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RESEARCH ARTICLE

CHARACTERISTICS OF SOIL QUALITY ATTRIBUTES UNDER DIFFERENT AGROECOSYSTEMS AND ITS IMPLICATIONS FOR AGRICULTURE IN THE CHOKE MOUNTAIN WATERSHED IN ETHIOPIA

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KEYWORDS

agroecosystem, Choke Mountain watershed, coefficients of variation, Ethiopia, soil quality indicator

HIGHLIGHTS

- Soil properties varied within coefficients of variation ranging from 7% to 169%.
- High variation in available phosphorus was caused by different management practices.
- Midland plains are dominated by Vertisol and Nitosols more suitable for agriculture.
- Lowland and mountainous highland area of the watershed are neither fertile nor suitable for agriculture.
- Lime application and organic fertilizer are fundamental to reversing soil acidity.

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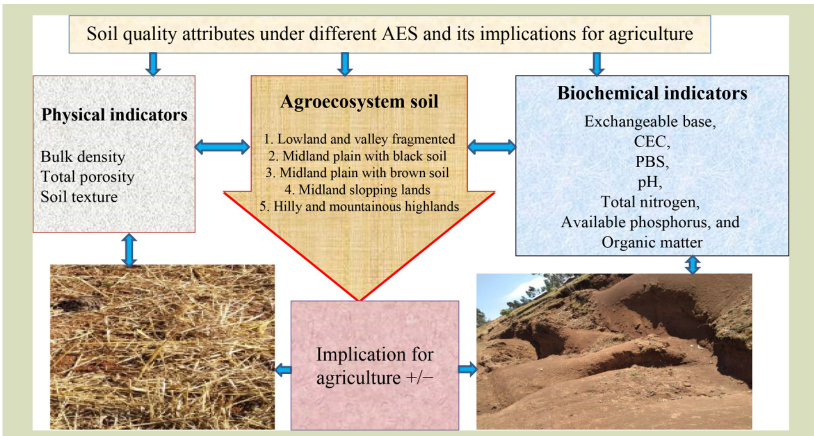
GRAPHICAL ABSTRACT



ABSTRACT

Awareness of how soil properties vary over agroecosystems (AES) is essential for understanding soil potentials and improving site-specific agricultural management strategies for a sustainable ecosystem. This study examined the characteristics of soil quality attributes and implications for agriculture in the Choke Mountain watershed in Ethiopia. Forty-seven composite soil samples (0–20 cm deep) were collected from lowland and valley fragmented (AES 1), midland plain with black soil (AES 2), midland plain with brown soil (AES 3), sloppy midland land (AES 4), and hilly and mountainous highlands (AES 5). Ten of 15 soil quality properties were significant ($P < 0.05$ or 0.01), including silt, exchangeable bases, cation exchange capacity, percent base saturation, pH, organic matter, total nitrogen and available phosphorous (P) across the five AES. However, all properties were variable with coefficients of variation from 7% (total porosity) to 169% (available P) across the AES. Although AES 2 and 3 are affected by waterlogging and acidity, these two have better prospects for agriculture, but AES 1, 4, and 5 are unsuitable for agriculture because of soil erosion. Therefore, appropriate and applicable soil management strategies, particularly lime application and organic fertilizer, are fundamental to reversing soil acidity and improving soil fertility.

1 INTRODUCTION

Soil quality degradation occurs globally through adverse effects on its physical, chemical and biological properties, and inorganic and organic contamination caused by human activities[1]. Ensuring soil acceptable quality is challenging due to the interaction of climate, soil, plant and human factors. However, using particular crop, plant and soil management techniques makes it feasible to slow soil deterioration or keep soil quality at ideal or threshold levels to increase crop production[2].

In addition, by practicing sustainable soil management and having a solid grasp of the diversity in soil properties, it is possible to prevent or minimize soil deterioration and increase soil health and fertility[3]. Farming activities like irrigation and fertilization, as well as soil formation elements including soil parent materials, climate and vegetation are the main contributors to the spatial variability of soil properties[4,5].

Ethiopia has wide climatic variation from dry to wet, various altitudes from lowlands to highlands and mixed farming systems caused soil variability between and within its agroecological zones[6]. The highland areas received a high amount of rainfall, which has caused the leaching of essential soil nutrients and reduced agricultural production, whereas the rugged terrain has significantly affected the weathering of soils[7]. This shows that soil properties vary in spatially areas because of the combined effect of natural and anthropogenic factors. However, deforestation, excessive grazing and inappropriate farming methods have been the main human-induced causes that exacerbated soil variability and have led to a remarkable decline in soil organic matter[8]. The highland regions of Ethiopia, where 87% of the population lives and poor farming practices have been used for centuries, have been particularly affected by these damaging activities[6].

