American Journal of Agriculture and Forestry
2022; 10(6): 220-229
http://www.sciencepublishinggroup.com/j/ajaf
doi: 10.11648/j.ajaf.20221006.12
ISSN: 2330-8583 (Print); ISSN: 2330-8591 (Online)

Explore the Profile Distributions and Patterns of Macronutrients and Related Soil Properties and Their Interrelationships in Cultivated Agricultural Lands

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To cite this article:
Assefa Menna. Explore the Profile Distributions and Patterns of Macronutrients and Related Soil Properties and Their Interrelationships in Cultivated Agricultural Lands. *American Journal of Agriculture and Forestry*. Vol. 10, No. 6, 2022, pp. 220-229.
doi: 10.11648/j.ajaf.20221006.12

Received: September 16, 2022; **Accepted**: October 18, 2022; **Published**: November 4, 2022

Abstract: The present investigations determined the vertical distribution and patterns of macronutrients and related soil properties in lands cultivated for wheat and/or faba-bean in the central Ethiopia. It also sought the interrelationships among the investigated soil variables. In doing so, in three representative locations, 30 soil samples were collected at five depth intervals from six profiles/pedons at (0–120 cm range), each profile representing a site. Results showed important variations in the soil properties across profiles and sites owing to multitude of factors. Though, the pattern of changes differ, the soil pH, SO_4^{2-}, CEC and base-cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were found to increase irregularly with depth, whereas the organic carbon (OC), total nitrogen (TN) and available P showed decreasing trends of change. Correlations among soil properties also varied significantly from topsoil to subsoil, though such relations are quite different when only topsoil (0–20 cm) depth intervals are considered. Furthermore, the particle size analysis showed an increasing percentage of clay with depth, possibly owing to the clay-illuviation. Most importantly, the increased levels of soil variable like K^+, SO_4^{2-} & Na^+ with depth may indicate that they are easily leachable in the soil system. However, the observed higher levels of OC, TN and P in the top-layer than the underlying horizons may indicate the role the biomass recycling and rates have played in their vertical distribution. Overall, for nutrients that are fairly abundant in the subsoil than topsoil, deep-tillage operation like sub-soiling are recommended to bring their available forms to top-layers for shallow rooted plants uptake and/or recycling. Deep capture of the nutrients by tree-roots (e.g., the agroforestry system) can also be practiced to recycle nutrients from deeper layers thereby improving nutrients' use efficiency; and reducing the potential environmental impacts over time (i. e., in small, medium or large) time-scales.

Keywords: Macronutrients, Soil Profile, Pedogenesis, Clay-Illuviation, Eluviation, Leaching, Pedoturbation

1. Introduction

Macronutrients are among the 17 essential elements in plant nutrition that are critically important in completing the lifecycle of plants or in performing a range of physiological functions. In recent years, the degradation of soil fertility, notably, the macronutrients depletion in topsoil due to continuous cultivation is becoming a serious problem affecting the sustainability of agricultural production, productivity and hence food security in Ethiopia. However, the low levels of macronutrients availability can not only be due to their inherent low levels in soils, but also due to either their chemical or biological fixation, spatio-temporal unavailability in the pedosphere (soils) etc. In fact such plant nutrients are found in the pedosphere (soil), hydrosphere (water), in the atmosphere and biosphere in various forms. Knowing the spatial and/or temporal variations of nutrients in agricultural lands and factors affecting them are important for improving management practices.

With regard to the soil system (pedosphere), soil is highly variable from place to place and across soil horizons owing to its vertical exchange of materials. According to Weil & Brady, [1], such differentiations in soil system are due to the physico-chemical changes from surface to subsurface as influenced by the interaction between natural processes and anthropogenic or management practices. Reasons for such processes in turn may include, the addition of organic resources on soil surfaces, weathering of rocks and minerals, decomposition of organic matter and translocation of soluble components by leaching resulting in variations across soil profiles [2]. Human management practices such as cultivation; grazing or similar uses also change soil properties with changing depth [3, 4, 5]. Particularly in cultivated lands macronutrient availability might be a matter of concern as soils are over exploited due to continuous cultivation. Furthermore, in such lands, soil particles are disintegrated mechanically due to tillage practices, thereby hastening the mineralization processes at the surface, modifying soil conditions across profiles thereafter. As a result, soluble nutrients are expected to migrate vertically to the deeper layers through leaching and other pedogenic processes. However, according to Rengel, and Marschner, [6], when plants are grown on such soils with low nutrient availability due to either chemical or biological fixation or spatio-temporal unavailability, nutrient-efficient plants can have greater yield in comparison with the in-efficient ones even when applied with micro-dose of fertilizers. From this, therefore, the present work was aimed at evaluating the patterns and vertical distributions of macronutrients and related soil properties in selected profiles, and their interrelationships in cultivated agricultural lands.

