffee production.

3.1.9. Socioeconomic determinants

Figure 11 displays the monthly income distribution of 248 respondents in Abaya and 150 in Gelana: 16.8 (67) earn <500 birr, 63.1% (251) earn between 500 and 5000 birr, and 20.1% (80) earn over 5000 birr. Most respondents have low-to-moderate incomes, limiting investment in coffee production. Among 398 respondents, 31.9% (127) earn their income from farming, with coffee serving as a primary source of livelihood. Landholding sizes varied 9.3% (37) owned <1.5 ha plots, 48.5% (193) with 1.5 – 2.5 ha plots, 33.2% (132) with 2.5 – 3.5 ha plots, and 9% (36) with >3.5 ha plots (Figure 11). Overall, income levels and land

Table 11. Land suitability for coffee production in Abaya and Gelana Districts

Suitability class	Abaya District		Gelana District	
	Area (ha)	Area (%)	Area (ha)	Area (%)
Highly suitable	417,671	19.63132657	81,677	5.137764839
Moderately suitable	916,105	43.05866682	239,017	15.03499319
Marginally suitable	10,557	0.496198957	1,137,589	71.55826935
Not suitable	783,241	36.81380765	131,455	8.268972623
Total	2,127,574	100	1,589,738	100

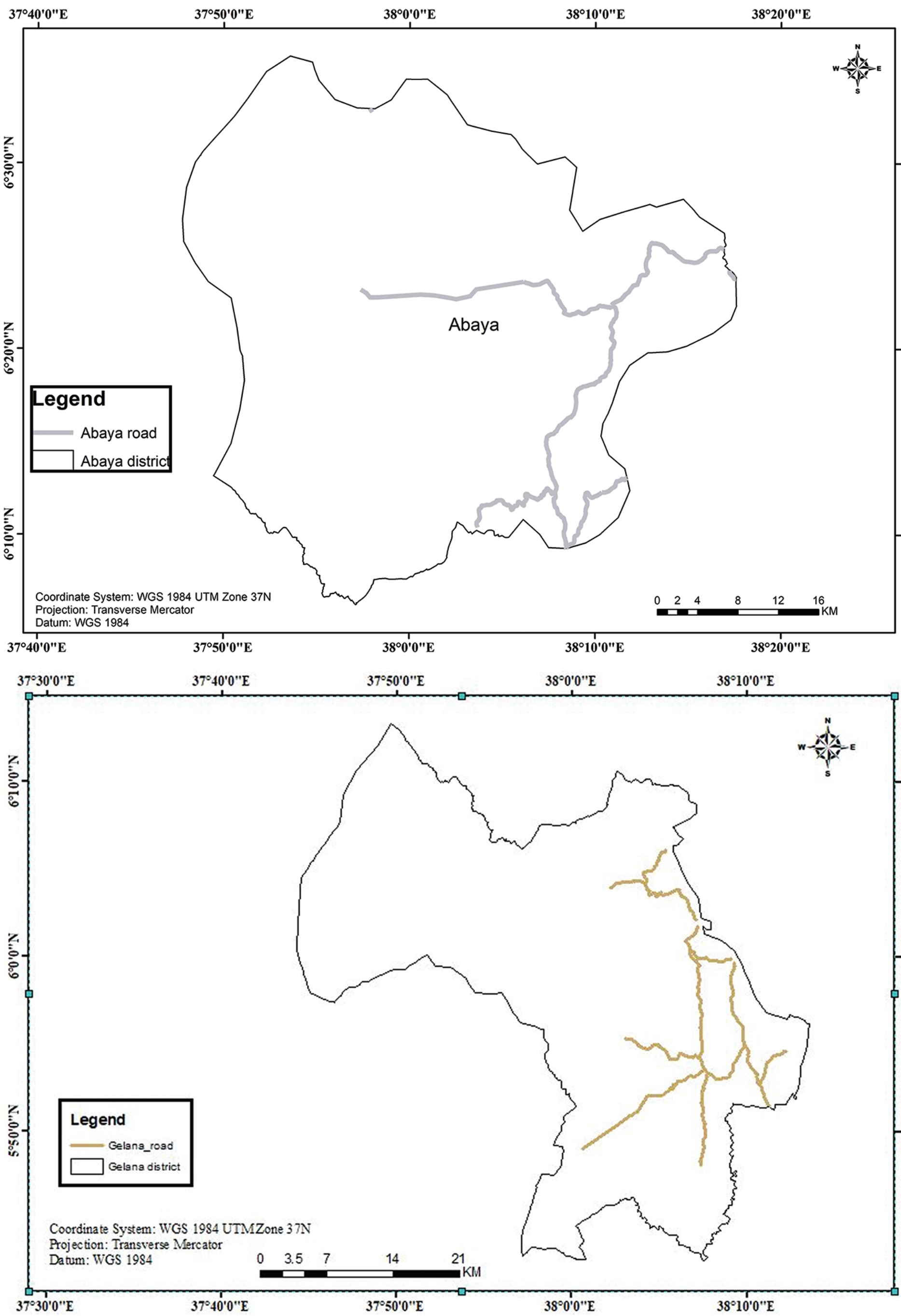

Figure 7. Constraint maps of Abaya (upper) and Gelana (lower) Districts with road buffer zones

sizes underscore key factors shaping coffee production sustainability, highlighting the need for targeted support to boost financial resilience and productivity.[65]

3.1.10. Statistical correlations between land suitability and determinant factors

In the Abaya and Gelana Districts, respondents identified key factors for selecting land suitable for coffee production (Table 12): 99.07% of respondents emphasized climate characteristics (temperature and rainfall), 97.5% of respondents highlighted soil fertility, and 98.59% of respondents recognized the importance of accessibility to roads, markets, and water sources. Landscape and topography were noted by 93.8% of respondents, while 92.68% of respondents considered land use and cover. Market demand was mentioned by 66.67% of respondents, and 92.86% of respondents acknowledged the role of new coffee varieties.

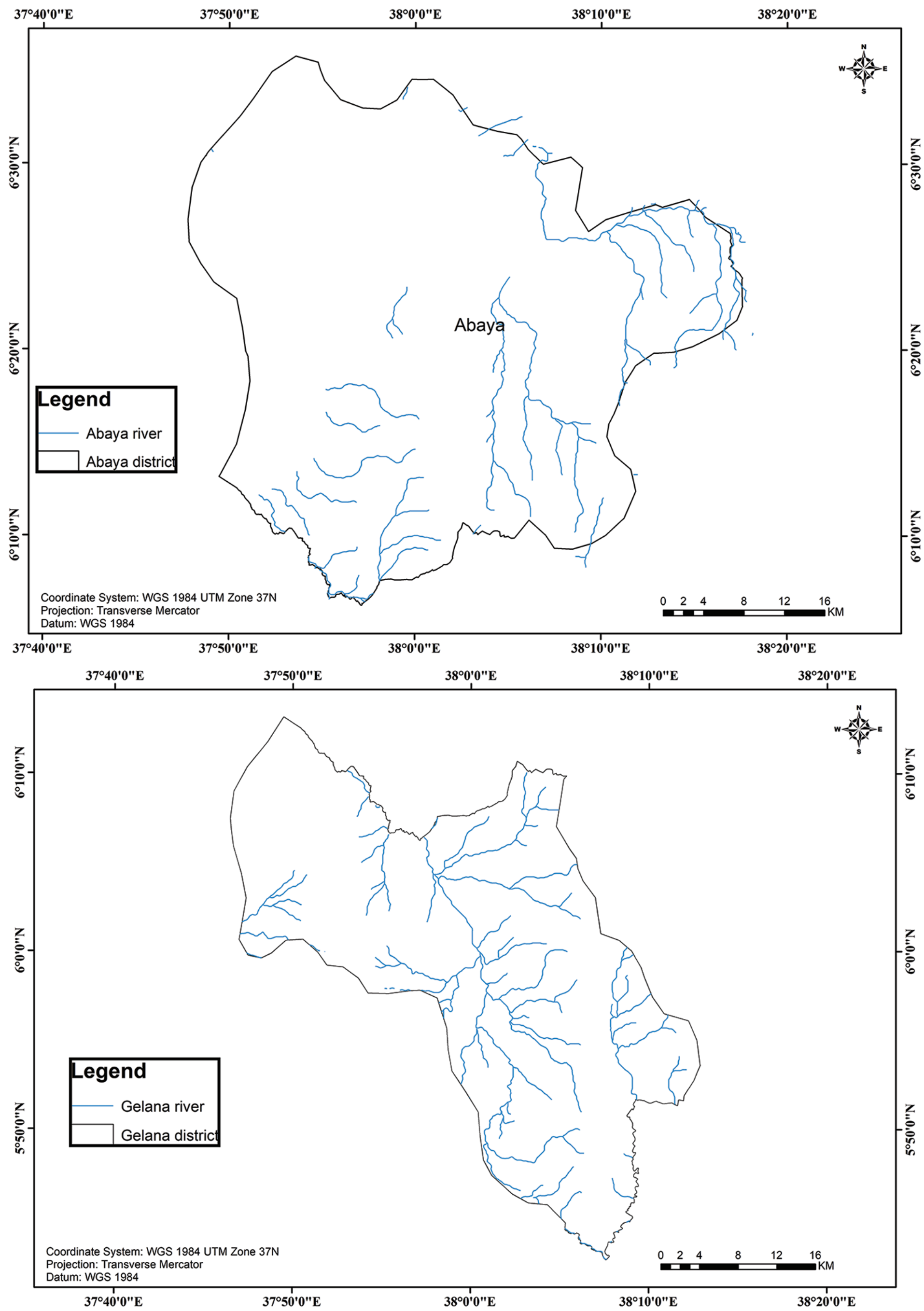

Figure 8. Constraint maps of Abaya (upper) and Gelana Districts (lower) with river buffer zones

Table 13 indicates a statistically significant correlation at 5%, with a Pearson Chi-square value of 49.075 with 8 degrees of freedom and a *p*-value of 0.0336. This implies that the categories of land suitability factors (slope, rainfall, temperature, elevation, and soil type) have significant variations in their effects on the potential for coffee production in the two districts.[13] Similarly, a *p*-value of 0.0328 and a likelihood ratio test value of 9.173 further confirm the significant correlations between the observed variables. These two tests reject the null hypothesis of independence, confirming that land attributes systematically influence coffee suitability rather than being randomly correlated.[3] Although relationships between variables exist, they are not strictly linear, as displayed by the non-significant *p*-value of 0.477 and the linear-by-linear association value of 0.505, indicating no strong linear trend between the ordinal variables.