The Choke Mountains watershed, one of the Ethiopian highland areas, is also characterized by long steep slopes, intensively used for agriculture and forestry, high-intensity rainfall, significant direct runoff generation, and soil erosion. Given that nutrients in Choke soils tend to be concentrated in the upper region of the soil column, high rates of in-field erosion pose a particular concern[9], which creates variability of soil properties in different agroecological zones.

Studies were conducted elsewhere regarding the variability of soil properties that might be attributable to altitude, the intensity of tillage, the cropping system with the management system and other factors. Alwani et al.[4] based on research in Iraq, found that climate variability and management practices could cause the variability of soil reactions from one place to another. Exchangeable bases are distributed differently depending on the particle size distribution, degree of weathering, soil management techniques and level of cultivation, as reported by Negasa et al.[10]. Abate et al.[11] also showed that altitude, tillage intensity, agricultural method, and soil management strategies could be the most likely causes of soil organic matter concentration variation among the land units.

Also, Ebabu et al.[8], Bewket & Stroosnijder[12] and Teferi et al.[13] conducted research on the impact of different land use categories on specific soil characteristics in one or two of the agroecological zones of the Choke Mountain watershed. The Choke Mountain watershed includes areas below 1000 masl and contains a variety of slope shapes and soil types. It stretches from tropical alpine habitats at over 4000 masl to the hot and dry Blue Nile Basin. However, the above studies did not incorporate the broad agroecosystems of the watershed, which is the main focus of this research.

Research was therefore conducted to fill this gap, investigating the characteristics of soil quality attributes and their implications for agriculture in five agroecosystems (AES) of the Choke Mountain watershed in Ethiopia. It is anticipated that the outcomes of experimental data on the physical and biochemical properties of soil quality will provide accurate information on the status and variability of soil nutrients at an AES level to develop future practical and sustainable soil management techniques for sustainable agricultural activities.

2 MATERIALS AND METHODS

2.1 Description of the Choke Mountain watershed

The Choke Mountains are a large block of highland found in central Gojjam, Amhara region centered at 10° N, and 36° E. Choke Mountain is the source for about 60 rivers and 270 springs in the upper Blue Nile Basin[14]. The landscape in the area is mountainous and occasionally steeply dissected. East Gojjam Zone, where the study was conducted, represents Blue Nile highland conditions and includes a large elevation gradient of 800 to 4200 masl from the lower part of the Abay Basin to the summit of Choke Mountain. In boreal summer, the intertropical convergence zone moves further north, bringing with it the rainy season[15] and is characterized by two seasons: *bega*[1] (covering the months of November through April) and *kiremt*[2] (May to October). Rainfall distribution across the Blue Nile highlands demonstrates variation brought on by topographic gradients. In the study sites, the most substantial precipitation gradients follow elevation: the high elevation has the wettest weather and the driest states are in the Blue Nile gorge. Rainfall on Choke Mountain varies locally due to topographic slopes and is not uniformly distributed, ranging from 600 to 2000 $mm \cdot yr^{-1}$[16]. These differences in precipitation and the elevation of the temperature gradient result in a series of unique agroecological zones. Different ecologies, soil types and crop mixes characterize the agroecosystems of the Choke Mountain watershed[16].

In agriculture, crop-livestock mixed farming techniques predominate in East Gojjam. The crops cultivated in the Choke Mountain watershed differ in the agroecological zone and the soil type. There is neither the crop-limiting cold of the highlands nor the sporadic droughts experienced in the valley in the midland AES, which has generally milder slopes and more productive soils[17]. Until recent decades, the highest elevation zones (up to 3800 masl) had largely untouched forests and grasslands[16]. These zones were only significantly encroached into for grazing, gathering fuel wood and occasionally for the production of barley or potatoes due to population pressure in the 1980s. Similarly, the lowest elevation zone (AES 1) is the steep and irregular terrain of the gorge that had good scrub and tree cover until recent decades. These woodland regions were encroached upon as population pressure mounted in the final decades of the twentieth century to construct new, albeit marginal, agriculture[16].