2. Materials and Methods

2.1. Soil Sampling, Preparation and Analysis

In three representative locations, six sites were selected randomly on lands cultivated for wheat and/or faba bean in central Ethiopia during 2015-16 cropping seasons. The sites were geo-referenced using global positioning system (GPS)–GARMIN-model #GPS-60. Site selection was based on such variations in vegetation, altitude/landscape, land-use and soil heterogeneity like soil reactions. In six sites, six soil profiles/pedons (P1–P6) were exposed accordingly. Then, before planting wheat or faba bean soil samples were taken from five depth intervals: 0–20, 20–40, 40–60, 60–90 and 90–120 cm from each profile. Overall, 30 composite soil samples representing topsoil and subsoil samples were collected. This form of soil sampling allows the assessment of spatial-variability of soil properties at different scales. Soil samples, then were air-dried and ground to pass 1-mm stainless steel sieve and analyzed for pH, organic carbon (OC), the macronutrients (N, P, S, Ca, Mg, and K), soil texture and related properties like bulk density (BD) in laboratory using the following procedures. Soil were analyzed for pH in water (1:2.5 soil:water ratio) solution using a combined glass electrode pH-meter as described by [7], while the electrical conductivity was determined from the same soil/water suspension or ratio by electrode method [8]. For exchangeable base cations (Na^{+1} & K^{+1}) determination samples were extracted with 1M: NH_4OAc (pH, 7.0). The Na^{+1} and K^{+1} content in the extracts were quantified using flame photometer as described by [9]. Also Ca^{+2} & Mg^{+2} were extracted with 1M: NH_4OAc (pH, 7.0) and measured by atomic absorption spectro-photometer (AAS) as described by [7]. Similarly, the CEC was determined by 1M: NH_4OAc solution (pH, 7.0) as described by [7]. Total N was determined by Kjeldahl digestion and distillation method as described by [10]. Soil OC was estimated in soil samples by the procedure used by Walkley-Black as described by [11]. Available P was determined by Bray-I method using NH_4F-extraction solution [12] for soils with pH < 7.0. Whereas, for soils with pH > 7.0, Olsen–$NaHCO_3$ extraction method [13] was used. Plant available sulfur (SO_4-S) was extracted by Ca-orthophosphate ($Ca(H_2PO_4)_2$) and quantified turbidi-metrically as described by [9]. The particle size distribution was determined by the hydrometer method as described by [14].

2.2. Statistical Data Analysis

Analysis of variance was performed to test the significance of variations of soil properties in different sites using PROC MIXED generalized linear model of the SAS system [15]. When the differences between the variables were significant, least significant difference (lsd) was used to separate the means with a significant level at (p= 0.05, 0.01 & 0.001). Soil variables were also evaluated by correlation and the slopes were compared through parallelism and coincidence test using PROC REG-corr procedure. Furthermore, the fertility status of soils of the study areas were evaluated based on the contents of respective variables obtained from the laboratories, which were then compared with established ratings or critical limits (CLs) using descriptive statistics.

3. Results and Discussions

Vertical distribution patterns of macronutrients and related soil properties of six profiles in five depth intervals (1.20 m range) in Arsi (Ar), East Shewa (ES) and West Shewa (WS) zones are presented in the Tables 1 & 2; and figures 1 through 6. The figures are based on the relative distribution data for individual soil profiles.

3.1. Particle Size Distribution

Results of soil particle size analysis showed significant variations in the distributions of textural classes corresponding from sandy, clay to clay-loam soils. The variations were attributable to the parent material, topography (slope), climate, biochemical and geochemical processes like leaching; weathering dissolution; inherent factors like soil-type and parent material and depth; and anthropogenic management practices like tillage. In general, the soils exhibited gradual fining in texture from topsoil to subsoil (Table 1) owing to clay-illuviation. Such tendency of increasing clay percentage (%) was also observed at the soils' surface level on the landscapes from highlands to low-lying areas owing to the clay-eluviation to the low-lying areas. This might also be ascribed to higher rate of down ward erosion or destruction of clay in the topsoil. In fact, this is in accordance with the findings reported by other workers [16-18]. But, the overall clay % of the Vertisols, was highest ranging from 60–80% in subsoils to about 25–35% in the topsoil compared with the other soil-types. For example, sandiness was the highest (35%) at Bekejo site topsoil in the rift-valley system. Overall, according to Weil & Brady, [1] such differences in soil variables could be due to the spatio-temporal variations in fields brought about by small, medium or large-scale variability. For the self-mulching Vertisols, the reasons for such clay accumulations in the subsoils can also be other pedogenic processes like pedoturbation.

3.2. Soil pH

Soil pH, as a measure of the acidity or basicity of soils, is a key characteristic that can be used to make both qualitative and quantitatively regarding soil characteristics. In the present investigations, the soil pH ranged from strongly acidic in WS-zone, near neutral range in Ar-zone; to slightly alkaline in ES-zone (Table 1). The soils, particularly in the ES-zone are rich in $CaCO_3$. Considering only topsoil, more acidic soils came from highlands, whereas those with alkaline soil reaction were found in valley bottoms.

Most importantly, the pH of soils was found to increase with depth in all profiles (Figures 1a–6a) which might be ascribed to the loss/leaching of base-cations from topsoil to subsoil. Similar findings were reported by different workers [19, 20]. This can also be due to the decrease in soil organic matter (SOM), whose decomposition that can release organic acids. Furthermore, the increasing trend of soil pH with depth can also be ascribed with the accumulation, particularly, of Na and calcium carbonate ($CaCO_3$).

3.3. Soil Organic Carbon

Carbon (C) is viewed in the same light as N in that it is re-cycled in the earth system as fast biological processes. Soil organic carbon (SOC) contents of the topsoil (0-20cm) ranged between 0.96–2.71 percent. Except one site, all are falling below the CLs suggested in literatures, hence low for sustaining soil health or quality.

Profile wise, SOC of subsoil from the topsoil were decreasing in all pedons and sites (Table 1; & Figures 1a–6a). This could be due to the fact that surface layers are the most biologically active or the physical restriction of movements of OM to deeper layers. In general, the relative high % of SOC in the active rooting depth (0–20cm), as a result of regular biomass addition and its subsequent mineralization in tropical climate and soil conditions are instrumental. However, tillage operations can physically combine soil-layers and result in its rapid decomposition transiently reducing the contribution of OM and microbial process to nutrient re-cycling. This is indeed in accordance with the findings reported by other workers [21] in which case the authors ascribed it to the low biological activity vis-à-vis the tropical soil and climate conditions that are responsible for rapid mineralization. However, for some soils, the total soil C is expected to be high in subsoil than the overlying profiles, because in most locations, the soils are enriched with consolidated materials of calcium carbonate in the depth intervals approximately below 0.5m.

3.4. Nitrogen

Nitrogen (N) is key for life. It is viewed in the same light as C in that it has also a fast, biologically mediated cycles connecting it to a slow, tectonically-controlled geologic cycle [22, 23]. Also, unlike other plant nutrients, N is ubiquitous in the solar system existing in the pedosphere, atmosphere (most commonly), in the lithosphere and hydrosphere. But, from annual crops production point of view, the N particularly in the pedosphere and/or probably followed by that in the atmosphere are more significant. Regardless of its abundance in the solar system, its contents, however, are very low in cultivated lands limiting crop production owing possibly to its dynamics in tropical soil conditions [24, 25].