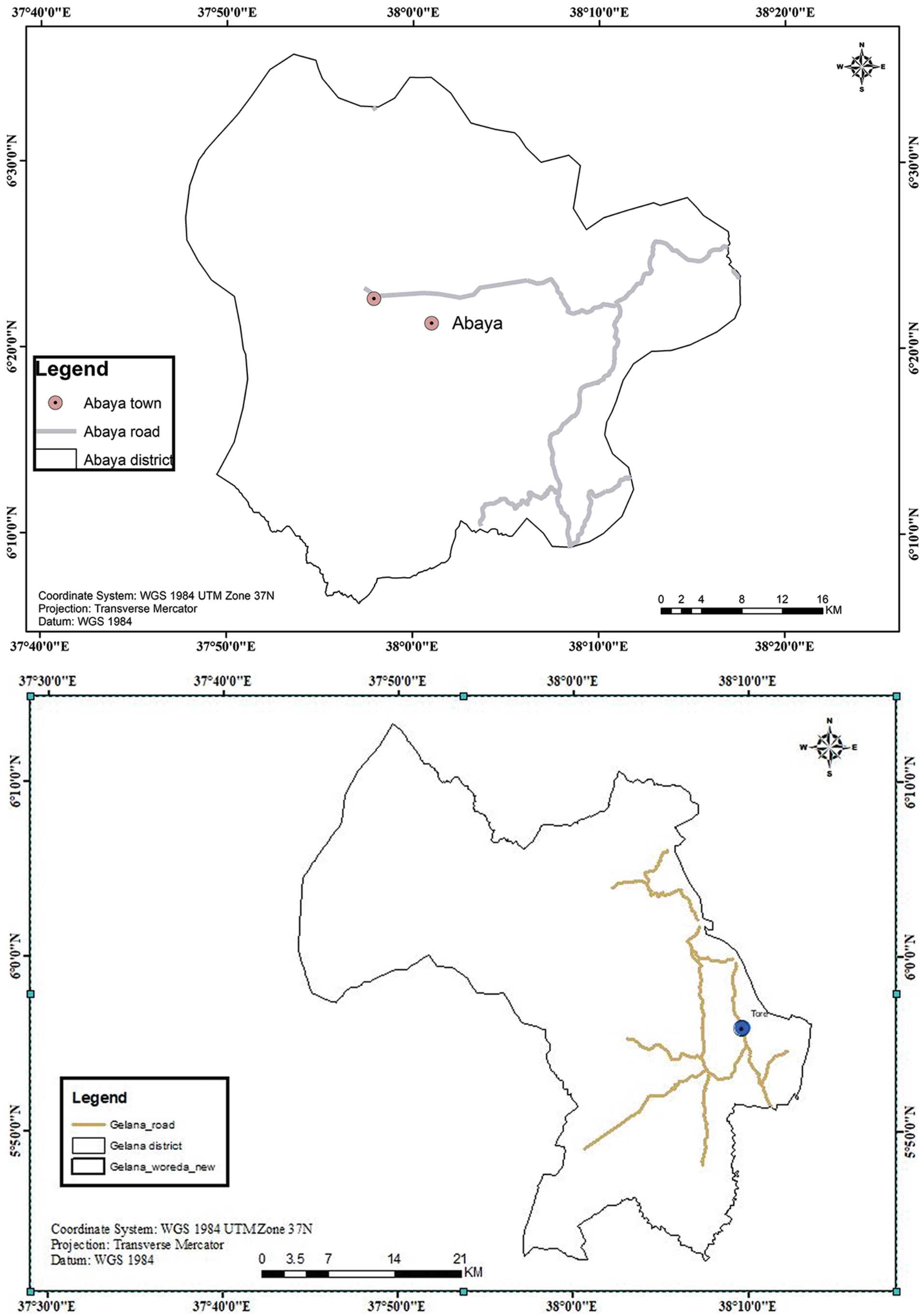

Figure 9. Constraint maps of Abaya (upper) and Gelana Districts (lower) with town buffer zones

An adequate dataset for inferential testing was provided by the analysis, which was carried out on a valid sample size of 398 cases. These results are consistent with previous empirical research conducted in Ethiopia and other coffee-producing locations, which highlights the significant impact that topographic and climatic variation has on land suitability for coffee production.[4] To increase yield and climatic resilience, it is implied that location-specific land management and zoning techniques that prioritize agro-ecologically suitable sites are necessary for sustainable coffee production in Abaya and Gelana Districts.

3.2. Ranking study areas by optimal suitability for coffee production

In the Abaya District, 9968.37 ha (95.73%) of the land is highly suitable, 10504.79 ha (79.06%) is moderately suitable, and 123.09 ha (21.87%) is marginally suitable

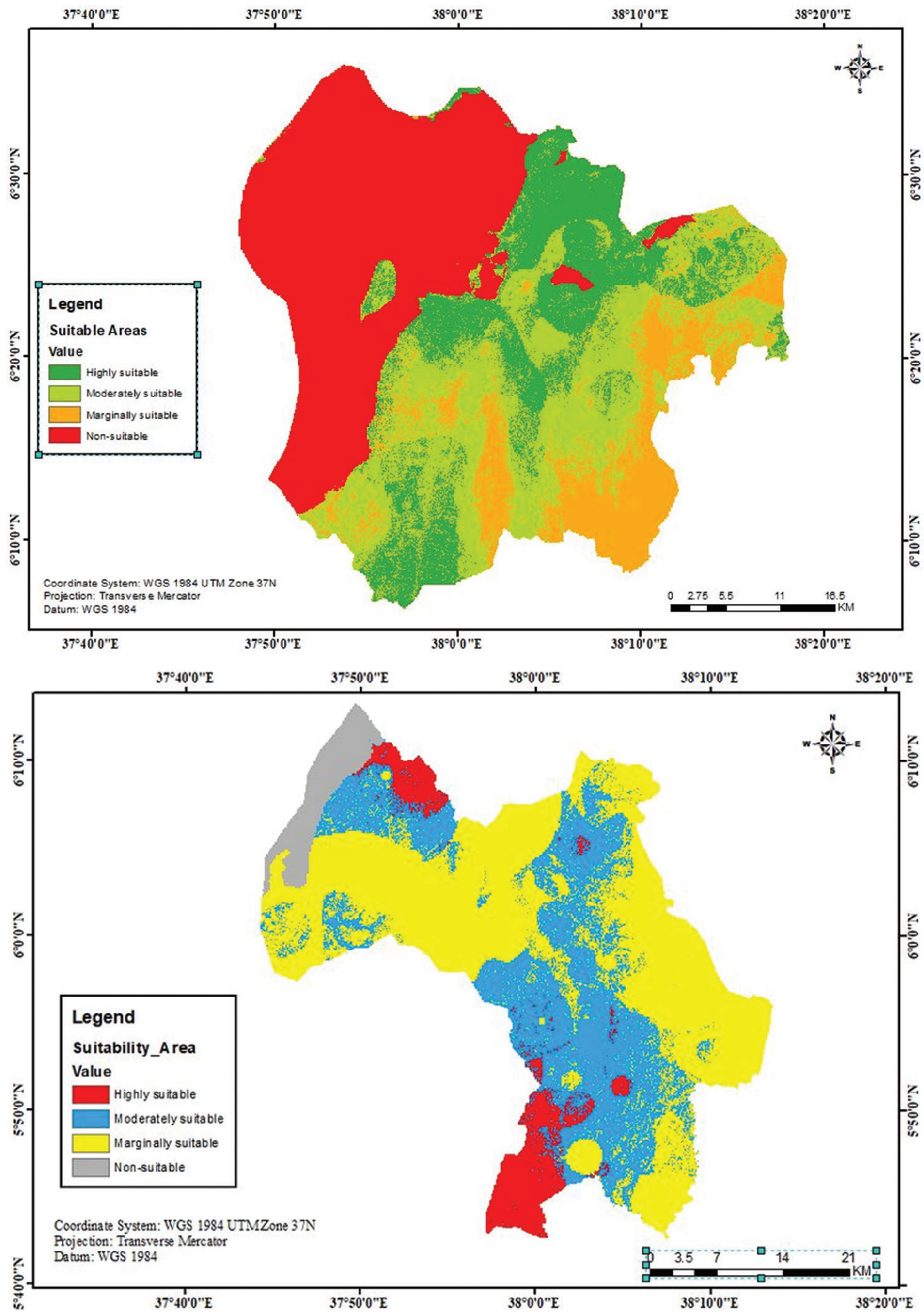

Figure 10. Final coffee suitability map of the Abaya (upper) and Gelana Districts (lower)

