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Research Article

Assessment and Mapping of Soil Fertility Status Under Different Land Use Systems of Yabello District, Borana Zone, Southern Oromia, Ethiopia

Isihak Lolo*, Fayisa Gurmu, Fenan Tola

Oromia Agricultural Research Institute, Yabello Pastoral and Dryland Agriculture Research Center, Yabello, Ethiopia

Abstract

Soil fertility status under different land use systems has been verified to be useful for soil fertility management practices and the efficient utilization of limited land resources. The study was conducted from 2021 to 2023 in the Yabello District to assess soil fertility status under different land use systems and mapping of selected soil fertility parameters. Consequently, based on soil factors such as parent materials, topography, climate, and geomorphology, Yabello District was divided into 87 sampling units. A total of eighty-seven (87) sample mapping units were identified, and composite soil samples were collected and analyzed for physicochemical properties at the Yabello and Batu Soil Research Centers. For soil parameter analysis, laboratory standards were followed. Based on laboratory results, the data was subjected to interpolation using ArcGIS 10.8 software (ordinary kriging), was used to predict values for unsampled locations and to map the whole district. Accordingly, soil texture was categorized as sandy clay loam in forest, cultivate and grazing lands, and sandy clay in shrub lands. Available phosphorus ranged from medium to high in forest land, medium in shrub and grassland, and low in cultivated land. Soil pH was categorized as slightly acidic to neutral in forest land, neutral in grassland, and slightly alkaline in cultivated and shrub lands. Organic carbon ranged from low to high in forest land, medium in grassland, and low to medium in cultivated areas. Therefore, further research should focus on correlating and calibrating soil test with crop responses to develop site-specific fertilizer recommendations and optimal application rates.

Keywords

ArcGIS, Geomorphology, Parent Materials, Physicochemical, Topography

1. Introduction

Soil is one of the most vital natural resources, playing a crucial role in sustaining life on Earth by supporting food production, regulating water cycles, and maintaining environmental quality. As a fundamental component of terrestrial ecosystems, soil quality reflects the dynamic interaction of its physical, chemical, and biological properties, which are influenced by various external factors such as land use, management practices, environmental conditions, and socio-economic priorities [1]. Understanding and managing soil quality is essential for ensuring food security and mitigating environmental degradation. Human activities, particularly those related to land-use changes, have profoundly impacted soil quality and ecosystem health over the past century. The conversion of natural landscapes into farmlands, driven by

*Corresponding author: isihaklolo@gmail.com (Isihak Lolo)

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agricultural expansion, has been a major contributor to ecosystem transformations worldwide [2]. Land degradation, often resulting from inappropriate land-use practices such as deforestation, overgrazing, and agricultural intensification, is a critical issue in the context of global climate change [3]. For instance, the conversion of rangelands into croplands, a common practice in agricultural deforestation, leads to significant changes in soil properties, including the loss of organic matter, reduced nutrient availability, and increased susceptibility to erosion [4, 5]. The decline in soil quality due to land degradation is often accompanied by a reduction in vegetation cover, which further exacerbates the loss of soil organic matter and moisture content. Inappropriate agricultural practices, such as the excessive use of chemical fertilizers, not only harm soil health but also contribute to environmental pollution [6]. As a result, evaluating soil fertility becomes a critical step in making informed decisions about sustainable land-use systems. Effective soil fertility assessment helps identify and address soil problems, ultimately preventing further degradation and enhancing agricultural productivity [7].

Recent advancements in technology, such as Global Positioning Systems (GPS) and Geographic Information Systems (GIS), have revolutionized soil fertility assessment and mapping. GPS technology enables precise collection of soil samples, while GIS facilitates the analysis, visualization, and management of complex datasets, including thematic soil fertility maps [8]. The integration of geo-statistical methods, such as ordinary kriging, with these technologies has significantly improved the accuracy of spatial predictions of soil fertility [9]. This approach allows researchers and land managers to better understand the spatial variability of soil properties and implement targeted interventions.

Assessing and mapping soil fertility status is particularly important in regions experiencing rapid land-use changes and degradation, such as the Yabello district. By evaluating the spatial distribution of soil fertility parameters, stakeholders can develop sustainable land management strategies that enhance soil productivity and support agricultural development [10], such efforts will provide valuable insights for sustainable land management and agricultural planning in the region. Keeping this in view the present study was proposed to assess and Mapping of Soil Fertility Status under Different Land Use Systems of Yabello District, Borana zone, Southern Oromia, Ethiopia.

2. Materials and Methods

2.1. Description of the Study Area

The study was conducted in Yabello district of Borana zone, southern Ethiopia. Yabello is located at 570 Km from Addis Ababa to south direction. The altitude ranges between 943 and 2,400 meters above sea level with average annual rainfall of 300 to 900 mm exhibiting bimodal rainfall (long and short rainy seasons). The long rainy season extends from March to May whereas the short rainy season occurs from mid-September to mid-November. The annual temperature varies between 19-42 ℃.

2.2. Topography

The Yabello district is characterized by physiographic features such as hills, plateaus, and valleys. The steep slopes of the Yabello district have gradients ranging from 3 to 30%. The plateau slopes are gentle, with gradients ranging from 0 to 3%. The valleys in the area are narrow and steep, creating a series of gorges. The topography of the Yabello district is therefore highly varied, with noticeable changes in elevation, slope gradient, and landform, creating unique landscapes [11].

2.3. Demarcation and Descriptions of Land Use Types

Land-use types were selected based on their differences in land management practices and associated activities including the historical and existing information. Moreover, among adjacent land-use types, differences in soil type and slope gradient (topography) of the study area were considered to the extent of minimizing these variations. Accordingly, the selected land-use types for the determination of soil physico-chemical properties were forest land, grazing land, cultivated land and shrub land (Table 1).