The % changes of the total nitrogen (TN) in the studied profiles were indicated in (Figures 1a–6a). In all profiles such changes from topsoil to subsoil were negative affirming that its contents were decreased with depth. Overall, the TN contents in the studded surface soils were low for sustaining crop production, given its strong correlation with SOC pool ($r= 0.800$; at $p \geq 0.05$). Indeed, this relationship is indicative of the fact that plants play a critical role in their vertical distribution controlling most of the organic additions to soils. In fact, this is in agreement with the finding reported by [26, 27]. It is worth mentioning, however, that N in the form of ammonium (NH_4^+) is immobile, though its nitrate (NO_3^-) form is highly mobile. In general, due to this factor, the NO_3^- form could be higher in the deeper layers depending on the history of the farming practices like fertilizer application.

3.5. Phosphorus

Phosphorus (P) is another vital nutrient element for life. However, it is non-substitutable in biological systems and its reservoirs are mostly in sedimentary rock deposits. As such, phosphorus places a limit on ecosystem productivity, which in turn is critical to C balances in the terrestrial ecosystems [28].

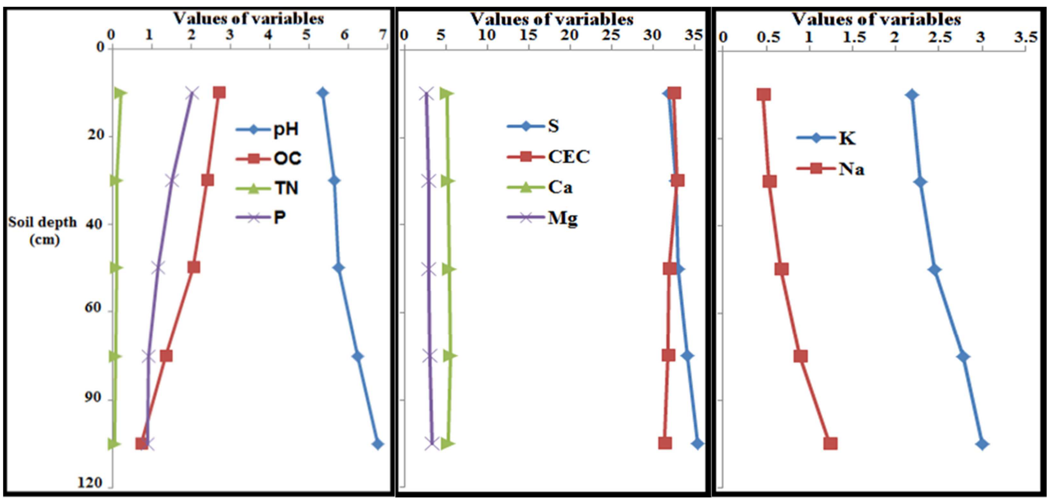
Table 1. *Contents of macronutrients in the soils: Arsi, East Shewa and West Shewa zones, before planting wheat or faba bean.*

Zone / Location	FA / Site	Lat. (N)		Long. (E)		Alt (m)	Soil Type	Depth (cm)	pH (1:2.5) (soil:H_2O)	OC (%)	Clay (%)	Nodules of $CaCO_3$	Soil Tex.
		X°	Y'.Z"	X°	Y'.Z"								
Arsi (Ar)	Wonji Gora1 (WG1)	7	59.944	39	8.876	2418.32	PV	0-20	5.36	2.71	45.8	no	C
Arsi (Ar)	Wonji Gora1 (WG1)	-	-	-	-	2418.32	PV	20-40	5.66	2.41	46.1	no	C
Arsi (Ar)	Wonji Gora1 (WG1)	-	-	-	-	2418.32	PV	40-60	5.76	2.06	55.4	no	C
Arsi (Ar)	Wonji Gora1 (WG1)	-	-	-	-	2418.32	PV	60-90	6.25	1.35	53.2	no	C
Arsi (Ar)	Wonji Gora1 (WG1)	-	-	-	-	2418.32	PV	90-120	6.76	0.71	65.0	no	C