2.2 Agroecosystems of the Choke Mountain watersheds

Agroecology, soil and farming systems have been combined to develop six AES in the Choke Mountain watershed[16]. Since AES 6, an afroalpine on the peak of Choke Mountain that stands between 3800 and 4200 masl is a protected bio-reserve, so it was excluded from the current study. Table 1 presents the fundamental traits of the study agroecosystems of Choke Mountain watershed.

2.3 Soil samplings and analysis procedures

Before collecting soil samples, each study site conducted a reconnaissance survey and fieldwork with the *woreda*[3]

Table 1 Characteristics of study agroecosystems (AES) of Choke Mountain watershed in Ethiopia

AES	Farming system	Rainfall (mm)*	Temperature (°C)*	Elevation (masl)	Major soil	Major crop
Lowland and valley fragmented (AES 1)	Fragmented sorghum-based, extensive	< 900	21–27.5	800–1400	Leptosols Cambisols	Sorghum (*Sorghum bicolor*), teff (*Eragrostis abyssinica*, maize (*Zea mays*), haricot bean (*Phaseolus vulgaris)*
Midland plain with black soil (AES 2)	Intensive teff-based	900–1200	11–15	1400–2300	Vertisols	Teff (*Eragrostis abyssinica*), durum wheat (*Triticum durum*), barley (*Hordeum vulgare*), chickpea (*Cicer arietinum*)
Midland plain with brown soil (AES 3)	Intensive maize–wheat based	900–1200	16–21	1400–2400	Nitosols Alisols	Maize (*Zea mays*), wheat (*Triticum* spp.), teff (*Eragrostis abyssinica*)
Sloppy midland land (AES 4)	Semi-intensive wheat/barley-based	1200–1400	11–15	2400–2800	Leptosols Nitosols Alisols	Wheat *(Triticum* spp.*)*, teff (*Eragrostis abyssinica*), barley (*Hordeum vulgare*), engido (*Avena* spp.*)*
Hilly and mountainous highlands (AES 5)	Barley/potato-based	⩾1400	7.5–10	2800–3800	Leptosols Luvisols	Barley (*Hordeum vulgare*), potato (*Solamum tuberosum*), fava bean (*Vicia fava), engido* (*Avena* spp.*)*

Note: * Mean annual values. Sourced from Mesfin et al.[18]

[1] Dry season in Ethiopia

[2] Rainy season in Ethiopia

[3] Third-level of the administrative division of Ethiopia after regional states and zones

development agents. Soil sampling locations were then selected to represent best each agroecosystem of the Choke Mountain watershed, which was considered a variation in the agroclimatic zone, farming system, and soil and terrain attributes. From the study area, surface soil samples (0–20 cm deep) were collected in January 2021 using a soil auger from five AES (Table 1) of the Choke Mountain watershed. Forty-seven samples of the soil were collected; 5, 9, 9, 12 and 12 samples from AES 1 to 5, respectively. At each sampling site, five subsamples were collected and mixed well, and only 1 kg of the composite soil sample kept for analysis. Using steel cylinder (6 cm × 6 cm) with a sharp edge was used to collect undisturbed soil cores at each site for bulk density (BD) determination after drying the cores at 105 °C[19] with BD calculated as soil dry weight per unit volume. Total porosity as (1 – BD) / d × 100%, where d is the particle density of 2.65 (g·cm^{-3})[20].

The collected composite soil samples were analyzed for soil texture, pH, cation exchange capacity (CEC), exchangeable base, percent base saturation (PBS), organic matter (OM), total nitrogen (TN) and available P. The soil samples were sealed in plastic bags and sent to the national soil testing center for laboratory analysis. Except for SOC and TN, all samples underwent 2 mm sieving after being air-dried, crushed, and ground in a pestle and mortar. Organic C and N preparation required a 0.5-mm sieve mesh[19]. The samples were analyzed using standard soil analytical techniques (Table 2).

2.4 Statistical analysis

The Shapiro-Wilk test was applied to see the distribution of the normality of variables. Non-normally distributed data were normalized using a logarithmic transformation. The measured soil data were subjected to statistical analysis using Microsoft Excel and SPSS (Ver. 26). Properties of soil quality in the samples were analyzed using descriptive statistics (means, standard deviations and standard error) and variability between agroecosystem was assessed using a coefficient of variation (CV%). Based on the classification of Phil-Eze[26] classification, CV% within a range of < 20%, 20%–50%, 50%–100% and > 100% were regarded as low, moderate, high and very high variability. A one-way analysis of variance (ANOVA) was performed on the data to compare the average values of the soil quality attributes across the AES. The mean comparison was conducted using the least significant difference (LSD) test at $P < 0.05$. Analysis of simple correlation coefficient between the different soil physical and biochemical properties was also performed to reveal the magnitude and direction of relationships.