Table 1. *Description of land uses of Yabello district.*

Land use types	Description of land use land cover
Forest land	The land is covered with native tree species with bushes and grasses and less disturbed area
Grass land	Land covered with grass and mainly used for communal grazing by livestock
Shrub land	Areas covered with shrubs and thorny bushes with sparsely scattered trees
Cultivated land	Land used for annual rained field crops (maize and tef) with crop rotation and intensive use of inorganic fertilizer (NPS and Urea)

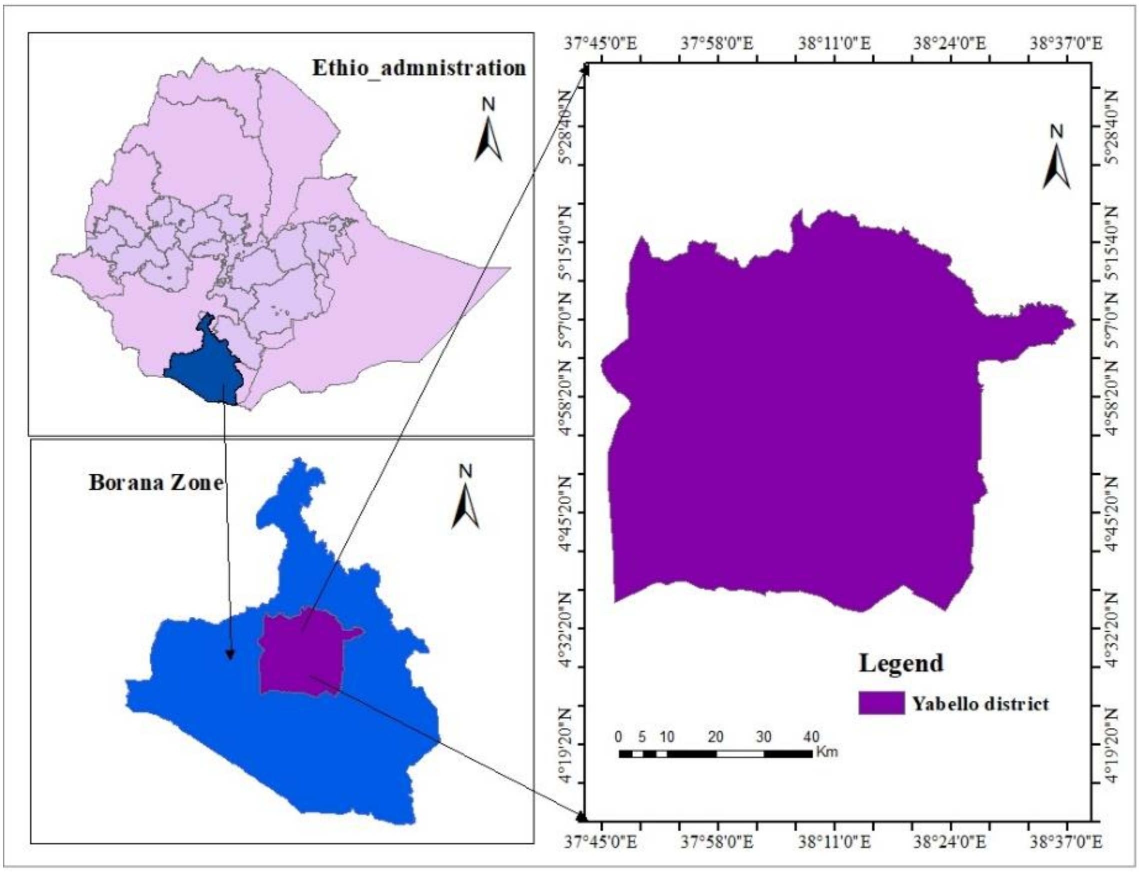

Figure 1. Location map of study area.

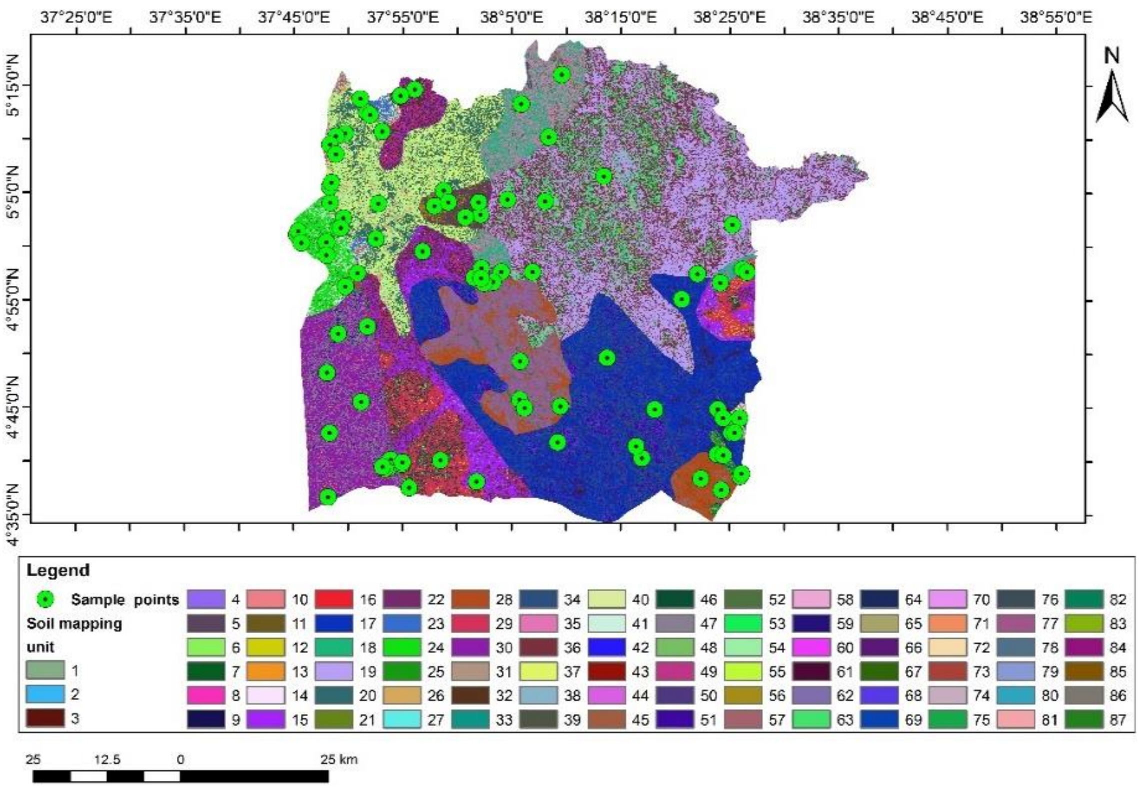

Figure 2. Map of soil mapping unit.