for coffee production (Figure 12). The top five kebeles include Dibichala Luniche with 5587.84 ha (53.23%), Gelo with 1595.41 ha (15.48%), Semero Gambela with 1316.25 ha (12.77%), Ledo with 870.15 ha (8.44%), and Wedeyiture with 598.72 ha (5.81%) of land (Table 14). In the Gelana District, 11492.32 ha (97.5%) of the land is highly suitable, 66334.19 ha (64.6%) is moderately suitable, and 9624.4 ha (51.25%) is marginally suitable for coffee production (Figure 12). The top five kebeles include Meteri with 6371.73 ha (53.64%), Odo Derba with 2597.95 ha (22.28%), Shamole with 1098.25 ha (9.42%), Kersa with 995.49 ha (9.42%), and Bore with 428.90 ha (3.68%) of land (Table 14). According to the suitability ranking, more than 95% of the evaluated lands are deemed to be highly suitable for coffee production, highlighting the vast territories that both the Abaya and Gelana Districts possess. Land suitability is particularly concentrated in kebeles such as Dibichala Luniche and

Gelo, which collectively comprise the bulk of the ideal coffee-growing area in Abaya. Similar to this, the Gelana District has a significant number of locations that are ideal for coffee production, particularly in the Meteri and Odo Derba kebeles. The existence of marginally and moderately favorable zones, however, suggests that site conditions vary, most likely due to terrain, soil quality, and microclimate. These findings are essential for directing resource allocation, focused agricultural planning, and sustainable coffee growing methods, ensuring efficient land use and raising output in both districts.

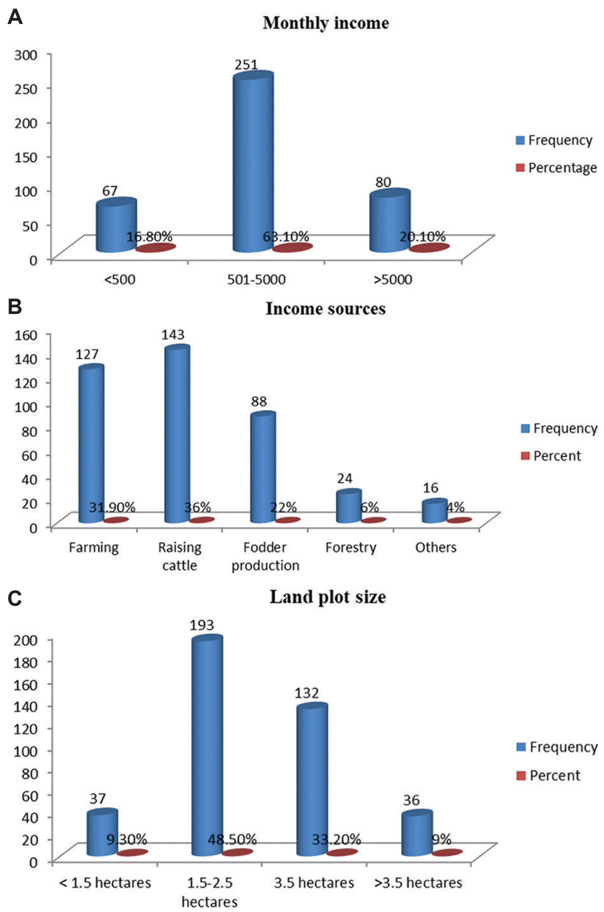

Figure 11. Analysis of socioeconomic factors: monthly income distribution (A), income sources (B), and land size (C)

In the Abaya District, Gwanigwa Badiya (297.74 ha; 2.27%) is moderately suitable for coffee production, while Bunata (20.52 ha; 3.81%) and Odo Mike (13.97 ha; 2.6%) are marginally suitable for coffee production (Figure 12). In the Gelana District, Jirme (1310.08 ha; 7.11%) is marginally suitable for coffee production, and Giwe (9288.78 ha; 9.27%) is moderately suitable for coffee production (Figure 12). Focus group discussions (FGD) and key informant interviews (KII) recommend these areas as optimal for coffee farming.

Survey and GIS analysis reveal significant differences in coffee suitability between Abaya and Gelana Districts. Abaya has larger, contiguous, highly suitable areas, such as Dibichala Luniche, Gelo, and Dokicha, supporting extensive coffee farming. In contrast, Gelana's smaller, fragmented suitable areas, like Meteri, Odo Derba, and Shamole, suggest smaller-scale operations. Abaya's favorable topography, soil, and climate enable scalability, while Gelana's varied conditions limit large-scale coffee production, favoring localized farming.

3.3. Optimal land suitability map for coffee production

Optimal land suitability for coffee production in Abaya and Gelana Districts is determined by factors like soil, temperature, rainfall, slope, elevation, and land use. In Abaya, Dibichala Luniche (24935.56 ha; 43.3%), Gelo

Table 12. Cross-tabulation of land suitability and determinant factors

Factor	Response, *n* (% within CP)		Total
	Yes	No	
Soil fertility	79 (97.5)	2 (2.47)	81
Landscape and topography	61 (93.8)	4 (6.15)	65
Land use/cover	38 (92.68)	3 (7.3)	41
Climate condition	107 (99.07)	1 (0.9)	108
Development of a new coffee variety	13 (92.86)	1 (7.1)	14
Growing demand for coffee	12 (66.67)	6 (33.33)	18
Accessibility to roads, markets, and water bodies	70 (98.59)	1 (1.4)	71
Total	380	18	398

Note: Column percentage total (CPT); dichotomy group tabulated at value 1.
Abbreviation: CP: Column percentage.

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Table 13. Statistical analysis of responses (*n*=398) on land suitability and determinant factors

Statistical test	Value	Degree of freedom	Asymptotic significance (two-sided)
Pearson Chi-square	49.075[a]	8	0.0336
Likelihood ratio	9.173	8	0.0328
Linear-by-linear association	0.505	1	0.477

Note: [a]Dichotomy group tabulated at value 1.

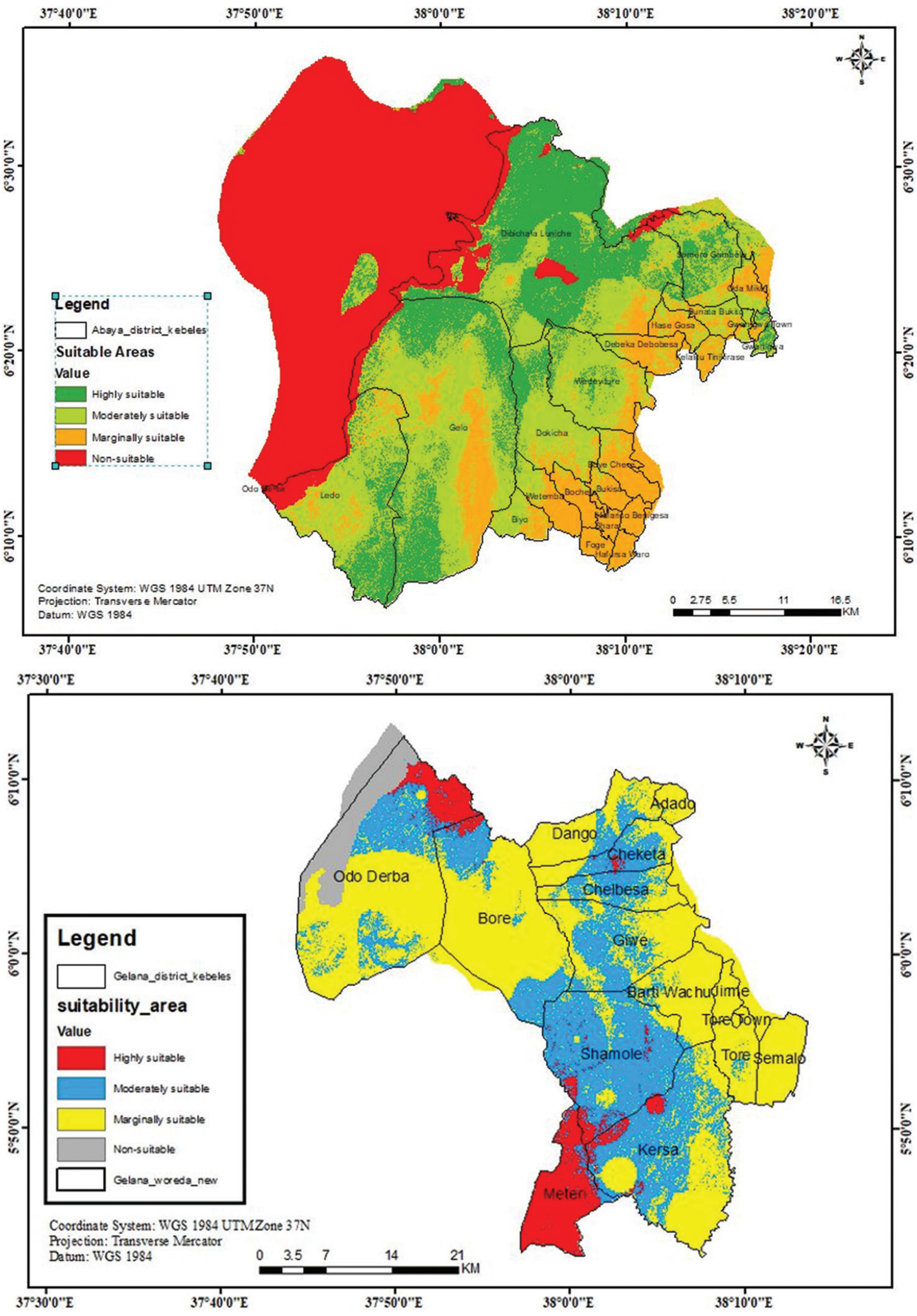

Figure 12. Map of land suitability for coffee production in the kebeles of Abaya (upper) and Gelana (lower) Districts