3 RESULTS AND DISCUSSION

3.1 Physical soil properties: textural class, bulk density and total porosity

Textural class. The most fundamental soil feature influencing exchange, retention, and absorption is soil texture, a master soil quality that enhances most other properties and processes as essential indicators for soil quality evaluation[27]. Clay fractions dominated the soil in the study area and the textural class was clayey in all soils across the AES except for AES 3, which was clay loam. There was no significant difference in soil clay and sand content between the AES. Nevertheless, the sand fraction between physical properties varied greatly, with a CV% of 40% between the AES with moderate variability according to the

Table 2 Analytical method for the selected soil quality attributes

Soil attribute	Analytical method	Reference
Particle size distribution	Bouyoucos hydrometric method	[21]
Soil pH	1:2.5 soil to water suspension	[19]
Total N	Kjeldahl method	[22]
Soil carbon content	Wet digestion method	[23]
CEC	Ammonium acetate method	[24]
Ca and Mg	Atomic absorption spectrophotometer	[24]
Na and K	Flame photometer	[24]
Percent base saturation	Divide the sum of base cations by the cation exchange capacity multiplied by 100	[20]
Available P	Olsen's extraction method	[25]

Note: CEC, cation exchange capacity; and Ca, Mg, Na and K as cations classification of Phil-Eze[26]. The result agreed with Yirgu et al.[7], who reported that soils in the upland regions, characterized by clay and silt, were less vulnerable to soil erosion. The clay content of the soils was higher in the midland plain (AES 3) of the Choke Mountain watershed, and such soils can resist soil erosion and are less susceptible to erosion hazards. Consequently, it is possible to infer from the results that most soils in the midland areas can be considered less erodible.

The results of ANOVA reveal that the silt content of the soil was statically significant (P < 0.05) between the AES. The highest mean silt content was recorded in AES 5. Sand fraction distribution ranged from 18.2% in soils of AES 3 to 26.7% in soils of AES 5, a hilly and mountainous highland (Table 3). This might be attributed to AES 5 being more susceptible to erosion, and most of the fine particles were washed away and deposited in the lowland part of the watershed. Thus, applicable and sustainable soil erosion control measures should be taken to reverse soil degradation in the mountainous highlands of the watershed.

Bulk density. Although the higher (1.11 $g \cdot cm^{-3}$) and the lower (0.98 $g \cdot cm^{-3}$) of bulk densities were observed in AES 2 and AES 4, respectively, no significant difference was found between the AES. Higher BD may have been brought on by intensive farming in AES 2. In agreement, Elias et al.[5] also showed high BD in areas where intensive cultivation and free grazing are common. However, AES 4 of the watershed is an area where cultivation is difficult because of its sloppiness, and is affected by erosion and shallow depth, BD is lower compared to other AES.

Total porosity. Across the watershed, the average total porosity (TP) values ranged from 58.2% in AES 2 to 63.7% in AES 4 (Table 2), which is within the normal range (30% to 70%) according to Landon[20]. The LSD showed that TP in AES 4 of the watershed was higher than other AES, implying a lower BD in AES 4. However, there is no significant difference between AES, and a CV% of TP is the lowest (7%) of the measured soil quality properties (Table 3).

3.2 Biochemical properties: exchangeable base, CEC, PBS, pH, total nitrogen, available phosphorus, and organic matter

Exchangeable base. The concentration of exchangeable bases (Ca, Mg and Na) in the soil can differ depending on the CEC. Ca varied significantly (P < 0.05) between AES. The overall mean for Ca varied from 1.78 $cmol \cdot kg^{-1}$ in AES 3 to 32 $cmol \cdot kg^{-1}$ in AES 2 of the watershed (Table 4). The result shows a very high variability of Ca with 104% of the CV% (Table 4). This might be attributed to variations in landscape, farming practice and climate variability between AES. AES had significant (P < 0.05) effect on Mg. Similar to Ca, Mg was also high in AES 2, while the lowest mean for Mg was observed in AES 3. The average exchangeable sodium (ENa) across the AES of the watershed ranged from 0.3 to 0.14 $cmol \cdot kg^{-1}$ (Table 4). As the result of ANOVA revealed, Na was significantly (P < 0.01) different between the AES. The variation of such an exchangeable base might be attributed to soil erosion and leaching of the bases from sloppy and mountainous highlands and should be problematic in the future unless successful measures are taken.