Table 2. Soil parameters and methods of analysis.

Soil parameter	Methods of analysis
PH	pH- meter
EC	EC- meter
Texture class	Bouyoucos hydrometer
Organic carbon	wet digestion method
Available phosphorous	Olsen *et al.* (1954)
Bulk density	Gravimetric (oven dry)
CEC	Ammonium acetate
TN	Kjeldahl digestion
Ex. Na^{+}	Flame photometry
Ex. Mg^{2+} and Ca^{2+}	AAS

2.4. Mapping Unit Preparations and Soil Sampling

To delineate mapping units, soil forming factors such as parent materials, topography, geomorphology and land use were considered digitally by spatial tools to categorize areas having similar properties. Based on these factors eighty-seven (87) mapping units were prepared and 87 soil samples (one composite sample from each land unit) (at 0-20 cm depth) were collected from developed land units (mapping units) during 2021 and 2022/23, registering their geographical location of each sampling point using GPS.

2.5. Soil Sample Preparation and Analysis

For determining the physicochemical characteristics of the soil, soil samples collected from each type were air dried, and passed through 2 mm sieves; however, samples for organic carbon were ground to pass 0.5 mm size sieves. Both statistical evaluation and geospatial evaluation were conducted. Then at the end of the activity's fertility map was prepared for soil pH, CEC, total nitrogen, organic matter, available phosphorous, exchangeable sodium, calcium, magnesium, and potassium. Likewise, Arc GIS map 10.1 with geo statically analyst extension of ARC GIS software was used to prepare spatial distribution maps of soil parameters, while interpolation method employed was ordinary kriging.

3. Results and Discussion

3.1. Physical Properties of Soils Under Different Land Uses

Soil Bulk density: The results revealed that the bulk density of grazing land and cultivated land was significantly higher compare with shrubs and forest land, while lower bulk densities were recorded in soils sampled from forest and shrub land (Table 3). This difference may be attributed to overgrazing, which likely increases soil bulk density. This finding aligns with [12] discuss the impacts of soil damage caused by grazing livestock on crop productivity and also reported that livestock trampling significantly raises soil bulk density and decreases porosity in the upper soil profile. Conversely, moderate bulk density was observed in cultivated land, likely due to intensive tillage practices that temporarily compact the tilled soil layer and increase bulk density over time, along with reduced soil organic matter content from the removal of crop residues. This result contrasts with [13], who found that the lowest bulk density values were associated with all cultivated land units.

Soil Texture: Soil texture significantly influences key properties such as drainage, water-holding capacity, aeration, erosion susceptibility, organic matter content, Cation exchange capacity, pH buffering capacity, and soil tilth [14]. Analysis of particle size distribution revealed that grazing and forest lands categorized under Sandyclayloam textural classes having mean values of 51.01% sand, 32.54% clay, and 17.96% silt and 58.77% sand, 30.54% clay, and 10.73% silt respectively. Cultivated land exhibited a Sandyclayloam textural classes having mean value of (47.47% sand, 34.63% clay, 17.9% silt), and shrub land also showed a sandy clay texture with 45.04% sand, 34.77% clay, and 20.18% silt (Table 4).

3.2. Chemical Properties of Soil Under Different Land Uses

Soil pH: The soil pH of grazing land ranged from 5.16 to 8.90, with an average of 7.11, indicating a distribution from slightly acidic to neutral (Table 4). In contrast, forest land exhibited a pH range of 5.4 to 7.25, averaging 6.28, which signifies slightly acidic conditions. The pH of cultivated land varied from 5.45 to 7.82 with mean value of 7.11, reflecting a transition from neutral to slightly alkaline. For shrub land, soil pH ranged from 6.32 to 8.22, with mean of 7.35 indicating conditions from slightly acidic to moderately alkaline. Overall, the soil pH in shrub land varied from slightly acidic to moderately alkaline (Table 5).

Soil Organic carbon: The organic carbon concentration levels were observed in the following order: forest land (0.79-3.45%) > shrub land (0.88-3.20%) > grassland (0.65-2.98%) > cultivated land (0.77-1.20%) (Table 6). The highest average organic carbon concentration was found in natural forest soils (2.20%) and shrub land (1.99%) (Figure 4). This higher accumulation of soil organic matter (SOM) is likely due to the addition of litter from diverse plant species, which contribute to increased biomass production and enhanced nutrient release through decomposition. Similar findings by [15] discuss the agro-ecological implications of forest and agroforestry systems on soil fertility in Ethiopia. This indicate that natural forests exhibit higher soil organic carbon concentrations compared to various exotic tree plantations in different regions of Ethiopia. The minimum organic carbon value (1.0%) was recorded in agricultural cropland, attributed to lower organic matter inputs from litter and losses due to wood and crop biomass harvesting. Continuous cultivation exacerbates organic matter oxidation, resulting in carbon loss from the soil in the form of CO_2. These results align with findings from [13, 17], which reported lower organic carbon levels in cultivated land and Eucalyptus plantation soils compared to other land-use systems.

Table 3. Soil bulk density of the study area.

Land use Range of BD	Mean BD	Rating remark
Forest 1.13-1.72	1.36	Moderate
Grazing 0.76- 1.76	1.41	Moderate
Shrubs 0.91-1.53	1.28	Low
Cultivated 1.23-1.71	1.45	Moderate

Table 4. Particle size distribution under each land use.