Zone / Location	FA / Site	Lat. (N)		Long. (E)		Alt (m)	Soil Type	Depth (cm)	pH (1:2.5) (soil:H_2O)	OC (%)	Clay (%)	Nodules of $CaCO_3$	Soil Tex.
		X°	Y'.Z"	X°	Y'.Z"								
Percent change						-	-	-	26.12	-73.80	41.92	-	-
Arsi (Ar)	Gora Silingo2 (GS2)	8	0.833	39	8.444	2151.10	Nit	0-20	6.24	2.18	22.6	No	CL
Arsi (Ar)	Gora Silingo2 (GS2)	-	-	-	-	2151.10	Nit	20-40	6.40	1.97	21.1	No	CL
Arsi (Ar)	Gora Silingo2 (GS2)	-	-	-	-	2151.10	Nit	40-60	6.55	1.67	24.5	no	C
Arsi (Ar)	Gora Silingo2 (GS2)	-	-	-	-	2151.10	Nit	60-90	6.75	1.00	26.2	no	C
Arsi (Ar)	Gora Silingo2 (GS2)	-	-	-	-	2151.10	Nit	90-120	6.75	0.50	27.2	no	C
Percent change						-	-	-	8.17	-77.06	20.35	-	-
E.Shewa	Keteba2 (Ke2)	8	52.814	39	2.344	2224.37	PV	0-20	8.00	1.15	35.0	yes	C
E.Shewa	Keteba2 (Ke2)	-	-	-	-	2224.37	PV	20-40	8.10	0.80	35.6	yes	C
E.Shewa	Keteba2 (Ke2)	-	-	-	-	2224.37	PV	40-60	8.40	0.81	40.2	yes	C
E.Shewa	Keteba2 (Ke2)	-	-	-	-	2224.37	PV	60-90	8.76	0.40	45.7	yes	C
E.Shewa	Keteba2 (Ke2)	-	-	-	-	2224.37	PV	90-120	8.99	0.40	47.4	yes	C
Percent change						-	-	-	12.38	-65.22	35.43	-	-
E.Shewa	Bekejo2 (Bk2)	8	37.378	38	55.796	1874.16	CV	0-20	7.15	1.17	25.5	yes	SC
E.Shewa	Bekejo2 (Bk2)	-	-	-	-	1874.16	CV	20-40	7.53	0.88	25.6	yes	SC
E.Shewa	Bekejo2 (Bk2)	-	-	-	-	1874.16	CV	40-60	7.46	0.79	30.8	yes	C
E.Shewa	Bekejo2 (Bk2)	-	-	-	-	1874.16	CV	60-90	7.64	0.70	34.3	yes	C
E.Shewa	Bekejo2 (Bk2)	-	-	-	-	1874.16	CV	90-120	7.78	0.30	40.1	yes	C
Percent change						-	-	-	8.81	-74.36	57.25	-	-
W.Shewa	Nano Suba2 (N/S2)	8	57.249	38	29.989	2229.54	Nit	0-20	5.85	0.96	22.0	no	C
W.Shewa	Nano Suba2 (N/S2)	-	-	-	-	2229.54	Nit	20-40	5.93	0.64	21.0	no	C
W.Shewa	Nano Suba2 (N/S2)	-	-	-	-	2229.54	Nit	40-60	5.89	0.61	22.3	no	C
W.Shewa	Nano Suba2 (N/S2)	-	-	-	-	2229.54	Nit	60-90	5.9	0.55	26.1	no	C
W.Shewa	Nano Suba2 (N/S2)	-	-	-	-	2229.54	Nit	90-120	5.91	0.35	27.5	no	C
Percent change						-	-	-	1.03	-63.54	25.00	-	-
W.Shewa	Berfeta Tokofa2 (BT2)	9	0.227	38	30.826	2252.64	PV	0-20	4.85	2.03	36.9	no	C
W.Shewa	Berfeta Tokofa2 (BT2)	-	-	-	-	2252.64	PV	20-40	4.94	1.70	41.5	no	C
W.Shewa	Berfeta Tokofa2 (BT2)	-	-	-	-	2252.64	PV	40-60	4.91	1.63	45.6	no	C
W.Shewa	Berfeta Tokofa2 (BT2)	-	-	-	-	2252.64	PV	60-90	4.93	1.00	52.9	no	C
W.Shewa	Berfeta Tokofa2 (BT2)	-	-	-	-	2252.64	PV	90-120	4.95	0.51	60.5	no	C
Percent change						-	-	-	2.06	-74.88	63.96	-	-

Key: Wherever it appears: Soil Texture: (SCL = Sandy clay loam, C = Clay, SC = Sandy Clay, and CL = Clay loam). Sites: WG1/(Do2) = Wonji Gora1 (Dosha2). The numbers 1 or 2 in the site names like WG1/Do2, GS-2, Ke-2 and N/S2, BT2 etc. indicate the season in which the soil samplings were made. FA = farmer field/site/village. The soil pH conditions: medium Arsi (Ar); high East Shewa (ES), and low West Shewa (WS) pH conditions. Pellic Vertisol (PV), nitisol (Nit), and Chromic Vertisol (CV). The locations or study areas are: Arsi (Ar), East Shewa (ES), and West Shewa (WS).

Unlike N (another most limiting nutrient but one with an abundant pool in the atmospheric), P availability in the ecosystems is restricted by its rate of release during weathering.



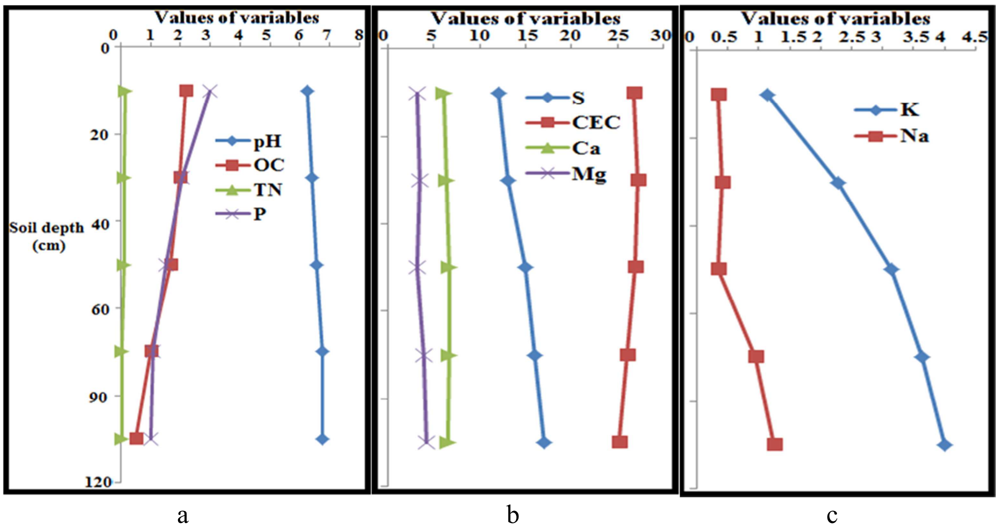
Figures 1. *a-c. Profile distribution of macronutrients & related soil properties in the first five depth intervals (0–120 cm) at Arsi, Wonji Gora1/or (Do2) site.*

With respect to profile distribution, the plant available P (Av.P) content of surface soils that came from East Shewa zone ranged between 9.02–12.01 mg/kg which is either low or marginal. Similarly, such surface soils that came from Arsi and WS zones that ranged between 0.50–3.01 mg/kg were also very low. In the whole, as depicted in Figures 1a–6a, the Av.P content of all sites was decreasing with depth which might be due to the increased clay content that was also found to be increasing with depth. It is widely reported that, the increased soil pH associated with high content of base-cations in subsoil may also cause P fixation; i.e., the fixation of released P by clay minerals and oxides of Fe and Al [29, 30]. On the other hand, the observed relatively higher levels of Av.P in the surface soils might also be due to the presence of OM which can increase its availability [31]. A strong negative correlation (Table 2) between Av.P and the base-cations might also corroborate the low P availability in such alkaline soil conditions. Similarly, the correlation between Av.P and OC was strongly negative ($r= -0.898$; at $p \geq 0.05$). However, this might be due to the fact that, P is a mineral derived element differing from OC and TN. As a result of this, plant cycling is assumed to be not a dominant control of P distributions in soils. But, according to Marschner; and Schlesinger, [32, 33] P also occurs in low amounts in rocks and soils and is often reported to constrain ecosystem productivity, necessitating constant replenishment with appropriate fertilizers.