Table 14. Suitable area coverage for coffee production in the Abaya and Gelana Districts

District	Kebele	Highly suitable area		Moderately suitable area		Marginally suitable area	
		Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Abaya	Dibichala Luniche	5587.84	53.23	2413.76	18.40	43.05	8.00
	Gelo	1595.41	15.48	3681.07	28.06	2.26	0.42
	Semero Gambela	1316.25	12.77	998.92	7.61	26.53	3.93
	Ledo	870.15	8.44	2871.19	21.88	31.01	5.76
	Wedeyiture	598.72	5.81	539.85	3.11	20.24	3.76
	Total	9968.37	95.73	10504.79	79.06	123.09	21.87
Gelana	Meteri	6371.73	53.64	596.80	0.60	0.00	0.00
	Odo Derba	2597.95	22.28	18161.88	18.12	3955.58	21.47
	Shamole	1098.25	9.42	15133.78	15.10	1.83	0.01
	Kersa	995.49	8.54	18165.45	18.13	817.78	3.44
	Bore	428.90	3.678	14276.28	13.25	4849.21	26.33
	Total	11492.32	97.558	66334.19	64.66	9624.4	51.25

(14246.49 ha; 25.3%), and Dokicha (8007.08 ha; 14%) are highly suitable for coffee production (Table 15). In Gelana, Meteri (6371.73 ha; 53.6%), Odo Derba (2597.95 ha; 22.2%), and Shamole (1098.25 ha; 9.4%) are highly suitable for coffee production (Table 15). These areas provide optimal conditions for productive and sustainable coffee production. The topography, soil type, climate, and land use play a role in optimal land suitability, which highlights important kebeles in Abaya and Gelana Districts with ideal conditions for coffee production. In Abaya, highly suitable areas include Dibichala Luniche (43.3%), Gelo (25.3%), and Dokicha (14%), collectively accounting for over 80% of suitable coffee production land. In contrast, Gelana has a more concentrated appropriateness, with Meteri alone accounting for 53.6% of its highly suitable land, followed by Odo Derba (22.2%) and Shamole (9.4%). These observations suggest that Gelana's suitable areas are more concentrated but highly productive, whereas Abaya's ideal coffee production zones are more widely distributed and dynamic. These trends provide a strategic foundation for prioritizing site-specific actions to enhance sustainable coffee production in both districts.

According to Figure 13, both Abaya and Gelana Districts are well-suited for coffee production, with Abaya's optimal areas in the northern, central, and southern regions, and Gelana's in the southwestern and northwestern regions (Table 14). Favorable rainfall, temperature, soil quality, elevation, market access, and infrastructure further enhance efficiency in these areas. Sustainable practices also support consumer demand

Table 15. Highly suitable area coverage for coffee production in Abaya and Gelana Districts

District	Kebele	Highly suitable area	
		Area (ha)	Area (%)
Abaya	Dibichala Luniche	24935.55581	43.3519773
	Gelo	14246.48793	25.33971627
	Dokicha	8007.076278	13.24189892
	Ledo	6840.525108	12.16699626
	Semero Gambela	1985.552748	3.531631341
	Gwanigwa	206.773109	0.367779901
	Total	56221.97098	100
Gelana	Bore	428.90	3.678
	Cheketa	151.65	1.301
	Chelbesa	16.77	0.144
	Kersa	995.49	8.54
	Meteri	6371.73	53.64
	Odo Derba	2597.95	22.28
	Shamole	1098.25	9.42
	Total	11660.74	100

and environmental health, positioning these areas for successful coffee cultivation.

The FGD and KI results emphasize the importance of coffee for households in Abaya and Gelana Districts, serving as a primary source of income to cover essential expenses, including food, healthcare, and education. Land sizes, income, ownership of animals, and off-farm activities have a significant impact on coffee farming participation. Higher-income

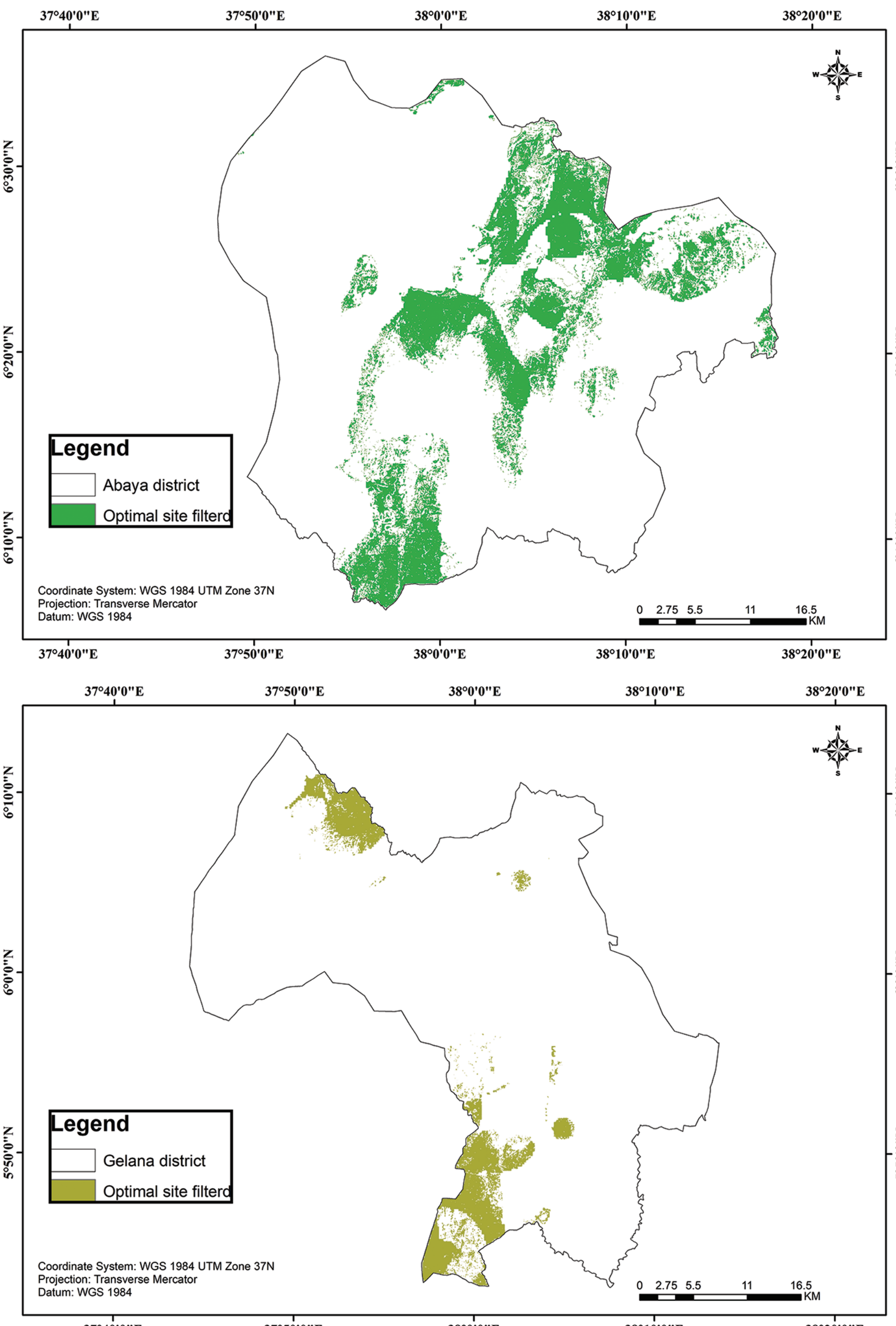

Figure 13. Optimal land suitability map for coffee production in Abaya (upper) and Gelana (lower) Districts

households with more land and cattle spend more on coffee, and people who work outside the farm frequently put their profits back into growing coffee. Conversely, households with limited resources find it difficult to continue or increase their coffee output. These results highlight the necessity for integrated assistance that addresses both on-farm and off-farm livelihood factors.

3.4. Actionable implications

This study offers local governments and land use managers a strategic roadmap for enforcing zoning ordinances that prioritize infrastructure development, such as irrigation and rural roads, in moderately suitable areas while protecting highly suitable areas.

The results can empower farmers and cooperatives to target interventions at the kebele level, enhancing production through improved soil management, climate-resilient coffee varieties, and informed land use planning. Localized training suited to particular agro-ecological circumstances should be provided as extended services.