Descriptive %Sand	%Clay	% Silt	Texture class	Land use
Minimum 23.28	1016	1.28		
Maximum 83.28	61.44	18.56	Sandyclayloam	Forest
Mean 58.77	30.50	10.73		
Minimum 12.56	9.80	1.28		
Maximum 84.56	66.80	60.0	Sandyclayloam	Grazing
Mean 51.01	32.54	17.96		
Minimum 25.12	15.44	10.92		
Maximum 67.28	47.60	34.92	Sandy clay	Shrubs
Mean 45.04	34.77	20.18		
Minimum 20.02	18.88	8.0		
Maximum 73.12	60.88	48.0	Sandyclayloam	Cultivated
Mean 47.47	34.63	17.9		

Table 5. Soil pH at different land uses of the study area.

Land use Ranges	Mean pH	Rating by mean
Forest 5.43-7.25	6.28	Slightly acid
Grazing 5.16-8.90	7.11	Neutral
Shrubs 6.32-8.22	7.35	Slightly alkaline
Cultivated 5.45-7.82	7.11	Neutral

Table 6. Level and rating of soil organic carbon under different land use.

Land use	Range of SOC (%)	Mean (%OC)	Rating
Forest	0.79-3.45	2.20	Low to high
Grazing	0.66-2.98	1.83	Low to high
Shrubs	0.88-3.20	1.99	Low to high
Cultivated	0.77-1.20	1.0	Low