3.6. Sulfur

Sulfur (S) is another plant nutrient element of sedimentary biogeochemical cycles. The pedosphere (soil) is the largest reservoir of S; others are like oceans, swamps, marshes, volcanic areas etc. In the biosphere, S is present in three forms: elemental S, inorganic S, and organic S. Sulfur is mineralized, assimilated, oxidized and reduced in the ecosystem by a variety of microbes. Its mineralization involves the decomposition of OM and sulfur containing compounds converting to simpler inorganic forms.

In the present investigations, the sulfate-S (SO_4-S) of surface soils for the six profiles ranged from 4.03–35.83 mg/kg. Based on the 10–13 mg/kg plant available SO_4^{2-} as CLs for most crops, about 50% of the studied soils were S limiting, whereas one site was marginal. Two sites (WG and BT) were found to be adequate in SO_4^{2-} (Figures 1b–6b). In the whole, as depicted in the figures, SO_4^{2-} content of all soils were found to increase with depth, a reverse trend of change that was observed for OC and TN. But, under natural conditions the SO_4^{2-} in the topsoil is expected to be correlating significantly and positively with OC and TN. For example, according to Khanday, et al.,; Sposito; & Verma, et al. [20, 34, 35], S in the topsoil is usually associated with the organic fractions and its supply to crops is largely regulated by OM decomposition (plant-cycling); and the amount of labile OC is considered to be a good indicator of the plant available S. Therefore, the observed negative correlation between OC and SO_4^{2-} (Table 2) ($r= -0.992$; at $p \leq 0.001$) may suggest that the relationship between the mean soil variables across soil profiles may take a different pattern of change owing to the spatial variations. Since the SO_4^{2-} seems to be among the mobile plant nutrients in the soil system, for its increased content with depth the role of leaching could be the major pedogenic process controlling its vertical distribution.

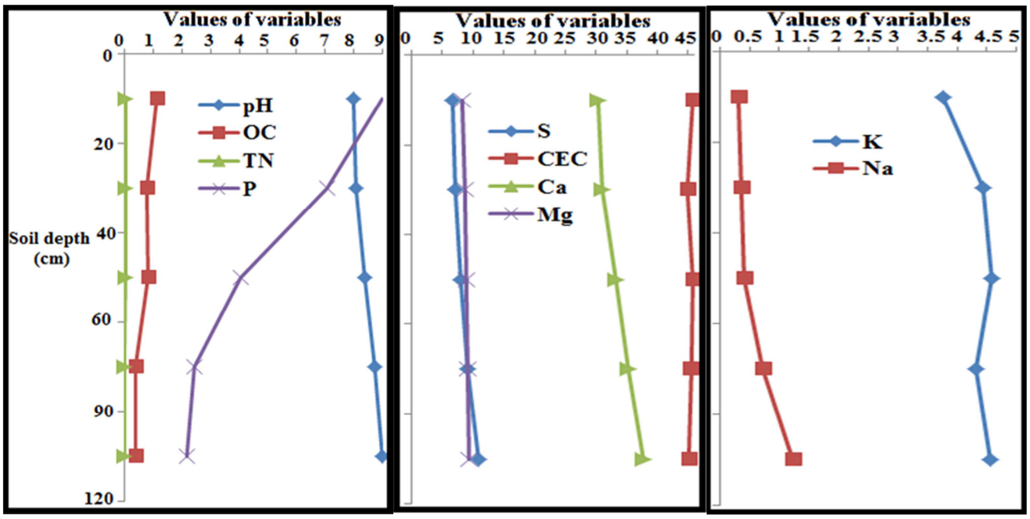


Figures 2. a-c. Profile distribution of macronutrients & related soil properties in the first five depth intervals (0–120 cm) at Arsi zone, G/Silingo site.

3.7. Cation Exchange Capacity

Cation exchange capacity (CEC) is the measure of the quantity of negatively charged sites on soil surfaces that can retain cations by electrostatic forces [1]. According to the authors, the CEC determines the ability of soils to bind or hold nutrients against leaching and it is usually influenced by soil texture, clay mineralogy and the OM. As a result, the CEC is critically important soil property governing nutrients dynamics. In the present investigations, the CEC of surface soils ranged from 13.80 cmol$_c$/kg (at N/S2 site) to 47.80 cmol$_c$/kg (at the BT2 site) (Figures 1b–6b). Under tropical soil condition, the CEC values < 6.0 cmol$_c$/kg are considered to be very poor and that between 6.0–12.0 cmol$_c$/kg are rated as poor [36]. Based this rating, therefore, 83.3% of the topsoil samples fall within the medium or high CEC range.