Development partners and policymakers may promote equitable, sustainable expansion of the coffee industry in Abaya and Gelana by coordinating land suitability data with more general measures, such as market access, climate resilience, and value chain strengthening.

3.5. Limitations and future research directions

Although the study's methodology is competent, the validation of its suitability classifications is limited because it relies more on environmental indicators than on production data. Moreover, the use of static climate inputs overlooks future climate variability and its potential impacts. Future studies should incorporate climate estimates, household-level behaviors, and production quality and profitability measures. Accuracy can be improved by combining socioeconomic profiling, participatory validation, and predictive geographical modeling. Planning for more resilient, varied land use can also be informed by investigating how coffee fits into broader livelihood initiatives.

4. Conclusion

In this study, we assessed land suitability for coffee production in Abaya and Gelana Districts using GIS, remote sensing, and MCE with AHP, focusing on topography, climate, soil, land use, and infrastructure. Topography, soil quality, climatic factors, land use patterns, and proximity to infrastructure were among the important biophysical and infrastructure criteria that were included in the analysis. According to the findings, both areas demonstrate the potential for sustainable coffee production, especially in kebeles with ideal agro-ecological characteristics; *i.e.*, 83.77% (10303.61 ha) of Abaya and 48.4% (11660.74 ha) of Gelana are highly suitable for coffee production, highlighting substantial opportunities for coffee farming.

Key factors for optimal land selection are climate (99.07%), soil fertility (97.5%), and infrastructure (98.59%). While coffee demand (66.67%) and new varieties (92.86%) are relevant, environmental factors are prioritized. The Chi-square test ($\chi^2 = 49.075$; $p<0.05$) confirmed that these factors significantly impact land suitability decisions. The study identified optimal coffee production areas in Abaya's northern, central, and southern regions and in Gelana's southwestern and northwestern areas. Abaya is suited for large-scale farming, while Gelana is better for smaller, localized systems. The need for coordinated land use policies that balance socioeconomic incentives with physical potential is emphasized by these findings.

Qualitative data from KIIs and FGDs support the crucial role that coffee plays in rural livelihoods. Coffee is more than just an agricultural product; it is a primary source of household income, supporting expenditures on essential needs such as food, healthcare, and education. Household participation in coffee farming is strongly influenced by socioeconomic factors, including income levels, livestock ownership, landholding size, and off-farm earning prospects. Better resource endowments encourage households to engage in labor, inputs, and innovation to increase their potential for output.

Recommendations for Abaya and Gelana Districts include focusing on coffee cultivation in highly suitable areas (central and southern Abaya; southwestern Gelana) and improving infrastructure in moderately suitable areas. Regular soil and climate monitoring, sustainable practices, and economic support, including investments in new coffee varieties, are essential. Promoting optimal land suitability analysis will improve decision-making, reduce losses, and boost productivity.

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Conflict of interest

The authors declare that they have no conflicts of interest.

Author contributions

Conceptualization: Teshome Deresse
Formal analysis: Teshome Deresse

Investigation: Teshome Deresse
Methodology: Teshome Deresse
Writing–original draft: Teshome Deresse
Writing–review & editing: All authors

Ethics approval and consent to participate

Permission to collect data was obtained from Bule Hora University Institutional Research Ethical Committee (BHUIREC) through a written letter with reference number BHUIREC/007/14/2024. Participants were thoroughly informed that their personal information would be kept confidential and that their names would not be mentioned in any papers, ensuring that the study posed no risk of harm to them. Informants had agreed and signed the informed consent before starting the survey and the interview.

Consent for publication

Not applicable.

Availability of data

Rainfall and temperature data used in this study were obtained from the Hawassa Meteorological Agency.

Further disclosure

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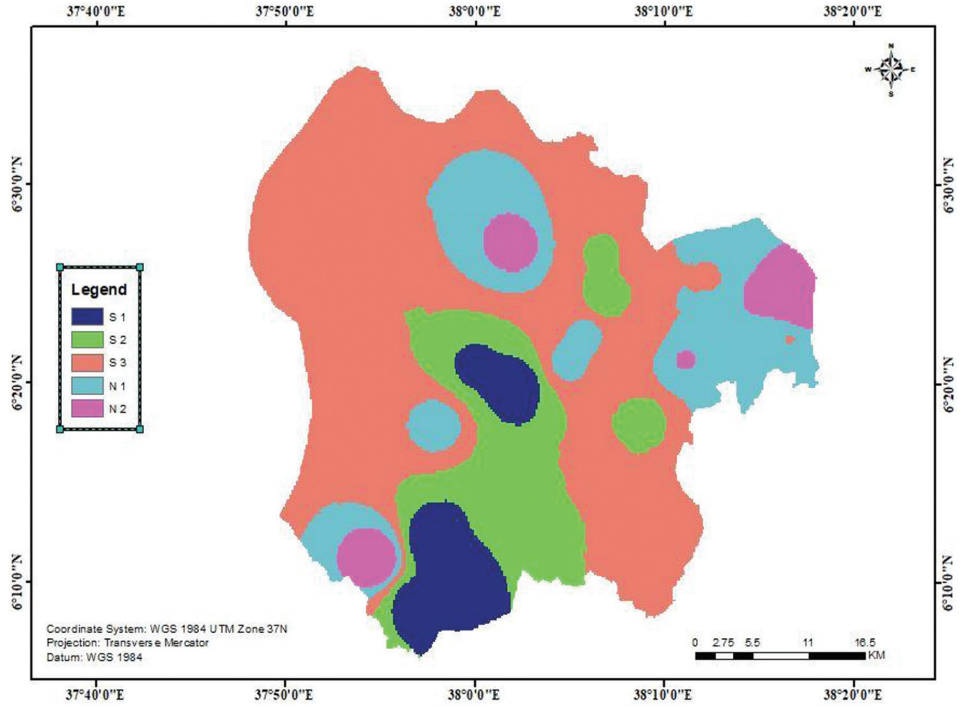
Appendices

Table A1. Descriptions of land use/cover classes

Land use/cover class	Description
Cultivated land (plantation includes coffee)	Land with minimal shade trees used primarily for smallholder coffee farming; resembles the semi-forest coffee system but involves modified forests, a higher density of coffee seedlings, and improved production methods, often in proximity to enset and annual crops
Forest land	The area hosts a mix of native and non-native species, such as eucalyptus and agroforestry home gardens, alongside sporadic natural woodlands; key species include Birbira (*Militia ferruginea*), Wanza (*Cordia africana*), Warka (*Ficus vasta*), and Sholla (*Ficus sycomorus*)
Grassland	Area with grass and little shrubs that are used for group-grazing and have a temporary grass cover
Settlement	Land covered by settlements and other man-made constructions, such as tiny market centers, communities, and coffee-processing zones
Bare land	Open spaces with little or no vegetation, including sandy and rocky areas
Woodland	Natural environment characterized by a mix of trees, shrubs, and open spaces
Water bodies	Include rivers, streams, and reservoirs



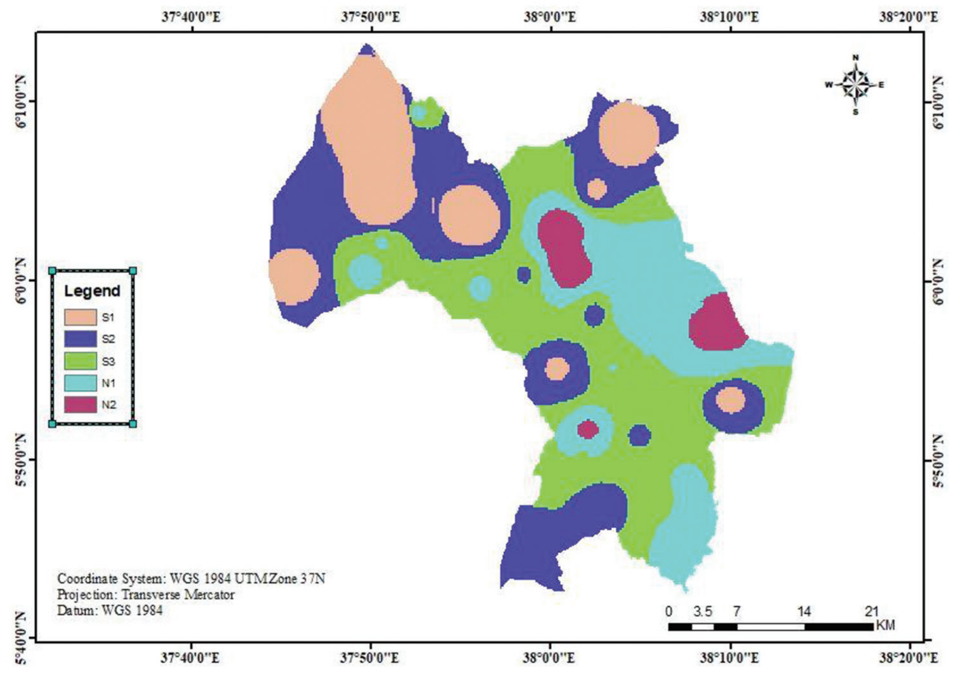
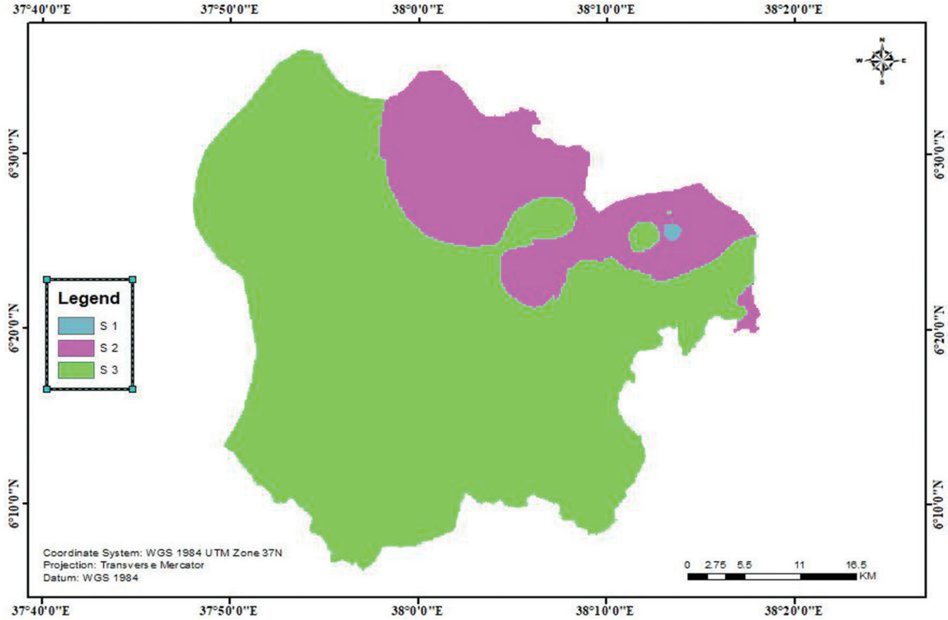