Table 3 Textural and physical characteristics of soil in agroecosystems (AES) of the Choke Mountain watershed in Ethiopia

Item	Clay (%)	Silt (%)	Sand (%)	Texture	BD ($g \cdot cm^{-3}$)	Total porosity (%)
AES 1	58.2^{a}	25.4^{a}	16.4^{b}	Clay	1.02	61.8^{a}
AES 2	53.7^{a}	25.0^{a}	21.3^{a}	Clay	1.11	58.2^{a}
AES 3	60.8^{ab}	21.0^{ab}	18.2^{c}	Clay loam	1.01	62.0^{a}
AES 4	52.8^{a}	26.7^{a}	20.6^{a}	Clay	0.98	63.7^{b}
AES 5	43.0^{ac}	30.3^{ac}	26.7^{d}	Clay	1.00	62.3^{a}
F	2.17	2.93	1.68		NS	1.27
P	0.089	0.031	0.173		0.335	0.301
CV%	29.1	31.6	40.2		12.6	7.8
SE	2.23	1.20	1.25		0.02	0.78

Note: AES 1, lowland and valley fragmented; AES 2, midland plain dominated by vertisols; AES 3, midland plain dominated by Nitosols; AES 4, sloppy midland land; AES 5, hilly and mountainous highlands; BD, bulk density; CV%, coefficient of variation; SE, standard error; NS, not significant; and values followed by the same letter within columns are not significantly different at P < 0.05 between AES.

Table 4 Exchangeable base, CEC and PBS of the soil in agroecosystems (AES) of the Choke Mountain watershed in Ethiopia

Item	Ca ($cmol\cdot kg^{-1}$)	Mg ($cmol\cdot kg^{-1}$)	ENa ($cmol\cdot kg^{-1}$)	EK ($cmol\cdot kg^{-1}$)	CEC ($meq\cdot(100g)^{-1}$)	PBS (%)
AES 1	31.8^a	7.84^a	0.07^a	0.61^a	41.0^a	94.5^a
AES 2	33.0^a	13.6^b	0.14^b	0.87^a	50.8^b	92.5^a
AES 3	1.78^b	3.04^c	0.03^a	1.06^b	27.1^c	21.8^b
AES 4	9.62^b	4.76^c	0.03^a	0.96^a	38.9^a	37.1^b
AES 5	13.0^c	5.23^{ac}	0.05^a	0.45^c	39.3^a	46.6^b
F	13.00	15.10	7.06	1.31	12.00	15.20
P	0	0	0	0.282	0	0
CV%	104	69.2	101	83.5	25.4	72.4
SE	2.40	0.66	0.01	0.10	1.45	5.63

Note: AES 1, lowland and valley fragmented; AES 2, midland plain dominated by vertisols; AES 3, midland plain dominated by Nitosols; AES 4, sloppy midland land; AES 5, hilly and mountainous highlands; Ca, exchangeable calcium; Mg, exchangeable magnesium; ENa, exchangeable sodium; EK, exchangeable potassium; CEC, cation exchange capacity; PBS, percent base saturation; CV%, coefficient of variation; SE, standard error; and values followed by the same letter within columns are not significantly different at $P < 0.05$ between AES.

A study by Negassa & Gebrekidan[28] revealed that variations in the distribution of exchangeable bases rely on particle size distribution, level of weathering, soil management techniques, climate factors and farming intensity. Similarly, Fetene & Amera[29] also demonstrate that soil erosion, limited crop residue reuse, continuous cropping, and leaching may have all contributed to the decline of basic cations in the soil.

Cation exchange capacity. CEC is a vital soil quality indicator that shows if the land is productive and capable of retaining and preventing nutrients from being leached[30]. The AES of the watershed had a significant ($P < 0.01$) effect on the CEC values of the soils in the research area (Table 4). AES 2 had the highest mean CEC compared to the other AES. Following Landon's[20] rating, the CEC of the surface soil of the study area was rated medium to high. Although such soil is valuable for cultivation, low SOM concentration and soil compaction (waterlogging) are the major problems. Additionally, a high CEC gives the soil a high buffering capacity, enabling one to apply the required amount of fertilizer without fearing that the soil will immediately suffer any detrimental effects[31].