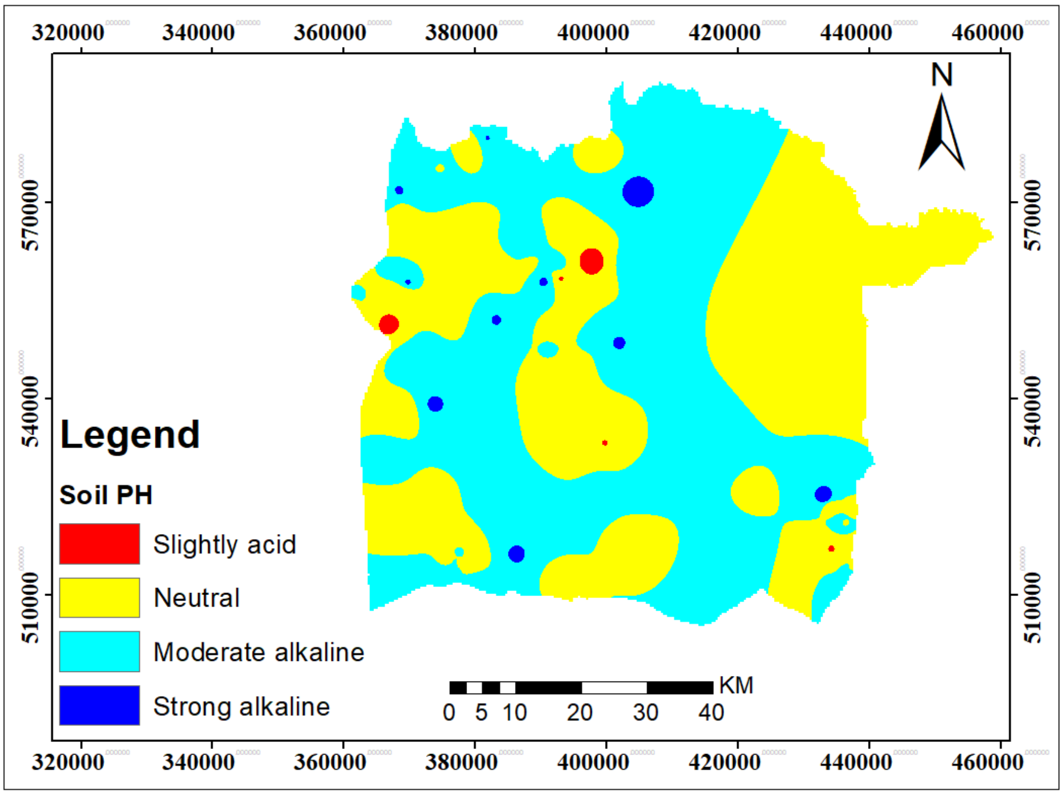

Figure 3. *Distribution of soil pH under different land use.*

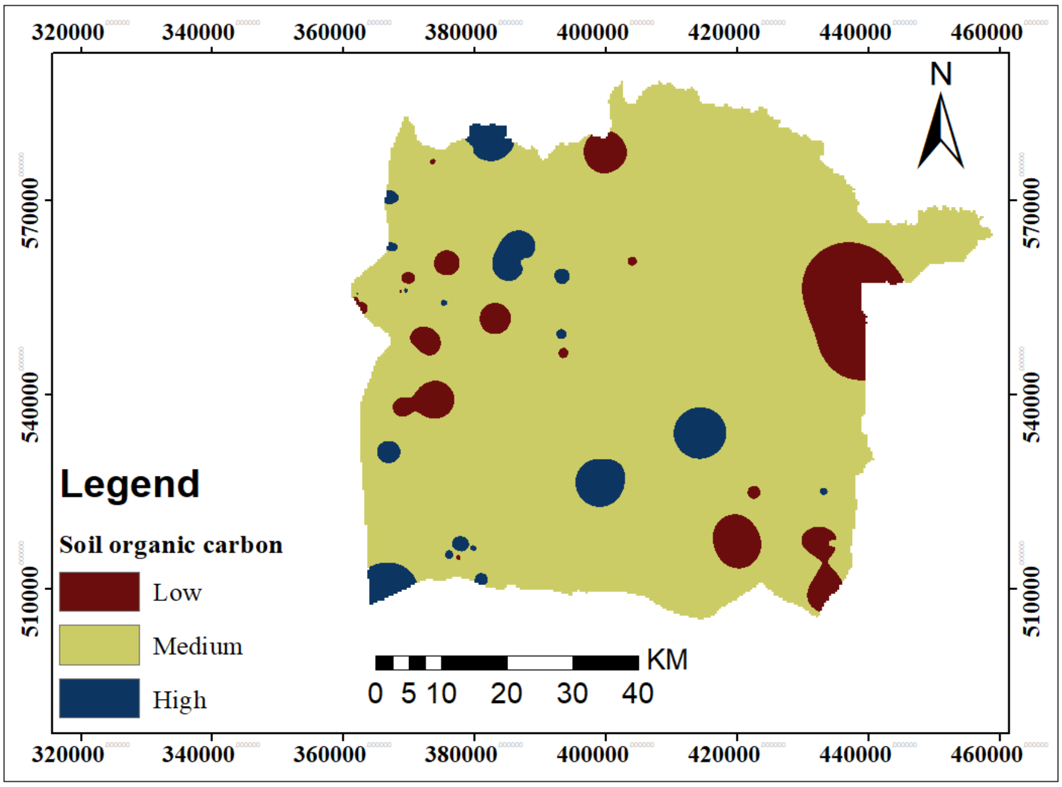

Figure 4. *Map of soil organic carbon content of Yabello district.*

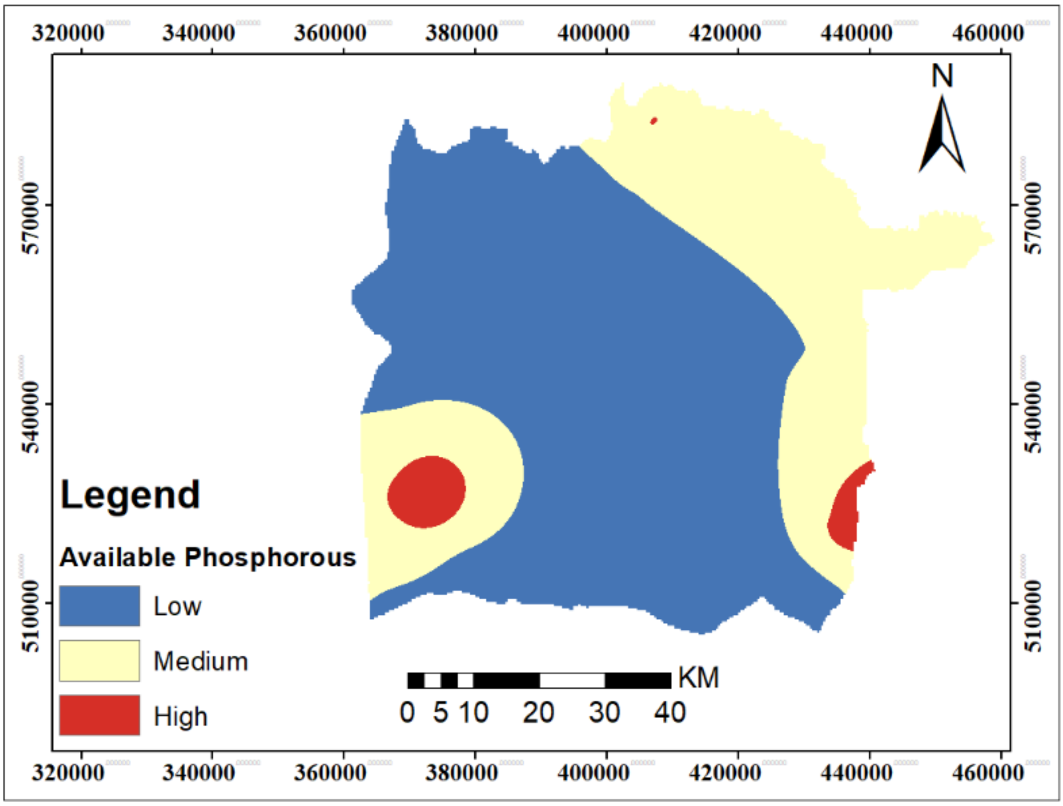

Figure 5. *Map of soil available phosphorous at yabello district.*

Available phosphorous: The results indicate that, except for cultivated land, the other land-use systems in the study area recorded phosphorus was medium ranges in forest land, grassland, and shrub land, respectively are classified as medium (Table 7). Conversely, cultivated land exhibited low available phosphorus (Figure 5). This low phosphorus content may be attributed to factors identified by [18] reported that phosphorus availability in most Ethiopian soils declines due to fixation, extensive crop harvesting, and erosion. Decomposing residues produce organic anions that compete with phosphorus for sorption sites.

Total Nitrogen: The total nitrogen (TN) content varied significantly across land use types, with the highest recorded in forest land at 0.26% and the lowest in cultivated land at 0.06% (see Table 8). The elevated TN levels in forest land are likely attributed to high organic matter content, which serves as a primary source of soil nitrogen through mineralization. Additionally, the favorable microclimate conditions in forests and shrublands help maintain soil temperature, reducing nitrogen loss through volatilization [19]. In contrast, the low TN mean of 0.06% in cultivated land may result from continuous monocropping, removal of crop residues, and increased soil exposure to sunlight (Figure 6). Research by [20] supports this observation, indicating that the continuous removal of crop residues leads to the depletion of organic matter, contributing to surface runoff and the downward leaching of negatively charged nitrates.