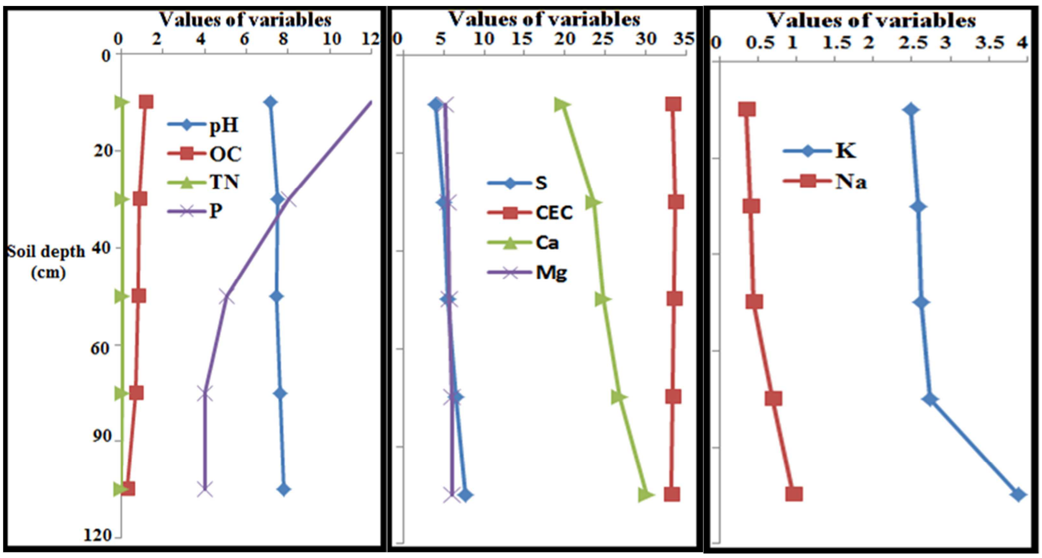
With respect to vertical distribution, the CEC values were found to increase from topsoil to subsoil. Quantitatively, the increments in the subsoil from topsoil were 4.14, 12.50, 2.86, 8.23, 8.70 and 4.46% at WG1, GS2, Ke2, Bk2, NS2 and BT2 sites respectively. The possible reason, for the increased % of clay in the deeper layer than the overlying horizon might be the clay migration (clay-illuviation). In addition, the coefficients of correlation between the CEC and clay (r= 0.996; and p ≤ 0.001) (Table 2) may affirm that the CEC is primarily controlled by clay mineralogy and/or the soil texture. In fact, this is in accordance with the findings reported by other workers [37, 38].



a b c

Figures 3. *a-c. Profile distribution of macronutrients & related soil properties in the first five depth intervals (0–120 cm) at ES zone, Keteba2 site.*

However, apart from the type of clay, the variability of CEC with depth among different soils or sites may also imply the difference in the ability of soils to hold the cations, affecting the stability of soil structure, nutrient contents, soil pH, soil's response to different fertilizer treatments and the soil OM. Indeed, all studied Vertisols had the highest levels of CEC (Table 1). Nutrient losses by running water (soil erosion) and through leaching are among the major challenges in the crop production and productivity, particularly in the Ethiopian high-lands and hot-humid low-land areas. Hence, the knowledge about the CEC of soils is found to be instrumental in understanding the vertical patterns of nutrients, especially the most mobile plant nutrients in soils.



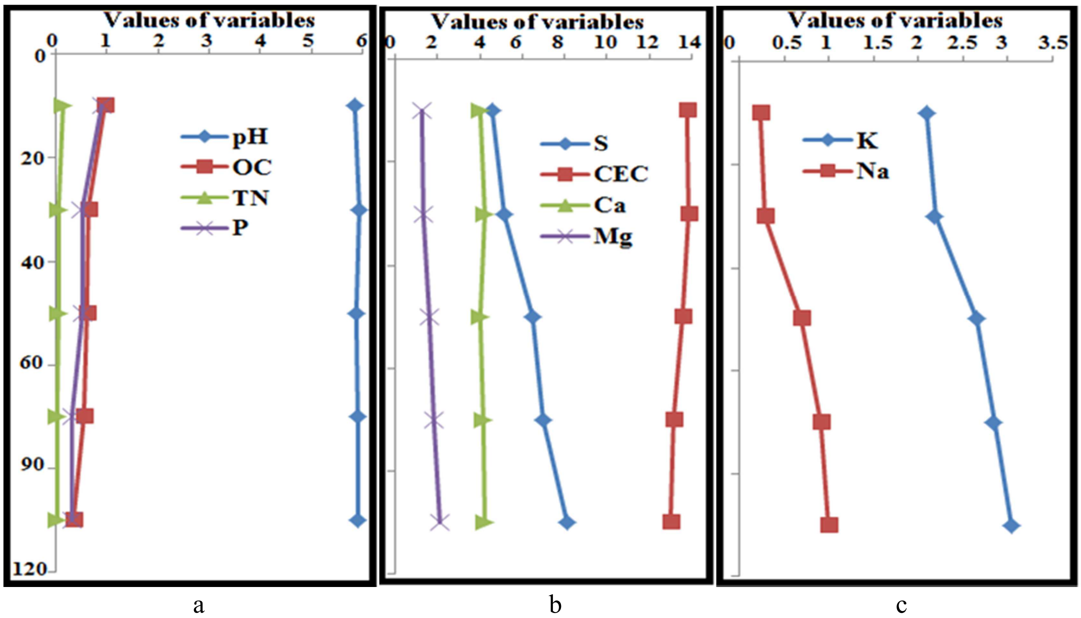
a b c

Figures 4. *a-c. Profile distribution of macronutrients & related soil properties in the first five depth intervals (0–120 cm) at ES zone, Bekejo2 site.*