Percentage base saturation. PBS is commonly used to measure soil nutrient content. Low, medium, and high fertility quality soils have a percentage base saturation of < 20%, 20%–60%, and > 60%, respectively[20]. Overall, PBS was the highest in AES 1 (94.5%) and the lowest in AES 3 (21.8%), with a very high CV% (72%). The soil in AES 1 and 2 contains a considerable $CaCO_3$, contributing to the highest concentration of PBS in the soil. However, leaching of bases (Ca, Mg and K) in AES 3 and 4 might have caused their lower of PBS. As a result, the soils in the current study showed medium to high PBS levels (Table 4), indicating that due to the excessive rainfall, basic cations were lost from the soil through leaching. Low potential quantities of basic cations may be one of these other major limiting factors in soil, as indicated above.

pH. There was substantial variation in soil pH (H_2O) between AES ($P < 0.05$) (Table 5). The overall mean pH varied from 5.3 to 6.97 across the watershed. Based on the Landon's[20] rating, the reaction of soils ranged from strongly acidic (AES 3) to neutral (AES 1) with a low CV%. The relatively lower degree of variation in pH observed is consistent with Ebabu et al.[8] and Bewket & Stroosnijder[12] who reported low pH variation across various types of land use. In agreement, Al Alwani & Al-Shaye[4] also found that climate variability and management practices could cause the variability of soil reactions from one place to another. Higher lime rates and organic material could be needed to reach optimum pH for those AES affected by acidity (AES 3 and 4).

Total nitrogen. The ANOVA revealed that TN was significantly different ($P < 0.05$) between AES of the watershed with a 58% CV%. The average TN values ranged from 0.15% in AES 1 to 0.35% in AES 5 between the watershed, showing a positive and strong correlation with OM (Table 5). According to Landon's[20] rating, TN ranged from low to medium. The concentration of TN was medium in all AES except AES 1, implying a substantial and positive correlation with OM ($r = 0.977$).

Available phosphorous. AES had a significant ($P < 0.05$) effect on available P, with the highest mean in AES 4 and the lowest in AES 3 of the watershed, with a very high (169%) coefficient

Table 5 variability of soil pH, organic matter, total nitrogen, and available phosphorus in the soil in agroecosystems (AES) of the Choke Mountain watershed in Ethiopia

Item	pH (H_2O)	OM (%)	TN (%)	P_{av} (mg·kg^{-1})
AES 1	6.97^a	2.59^a	0.15^a	12.00^a
AES 2	6.59^a	3.72^a	0.22^a	4.83^a
AES 3	5.30^b	3.82^a	0.23^a	3.96^a
AES 4	5.53^b	5.01^{ab}	0.29^a	16.00^a
AES 5	5.59^b	6.32^b	0.35^b	5.61^a
F	28.60	4.33	3.18	2.99
P	0	0.005	0.023	0.029
CV%	14.1	62.7	58.3	170
SE	0.12	0.42	0.02	2.10

Notes: AES 1, lowland and valley fragmented; AES 2, midland plain dominated by vertisols; AES 3, midland plain dominated by Nitosols; AES 4, sloppy midland land; AES 5, hilly and mountainous highlands; OM, organic matter; TN, total nitrogen; P_{av}, available phosphorus; CV%, coefficient of variation; SE, standard error; and values followed by the same letter with columns are not significantly different at $P < 0.05$ between AES.

of variation (Table 5). Based on the classification of Phil-Eze[26], available P was one of the most variable soil quality properties measured in this study. In agreement, Ebabu et al.[8] also found available P was a highly variable attribute of soil quality within the three AES zones, showing the variation in the addition or application of diammonium phosphate, a concentrated fertilizer with high phosphorus content, to soils of AES of the watershed.

According to FAO[32] ratings, soils with > 25, 18–25, 10–17, 5–9, and < 5 mg·kg^{-1} are classified as very high, high, medium, low and very low, respectively. Grounded on this range, AES 1 and AES 4 had a medium available P, AES 5 had a low available P, and AES 2 and AES 3 had very low available P, which is consider as being deficient in available P. The alkaline soils in the lowland valley of the Abay Basin may be responsible for the higher soil available P. Jensen[33] reported the best P availability in soils with intrinsic pH values between 6.5 and 7.5, which is consistent with AES 1 in the current study. On contrast, AES 4 was strongly acidic but with a medium available P.

Organic matter. Variation and distribution of OM between the five AES were high (62%), as shown in Table 5. The overall mean of OM across the watershed was highest in AES 5 and lowest in AES 1. In AES 1, the content of OM was low (2.59%) according to the critical levels adopted by Tadesse et al.[34]. The local climate, farming system, and dominating soil type of the particular area may cause a variance in SOM between the five AES of the watershed[18]. Following this study, Abate & Kibret[35] show that variations in altitude, the intensity of tillage, cropping systems, and soil management strategies may be the most likely sources of diversity in SOM composition between the land units. Low temperatures (7.5–10 °C) in the mountainous portion of the watershed (AES 5) can slow down the decomposition of SOM, but high temperatures (AES 1) in the lowland portion (AES 1) handle the rapid combustion of OM, resulting in the low content of SOM in those places[12].