Figure A1. Rainfall suitability class map of Abaya (upper) and Gelana (lower) Districts



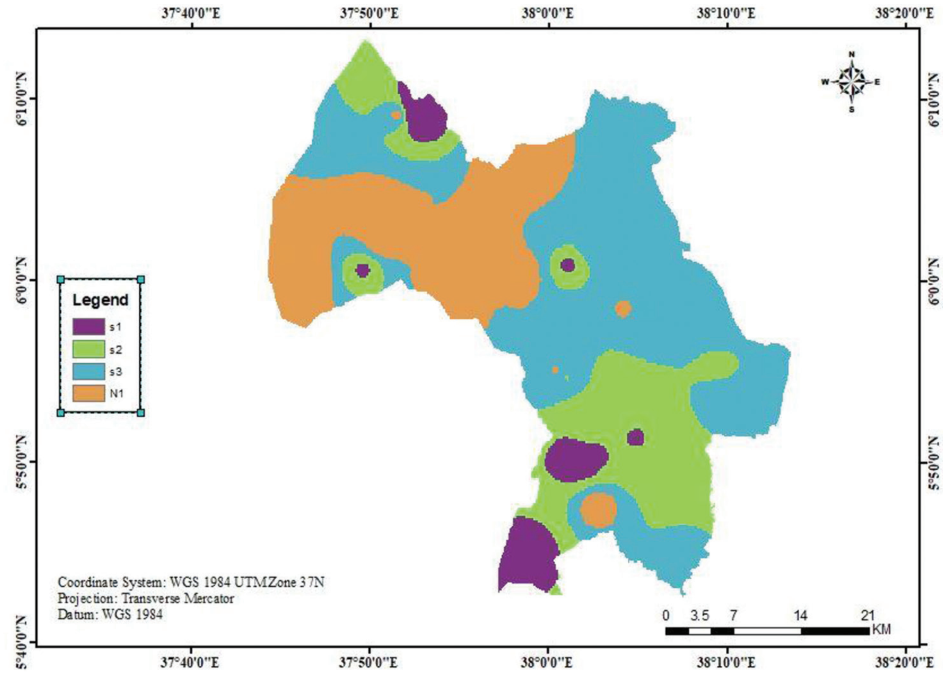
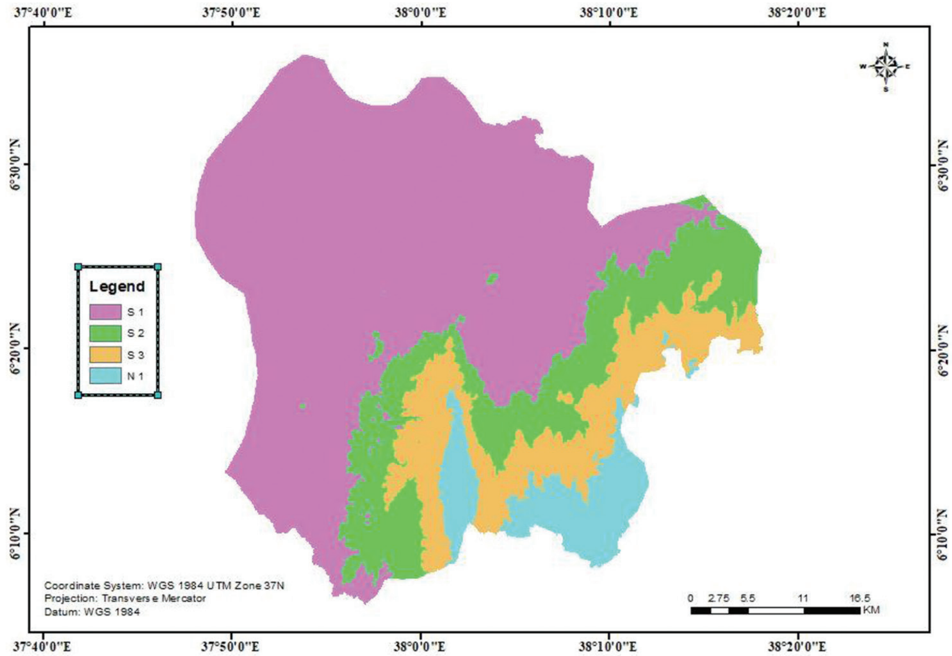


Figure A2. Temperature suitability class map of Abaya (upper) and Gelana Districts (lower)



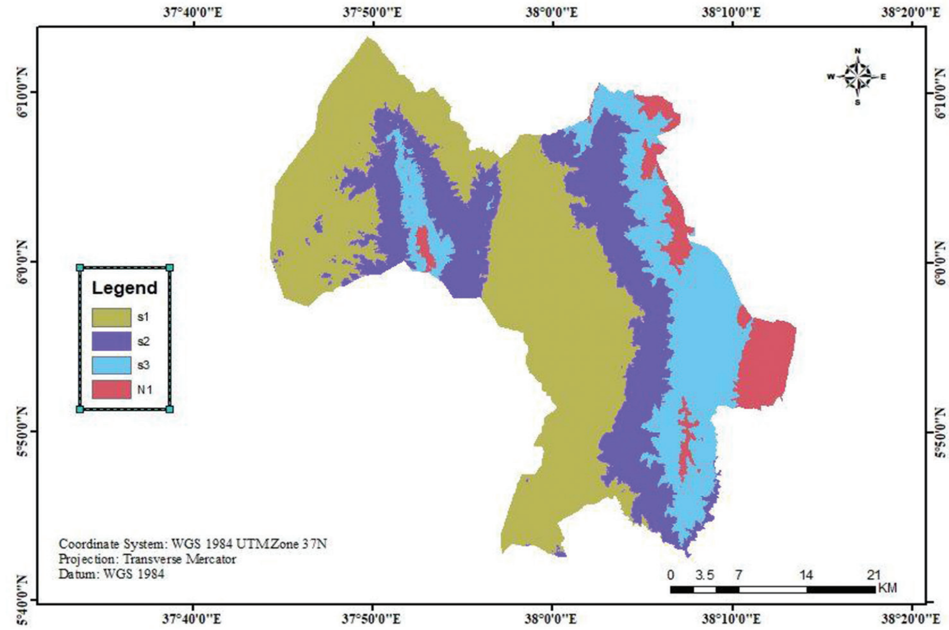
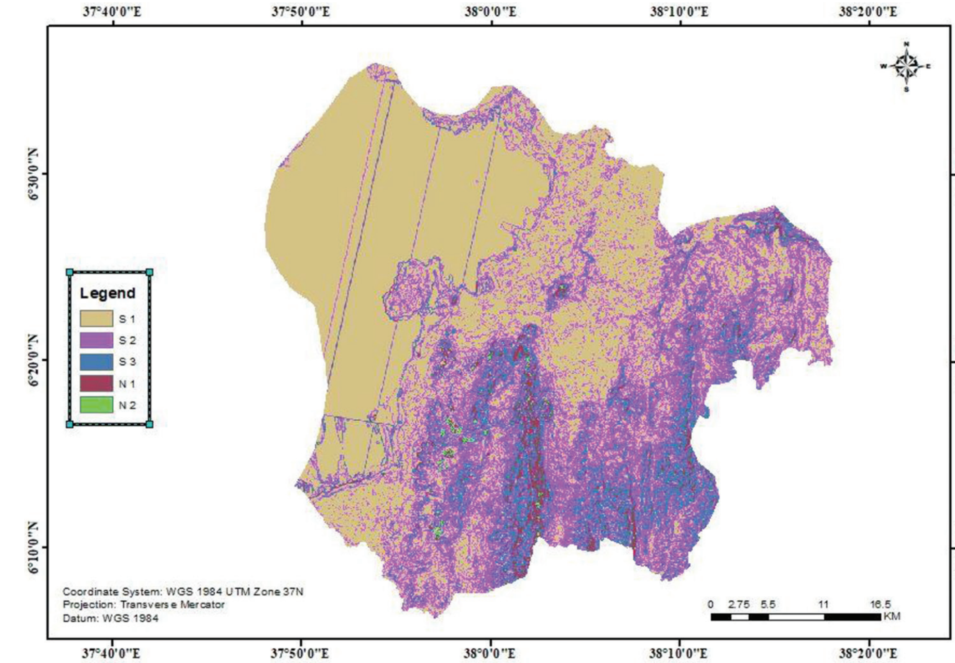