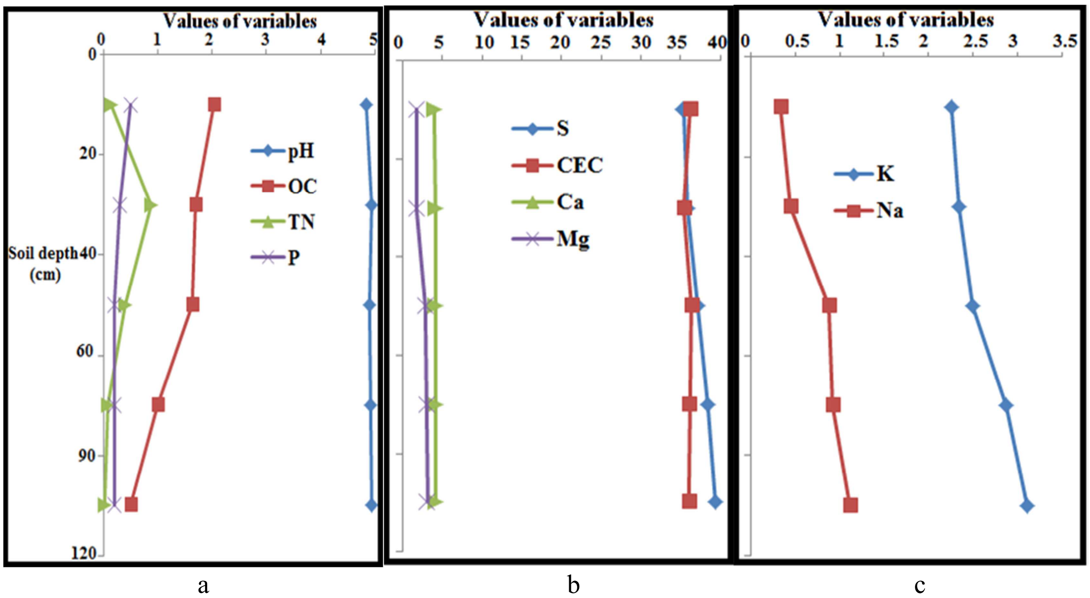
3.8. Calcium

Exchangeable calcium (Ca^{2+}) content of surface soils ranged from 4.01 $cmol_c/kg$ at N/S2 site (acidic soils) to 30.05 $cmol_c/kg$ at Ke2 site (calcareous soils) (Figures 1b–6b). The high Ca content in the soils that came particularly from ES zone suggests that Ca was dominating the soils colloids. Indeed, this may affirm an earlier report by [34]. According to the author, the adsorptive affinity of base-cations to the soils exchange complex follows the order: $Ca^{2+} > Mg^{2+} > K^{+} > Na^{+}$. However, based on the threshold values, only two out of the six investigated sites were found to be deficient in Ca. In fact, the soils that are deficient in Ca are the strongly acidic soils that came from WS zone (highland soils).

Profile wise, the overall Ca^{2+} content of the investigated soils is found to increase regularly with depth in all profiles (Figures 1b–6b) with % increases of Ca from topsoil to subsoil: 2.54, 6.38, 24.25, 52.79, 5.99 and 4.74 at WG1/Do2, GS2, Ke2, Bk2, N/S2 and BT2 sites respectively. For the soils sampled from few centimeter depths, [39] reported similar finding. Furthermore, on average, the Ca content was found to correlated strongly with CEC (r= 0.987; at $p \leq 0.001$) (Table 2). The increased levels of Ca with depth might have been brought about by the calcium carbonate ($CaCO_3$) rich parent material in addition to other pedogenic processes in the some locations like (e.g., in the ES zone).



Figures 5. *a-c. Profile distribution of macronutrients & related soil properties in the first five depth intervals (0–120 cm) at WS zone, N/Suba2 site.*



Figures 6. *a-c. Profile distribution of macronutrients & related soil properties in the first five depth intervals (0–120 cm) at WS zone, BT2 site.*

3.9. Magnesium

Exchangeable magnesium (Mg^{2+}) content of topsoil (upper 20cm) ranged from 1.27 $cmol_c/kg$ at (N/S2) site to 8.29 $cmol_c/kg$ at Ke2 sites. Based on the suggested threshold values, two out of the six sites were found to be deficient in Mg. Similar to Ca^{2+}, the sites which showed Mg deficiency are, the strongly acidic soils and soils that are sandier in texture. With respect to its vertical distribution, the overall exchangeable Mg contents of all profiles or sites were found to increase regularly with depth (Figures 1b–6b). The % increases in Mg content from topsoil to subsoil were, 27.10, 31.56, 13.51, 17.24, 68.50 and 81.98% at WG1, GS2, Ke2, Bk2, N/S2 and BT2 sites respectively. The relatively increasing trends of Mg from topsoil to subsoil may suggest that the underlying horizons might have higher levels of Mg possibly due to the pedogenic processes other than leaching and/or the presence of high Mg bearing materials in the soil's parent rocks. Korkanc, et al., [40] reported similar trend of changes. According to the authors, the reasons for such irregular trends of change in Mg contents could be the result of localized enrichments of the cation containing minerals of the parent rock. Overall, it is well noted that, there is a more general picture about the relative concentrations of basic cations in soil profiles that provide the basis for assessing soil fertility as individual cations are the indicators of nutrient status and balances.

3.10. Potassium

In general, potassium (K) is recognized to be one of the most abundant elements in soils. However, though its chemical compounds are very soluble, its mineral forms like micas and orthoclase feldspars are slowly soluble. Accordingly, K is found in large quantities in most of the investigated soils corroborating the general perception on the Ethiopian soils for K. Exchangeable potassium (K^+) contents of surface soils ranged from 2.09 $cmol_c/kg$ at N/S2 site to 3.77 $cmol_c/kg$ at Ke2 site (Figures 1c–6c). Based on the threshold values, none of the sites were found to be deficient in K, which means that all sites or soils under investigations had either high or very high levels of exchangeable K. Indeed, this is in accordance with that reported by [39, 41].

With respect to its vertical distribution, in general, the K contents of the investigated profiles from topsoil to subsoil were found to be increasing, with the percentage increases of 36.99, 250.88, 20.95, 55.60, 45.93 and 37.61 at WG1, GS2, Ke2, Bk2, N/S2 and BT2 sites respectively. The coefficient of correlations (r) analysis showed that, K had a significant positive relation with CEC (r= 0.986, at $p \leq 0.001$); and also with clay (Table 2), but negatively with OC in terms of its profile distribution. The strong negative correlation of K^+ with OC may strongly suggest that the major sources of K are the parent material other than OM. Indeed, this is in accordance with that reported by [1]. According to the authors the main source of K for plants growing under natural conditions are the weathering of K minerals and organic K sources such as composts. This may suggest that plant residues are of secondary importance as the source of K. Furthermore, since the studied soils had very low levels of OC, the parent materials of the investigated soils must be dominated by the micas and orthoclase feldspars, i.e., the parent materials very rich in K.