3.3 Correlation analysis of soil quality attributes

The clay content of the soil fraction significantly and negatively correlated with silt (r = −0.9, P < 0.01) and sand (r = −0.9, P < 0.05) contents (Table 6). This shows that soils in the AES with variations in climate, topography and farming practice result in the concentration of sand content as a result of the selective removal of the clay and silt fractions, which over time reduces the ability of the soil to retain water and nutrients and increases its vulnerability to soil erosion.

CEC and the content of OM have a positive correlation (r = 0.3, P < 0.05) and the silt content of the soil (r = 0.2, P = 0.05). Most of the soil nutrients accessible to the plant are, therefore, probably sourced from OM. The correlation between CEC and OM (r = 0.3) was stronger than between CEC and silt content (r = 0.2), indicating that OM provided more nutrients to plants to the soil in the AES studied. CEC was also significantly and positively influenced by soil pH (r = 0.5, P < 0.01), PBS (r = 0.6, P < 0.01), Ca (r = 0.7, P < 0.01), Mg (r = 0.7, P < 0.01) and ENa (r = 0.6, P < 0.01) contents (Table 6). Therefore, the critical soil quality characteristics that govern CEC and, consequently, the adsorbing and exchanging capacity of soil nutrients available to plants are OM, silt fractions, pH and exchangeable bases. Similar results were observed by Guteta & Abegaz[36] in the

Table 6 Correlations between soil properties in agroecosystems of the Choke Mountain watershed in Ethiopia

	Clay	Silt	Sand	BD	Porosity	Ca	Mg	ENa	EK	CEC	PBS	pH (H_2O)	OM	TN	P_{av}
Clay (%)	1														
Silt (%)	−0.905**	1													
Sand (%)	−0.913**	0.651**	1												
BD ($g \cdot cm^{-3}$)	0.366*	−0.331*	−0.331*	1											
Porosity (%)	−0.371*	0.336*	0.335*	−0.998**	1										
Ca ($cmol \cdot kg^{-1}$)	−0.004	−0.005	0.011	0.203	−0.2	1									
Mg ($cmol \cdot kg^{-1}$)	0.07	−0.098	−0.031	0.319	−0.319	0.814**	1								
ENa ($cmol \cdot kg^{-1}$)	−0.01	0.069	−0.049	0.059	−0.066	0.373**	0.535**	1							
EK ($cmol \cdot kg^{-1}$)	0.075	−0.12	−0.019	−0.245	0.258	0.247	0.276	0.008	1						
CEC ($meq \cdot (100g)^{-1}$)	−0.336*	0.297*	0.314*	−0.018	0.018	0.762**	0.725**	0.485**	0.086	1					
PBS (%)	0.051	−0.041	−0.051	0.206	−0.2	0.948**	0.835**	0.327*	0.310*	0.615**	1				
pH (H_2O)	0.077	−0.071	−0.069	0.215	−0.206	0.891**	0.735**	0.277	0.267	0.522**	0.940**	1			
OM (%)	−0.705**	0.624**	0.656**	−0.677**	0.679**	−0.108	−0.201	0.158	0.109	0.306*	−0.217	−0.312*	1		
TN (%)	−0.656**	0.566**	0.625**	−0.693**	0.693**	−0.121	−0.216	0.166	0.078	0.284	−0.238	−0.325*	0.977**	1	
P_{av} ($mg \cdot kg^{-1}$)	0.041	−0.003	−0.071	−0.209	0.223	0.227	0.255	−0.074	0.698**	0.136	0.318*	0.298*	0.073	0.05	1

Notes: BD, bulk density; Ca, exchangeable calcium; Mg, exchangeable magnesium; EK, exchangeable potassium; CEC, cation exchange capacity; PBS, percent base saturation; OM, organic matter; TN, total nitrogen; P_{av}, available phosphorus. ** Correlation is significant at the 0.01 level (2-tailed); and * correlation is significant at the 0.05 level (2-tailed).

Arsamma watershed in the south-western highlands of Ethiopia.