Table 7. *Mean of available phosphorous under different land use.*

Land use min	max Mean Av. P (ppm)	Rating of P as of London, 1991
Forest 3.32	9.11 5.7	Medium
Grazing 3.73	19.91 6.92	Medium
Shrubs 4.61	7.91 6.29	Medium
Cultivated 4.06	6.89 5.01	Low

Table 8. *Total nitrogen under different land use.*

Land use	Mean TN (%)	Rating
Forest	0.26	High
Grass	0.07	Low
Shrubs	0.09	Low
Cultivated	0.06	Low

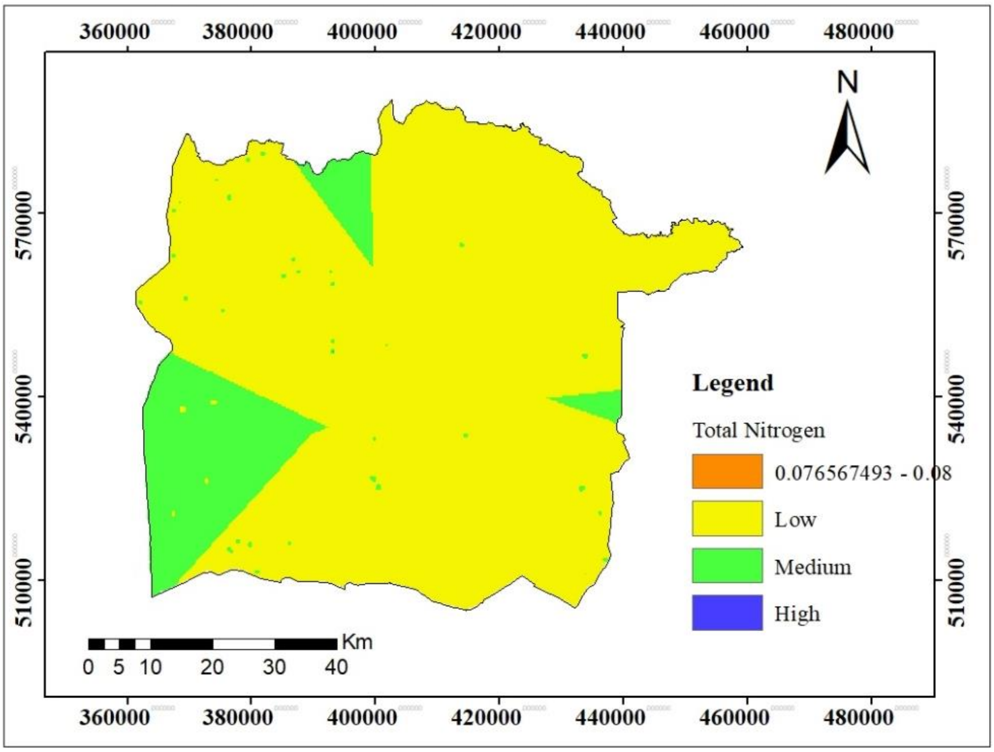

Figure 6. Map of total nitrogen under different land uses at Yabello district.

Cation Exchangeable Capacity: Cation exchange capacity (CEC) is a critical measure of a soil's ability to retain positively charged ions. This property significantly influences soil structure stability, nutrient availability, soil pH, and the soil's response to fertilizers and other amendments (Hazleton and Murphy, 2007). According to the classifications by [21], the soils in the study area exhibit a range of CEC levels: very low, low, moderate, high, and very high (Figure 7). Specifically, more than 26% of the study area has a moderate CEC, 23% has low CEC, 14% has high CEC, and 19% has very high CEC (Table 9). The presence of very low and low CEC levels may be attributed to inadequate soil fertility management practices, including continuous overgrazing, monocropping, and limited vegetation cover, as well as the sandy loam texture with low clay content. These results align with findings from [16] explore the variation in soil properties under different land-use types managed by smallholder farmers in central Ethiopia, which indicate that the depletion of organic matter due to intensive cultivation has contributed to lower CEC levels in the soils. Notably, soils under natural forest land cover systems exhibited the highest mean CEC concentration at 27 cmol(+)/kg soil. This result is consistent with the findings of [17], who reported that soils beneath natural forest land cover had a mean CEC of 25.8 cmol(+)/kg soil, followed by those under Eucalyptus saligna plantations at 24.7 cmol(+)/kg soil.

Table 9. Soil CEC under different land use at Yabello district.

Land use	CEC cmol (+)/kg	Rating
Forest	27	High
Grass	20	Moderate
Shrubs	29	High
cultivated	11.5	Low

3.3. Exchangeable Bases of Soils Under Different Land Uses

Exchangeable Sodium: Table 10 shows that the exchangeable sodium levels in the study area ranged from 0.4 to 5 cmolc/kg, with a mean of 1.63 cmolc/kg. Based on the classification by Hazelton and Murphy (2007) [10], the exchangeable sodium was categorized as follows: 12%, 69% and 18% medium, high and very high respectively (Figure 8).

Table 10. Exchangeable sodium under different land use.

land use	Ex.Na+	Rating
Forest	1.00	High
Grass	1.48	High

land use	Ex.Na+	Rating	land use	Ex.Na+	Rating
Shrubs	2.58	very high	cultivated	1.36	High