Figure A3. Elevation suitability class of Abaya (upper) and Gelana Districts (lower)



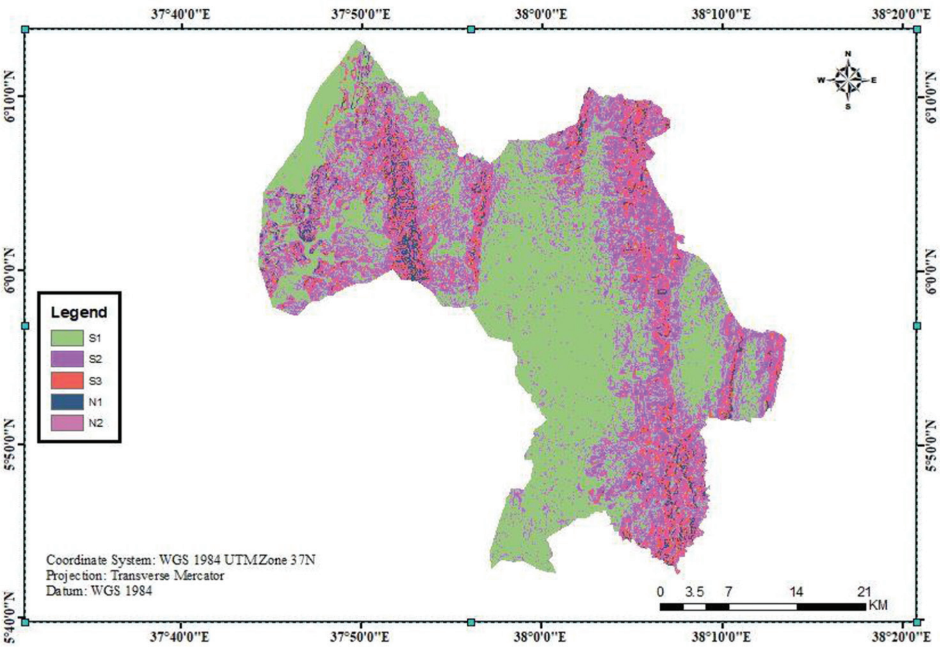


Figure A4. Slope suitability class of Abaya (upper) and Gelana Districts (lower)

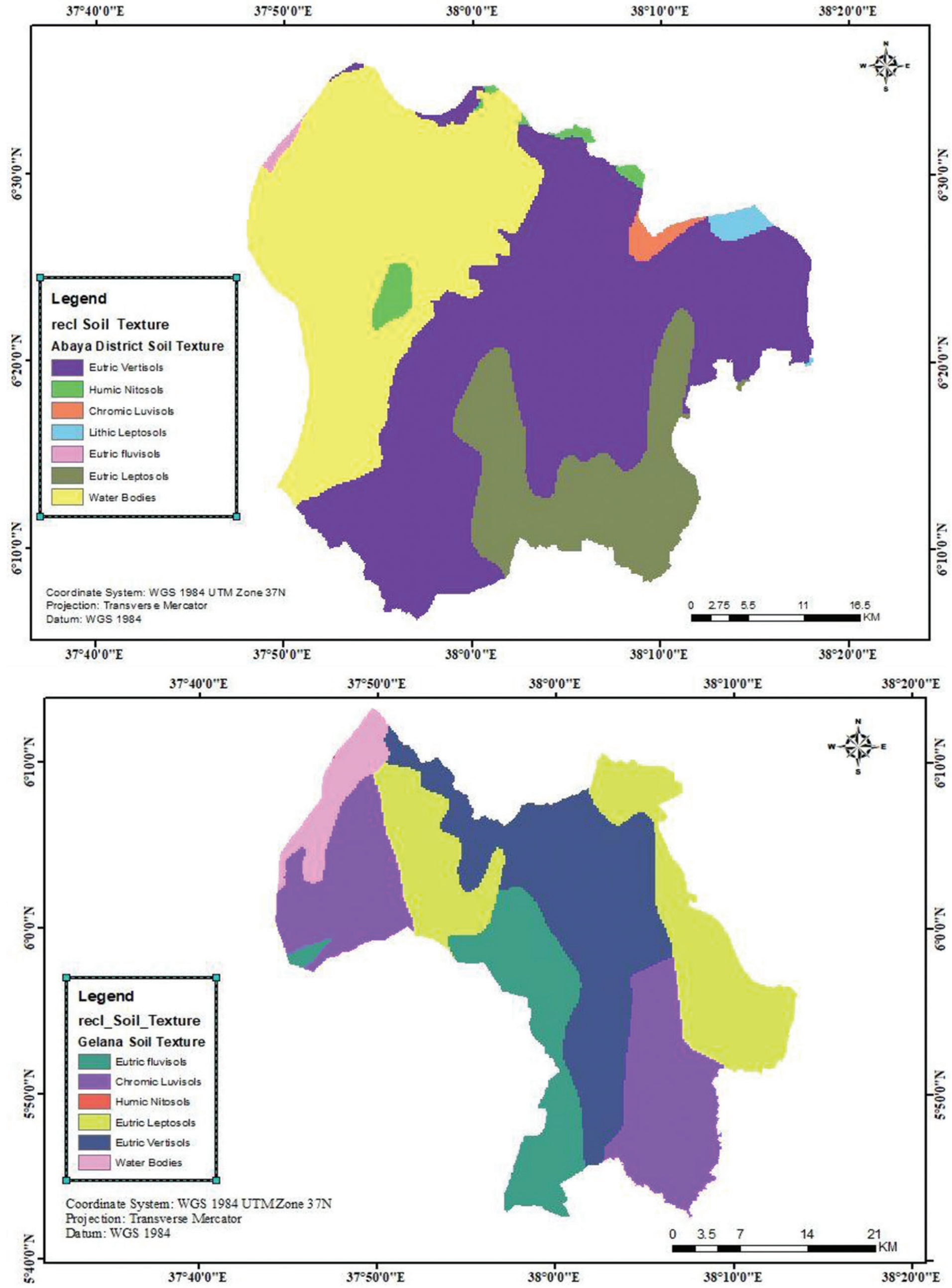
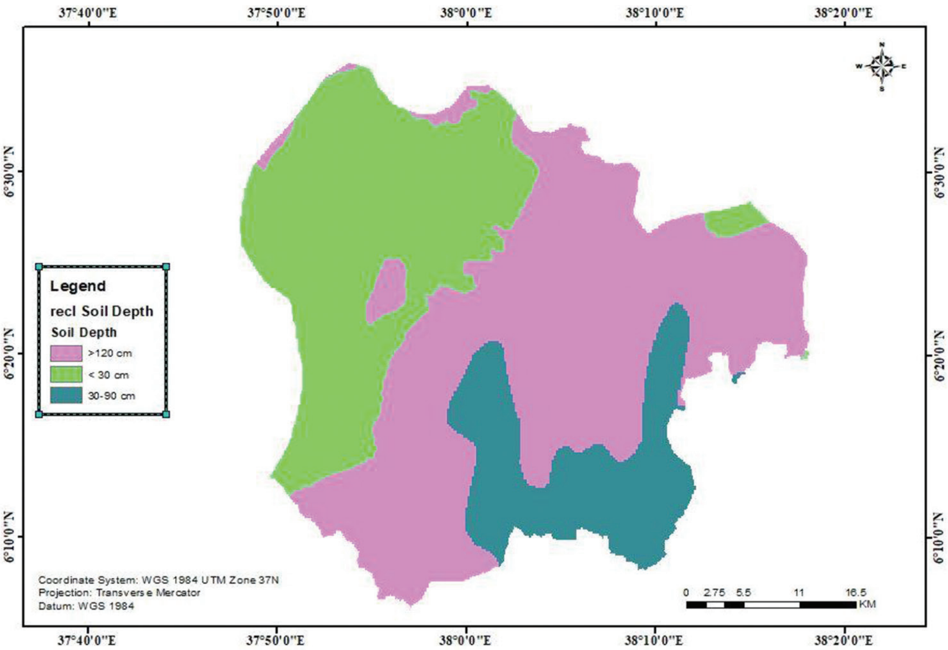


Figure A5. Soil texture suitability class of Abaya (upper) and Gelana Districts (lower)