The significantly positive correlation of soil pH with CEC, Ca, Mg and available P shows the influence of soil pH on other chemical soil properties (Table 6). Doran et al.[37] also reported soil pH as one of the vital chemical characteristics representing the general health of chemical and biological activities in the soil. The positive correlation between pH and Ca was related to the higher solubility and greater potential for hydrolysis of $CaCO_3$ at a higher pH. A similar result was presented by Somasundaram et al.[38]. However, soil pH negatively correlated with OM and TN (r = 0.3, P = 0.05). This could be explained by the fact that AES affected by low concentrations of OM have a high content of $CaCO_3$ or lime, especially in the lowland valley of the Abay Basin (AES 1), where the pH of the soil is high, and SOM is low. This result contradicts a previous study reporting the positive correlation between OM and pH[36].

SOM is a vital factor in soil fertility and agricultural productivity as it is known to store important plant nutrients[39]. The positive and significant correlation of OM with TN and CEC contents of the soils shows the intimate association of OM with other chemical soil properties. As a result, the organic component of soil likely releases a more significant proportion of its N than its inorganic components.

3.4 Implications for agriculture

The soil quality assessment results for each AES of the Choke Mountain watershed provide important information from an agricultural perspective. The study found that midland AES (AES 2 and 3), characterized by gentle slopes, have productive soil. As reported by Mesfin et al.[40], the overall soil quality index of AES 2 and 3 is better than the soil quality of other AES and create good condition for agriculture. Simane et al.[16] also found productive and suitable soil types in AES 2 and 3. AES 2 is an intensively cultivated area but is affected by waterlogging during the rainy season, which is difficult for agricultural activities. In contrast, AES 3 is affected by soil acidity, which is an essential constraint for agricultural productivity, followed by available P and soil N content[41].

Similarly, AES 4 is also affected by acidity, attributed to the sloppiness of the area, and high rainfall causes the leaching of essential nutrients and constrains agricultural production and productivity. In some instances, farmers have even abandoned their lands because of low crop productivity. The cropping pattern in the area has also changed from initially grown crops (wheat and barley) to low value crops (*Avena* spp.). The local government has initiated the liming program to improve the productivity of acid soils. Despite this effort, almost all farmers are not using liming to improve their soil[16].

AES 1 and 5 are not suited for agricultural production, as are low fertility soils, steep slopes and shallow soils, according to the results of physical and biochemical soil parameter assessment. Additionally, AES 1 is an adverse agroecological environment with less consistent rainfall than other AES.

4 CONCLUSIONS

This study found that farming systems with various soil management practices, agroclimatic variability of the area and soil type of AES with varying landscapes were the essential elements causing the variation of physical-biochemical soil characteristics in the Ethiopian highlands in general and particularly in the agroecosystems of Choke Mountain watershed. The result revealed that the measured soil quality attributed varied significantly across the study watershed. Clay fractions dominated the soil in the study area and the textural class was clayey in all soils across the five AES except in AES 3 of the soil, which was clay loam. The highest mean silt and sand content was observed in AES 5. This might be attributed to increased soil erosion from the upper part of the watershed and deposited in the middle and lower parts of the Abay Basin, which contains higher soil clay content. However, the higher SOM and TN were also recorded in AES 5. The lower temperature (7.5–10 °C) of AES 5 of the watershed, which slows down the decomposition of SOM and less addition of mineral fertilizers to the soil, might be the reason for the higher OM content of the area.

In contrast, in AES 1, where the temperature was high, SOM content was low. Exchangeable bases (Ca, Mg and ENa) were the highest in AES, dominated by vertisol soil (AES 2), with high CV%. Nevertheless, the major problem of this type of soil was a low content of OM and waterlogging during the high rainy season. The soil pH of the study area varied from strongly acid soil (AES 3 and 4) to neutral (AES 1) because of varying of $CaCO_3$ content, amount of rainfall, the intensity of cultivation and type of soil management. Another essential soil nutrient that varied greatly (CV% = 169%) between AES was available P, observed in deficient amounts except AES 1 and 4. To reverse soil acidity and improve soil fertility status in those AES affected by leaching and nutrient depletion of soil, farmers would be advised to use efficient and practical soil management techniques. In particular, lime application and organic fertilizers (compost, manure, and mulching) are essential. Adopting agroforestry and economically viable multipurpose perennial crops should be promoted to reduce soil erosion for AES with steep slopes in the watershed, improve soil quality and maintain sustainable agriculture and environment in agroecosystems.

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Compliance with ethics guidelines

Demeku Mesfin, Engdawork Assefa, and Belay Simane declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any authors.

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