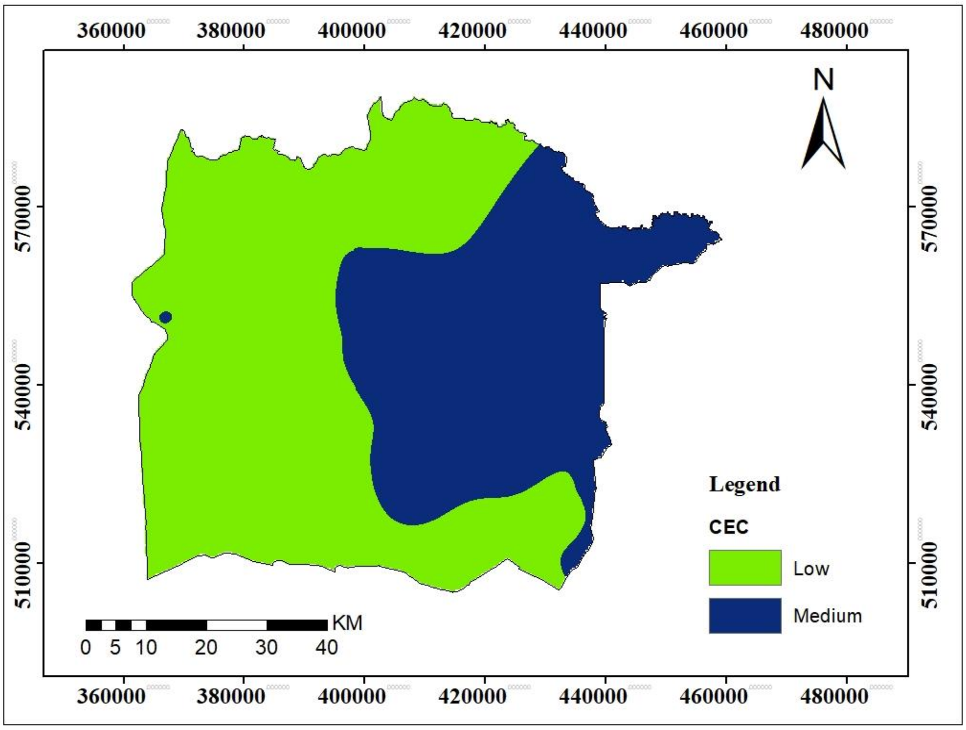

Figure 7. Map of Soil Exchangeable Capacity of the study area.

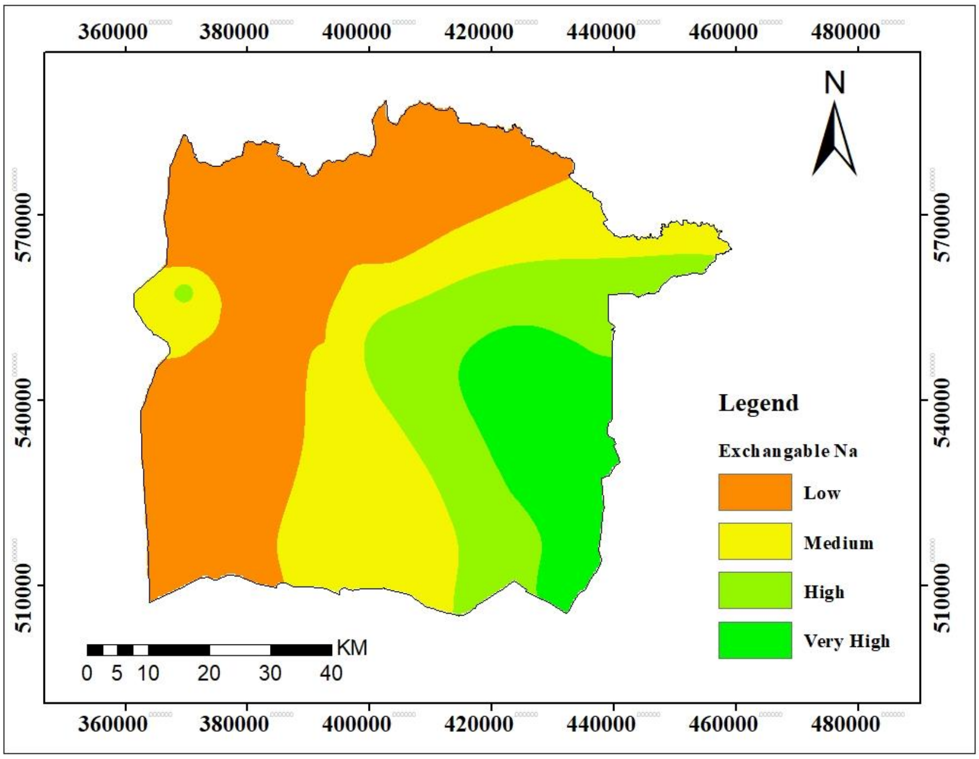

Figure 8. Map of soil exchangeable sodium of the study area.

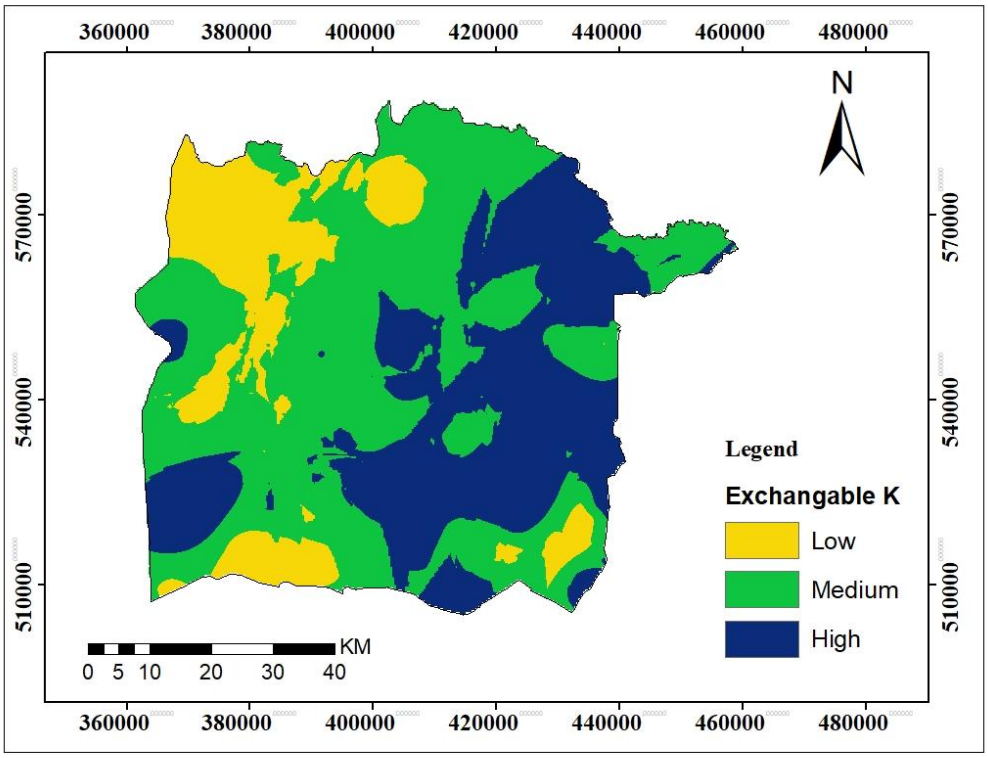

Figure 9. *Maps of exchangeable potassium at the Yabello district.*

Exchangeable potassium: Figure 9 revealed that the exchangeable potassium levels in the study area ranged from low to high, according to the classification established by [10]. This variation is likely attributed to the parent materials from which the soil is derived. These findings are consistent with those reported by [22], which suggest that elevated levels of exchangeable potassium may result from the lateral movement of iron from the upper slopes.