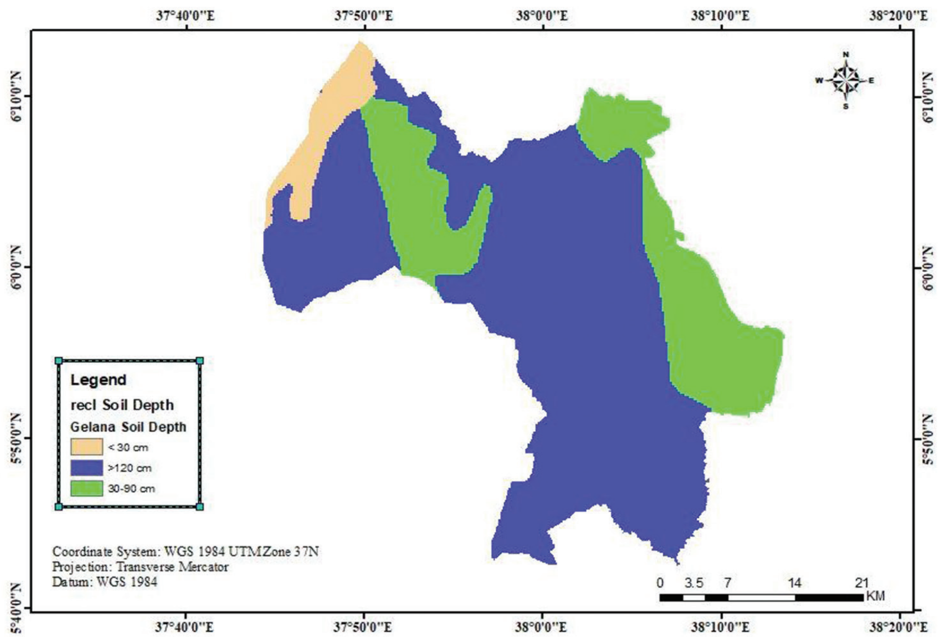
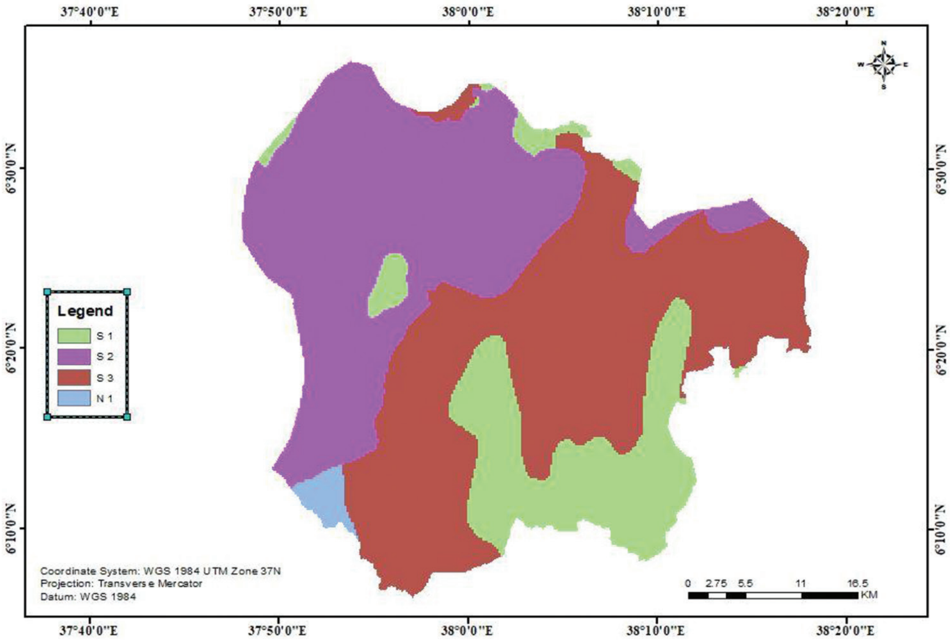


Figure A6. Soil depth suitability class map of Abaya (upper) and Gelana Districts (lower)



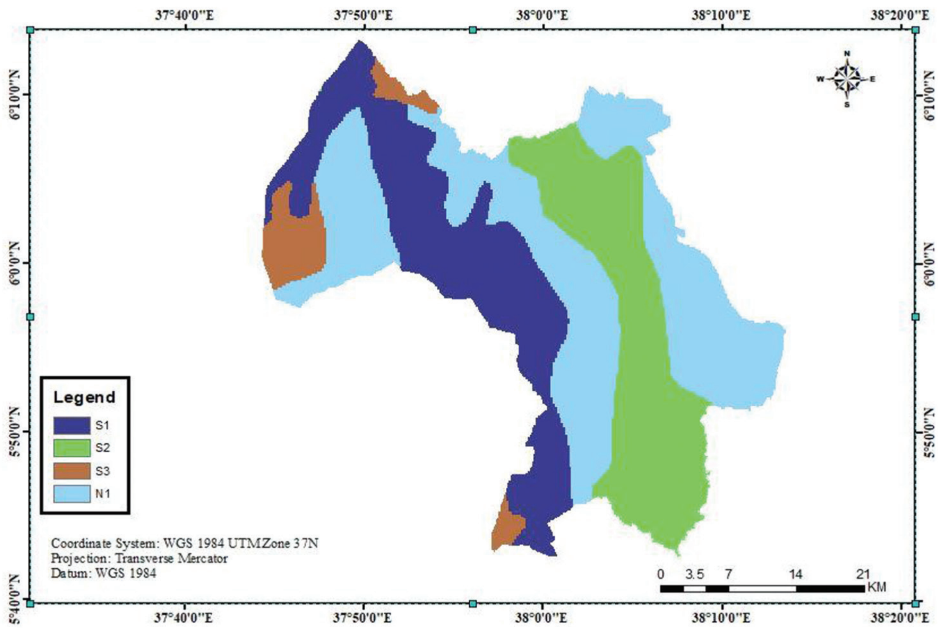


Figure A7. Soil pH suitability class map of Abaya (upper) and Gelana Districts (lower)

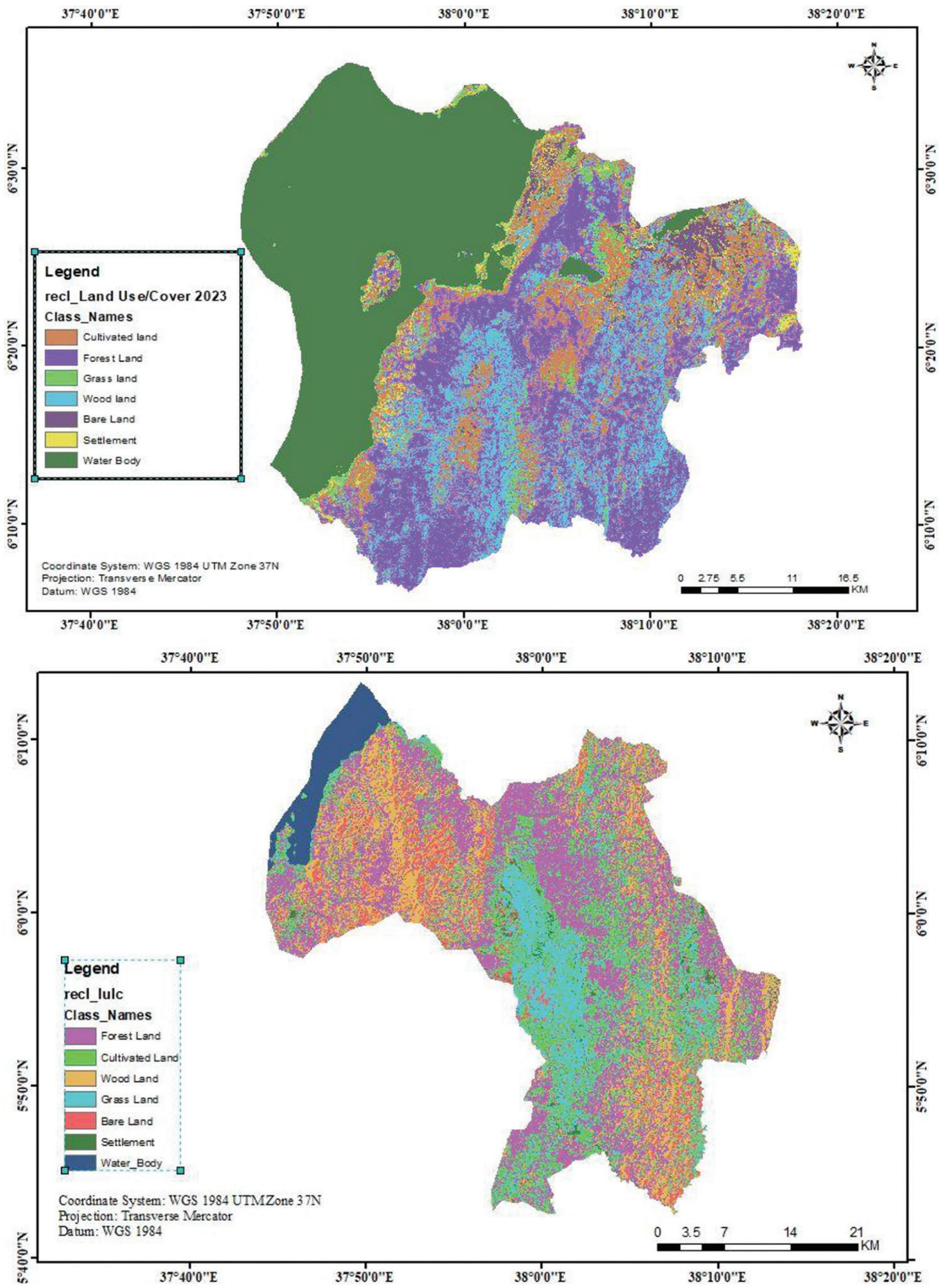


Figure A8. Land use/cover suitability class map of Abaya (upper) and Gelana Districts (lower)