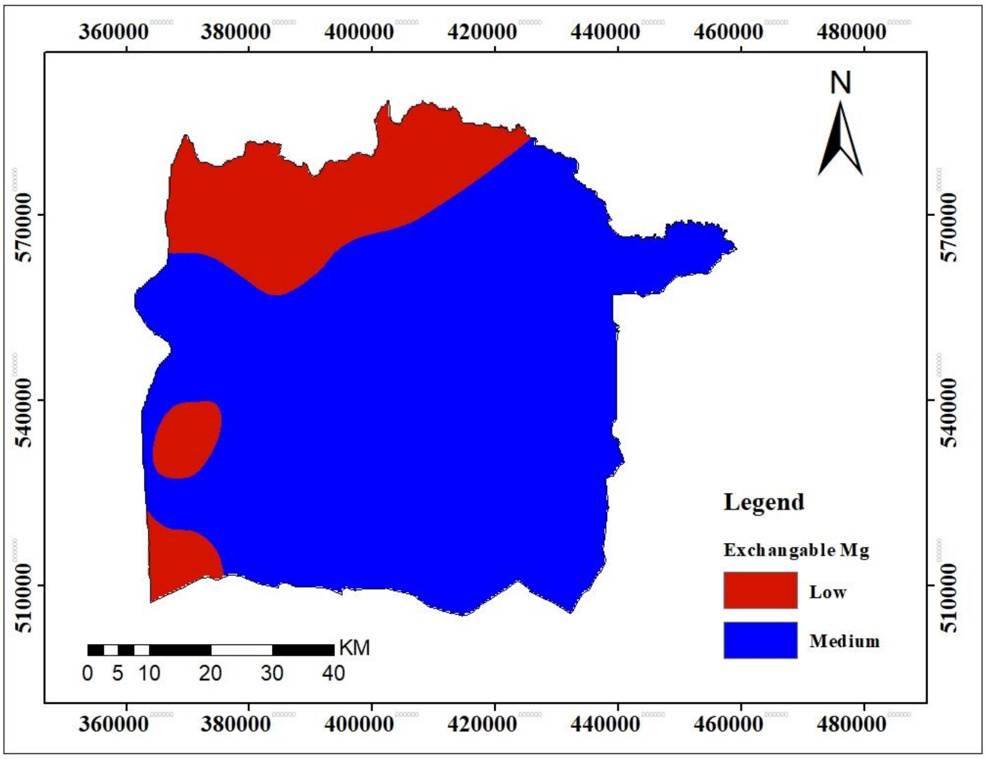

Figure 10. *Maps of exchangeable magnesium at yabello district.*

Exchangeable Magnesium: Magnesium is a key component of the chlorophyll molecule in plant tissues and is adsorbed onto the surfaces of clay and organic particles. It exists in exchangeable forms that are readily available to plants and is not easily leached from the soil. In the study area, the levels of exchangeable magnesium ranged from low to medium, as classified by [10]. This variation is likely influenced by the parent materials from which the soil is derived (see Figure 10). Most land uses in the study area exhibited medium levels of exchangeable magnesium, likely due to the combination of parent materials, moderate organic carbon content, and medium cation exchange capacity (CEC) of the soils. Soils with low CEC are more prone to deficiencies in basic cations such as Na^+, K^+, Mg^{2+}, and Ca^{2+}, making them susceptible to leaching.

4. Conclusions

The study revealed significant spatial variations in soil physicochemical properties across various land use systems in the Yabello district. Forest and shrub lands demonstrated superior soil fertility indicators, including higher organic carbon and total nitrogen levels, along with moderate available phosphorus. These findings highlight the ecological benefits of maintaining natural vegetation for soil health. In contrast, cultivated lands exhibited degraded soil quality, characterized by low available phosphorus, low organic carbon, and slightly alkaline pH levels. This degradation is primarily attributed to intensive farming practices, nutrient depletion, and insufficient organic carbon inputs. Additionally, grazing lands face challenges such as increased bulk density, low available phosphorus, and moderate organic carbon levels, compounded by slightly alkaline soil pH due to overgrazing, which indicates soil compaction. Overall, these results underscore the importance of sustainable land management practices to enhance soil health and fertility across different land use systems.

5. Recommendations

Based on the information regarding soil fertility, stakeholders should invest in soil conservation and reforestation programs to mitigate soil degradation and enhance soil fertility in the Yabello district. Additionally, further research should focus on correlating and calibrating soil test data with crop responses to establish site-specific fertilizer recommendations, ensuring appropriate application rates for optimal crop performance.

Abbreviations

AAS	Atomic Absorption Spectrophotometer
BD	Bulk Density
CEC	Cation Exchangeable Capacity
Ec	Electrical Conductivity
FAO	Food and Agriculture Organization
NMA	National Metrology Agency
OC	Organic Carbon
pH	Potential of Hydrogen
TN	Total Nitrogen

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Author Contributions

Isihak Lolo: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Resources, Writing - original draft, Writing - review & editing

Fenan Tola: Conceptualization, Data curation, Supervision, Writing - original draft, Writing - review & editing

Feyisa Gurmu: Data curation, Investigation, Methodology, Writing - review & editing

Disclaimer (Artificial Intelligence)

I just declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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