Table 2. *Persian-correlation coefficients of the mean values for the macronutrients and related soil properties before planting wheat or faba bean.*

	Depth	pH	OC	TN	Av.P	SO_4-S	CEC	Ca^{2+}	Mg^{2+}	K^+	Na^+
Depth	1.00000	0.99346	-0.99701	-0.81986	-0.91253	0.99850	0.99558	0.99312	0.99311	0.98953	0.99171
		0.0006	0.0002	0.0893	0.0306	<.0001	0.0004	0.0007	0.0007	0.0013	0.0009
pH	0.99346	1.00000	-0.99627	-0.76718	-0.92799	0.98885	0.97971	0.99384	0.98803	0.98784	0.97848
	0.0006		0.0003	0.1300	0.0229	0.0014	0.0035	0.0006	0.0016	0.0016	0.0038
OC	-0.99701	-0.99627	1.00000	0.79951	0.89811	-0.99145	-0.98869	-0.98953	-0.98425	-0.98287	-0.99174
	0.0002	0.0003		0.1045	0.0384	0.0009	0.0014	0.0013	0.0024	0.0027	0.0009
TN	-0.81986	-0.76718	0.79951	1.00000	0.65768	-0.82307	-0.83239	-0.75565	-0.81611	-0.75126	-0.82336
	0.0893	0.1300	0.1045		0.2277	0.0869	0.0803	0.1396	0.0920	0.1432	0.0867
Av.P	-0.91253	-0.92799	0.89811	0.65768	1.00000	-0.92254	-0.89089	-0.94065	-0.94970	-0.94552	-0.85583
	0.0306	0.0229	0.0384	0.2277		0.0256	0.0425	0.0172	0.0134	0.0151	0.0643
SO_4-S	0.99850	0.98885	-0.99145	-0.82307	-0.92254	1.00000	0.99666	0.99375	0.99604	0.99258	0.98770
	<.0001	0.0014	0.0009	0.0869	0.0256		0.0002	0.0006	0.0003	0.0008	0.0016
CEC	0.99558	0.97971	-0.98869	-0.83239	-0.89089	0.99666	1.00000	0.98666	0.98571	0.98569	0.99488
	0.0004	0.0035	0.0014	0.0803	0.0425	0.0002		0.0018	0.0020	0.0020	0.0004
Ca^{2+}	0.99312	0.99384	-0.98953	-0.75565	-0.94065	0.99375	0.98666	1.00000	0.99192	0.99894	0.97813
	0.0007	0.0006	0.0013	0.1396	0.0172	0.0006	0.0018		0.0009	<.0001	0.0039
Mg^{2+}	0.99311	0.98803	-0.98425	-0.81611	-0.94970	0.99604	0.98571	0.99192	1.00000	0.99123	0.97102
	0.0007	0.0016	0.0024	0.0920	0.0134	0.0003	0.0020	0.0009		0.0010	0.0059
K^+	0.98953	0.98784	-0.98287	-0.75126	-0.94552	0.99258	0.98569	0.99894	0.99123	1.00000	0.97339
	0.0013	0.0016	0.0027	0.1432	0.0151	0.0008	0.0020	<.0001	0.0010		0.0052
Na^+	0.99171	0.97848	-0.99174	-0.82336	-0.85583	0.98770	0.99488	0.97813	0.97102	0.97339	1.00000
	0.0009	0.0038	0.0009	0.0867	0.0643	0.0016	0.0004	0.0039	0.0059	0.0052	

Wherever it appears: *,**, ***. Significant at the 0.05; 0.01; and 0.001 probability level, respectively.

3.11. Sodium

In Ethiopia, sodaic soils are commonly found in the great rift-valley system and its peripheries running down from Djibouti area (eastern corner) to Arba Minch area (southern corner) stretching to Kenya. In the present investigations, the exchangeable sodium (Na^+) of surface soils ranged from 0.24 $cmol_c$/kg at the N/S2 site to 0.47 $cmol_c$/kg at WG1/Do2 site (Figures 1c –6c). Based on the threshold values, only one site was below this threshold, whereas the rest were marginal or in equilibrium with the suggested critical level. Therefore, the studied soils had no sodicity problem including the sub-surface layers. This would also mean that the studied soils had low exchangeable sodium % (ESP) values < 6.0%. Generally, the relative higher levels of Na were observed in the soils sampled from the peripheries the rift-valley systems.

With respect to the vertical distribution, similar to the other base cations, Na^+ was also found to increase irregularly with depth in all profiles. Its % increases from topsoil to subsoil were 48.94, 114.71, 109.38, 94.12, 208.33 and 158.82 at WG1, GS2, Ke2, Bk2, N/S2 and BT2 sites respectively. For the soils sampled form the first few cm layers, [39] made a similar observation. However, similar to P, Na is also a mineral derived nutrient and its vertical distribution is expected to be dominantly controlled by the CEC as influenced by clay-illuviation. Usually, the soils from the rift-valley system of Ethiopia are also rich in the base-cations other than Na. Similar to SO_4^{2-}; leaching of Na vis-à-vis its mobility in the soil system might have played a significant role in its vertical distribution. However, the role of plant-cycling on the vertical distributions of soil properties can be noticeable at various temporal scales. In general, the overall increasing tends of base-cations including Na with depth are suspected to impair nutrient balances for plants uptake.

4. Conclusions

The results of investigations showed wide of variations in soil properties across soil profiles and sites owing to multitude of interacting factors. From the variables under investigations, soil pH, SO_4^{2-}, CEC, Ca^{2+}, Mg^{2+}, K^+ & Na^+ were found to increase irregularly with depth, whereas the OC, TN and Av.P showed reverse trends of change. The results also showed increased % of clay with depth owing to clay-illuviation and/or pedoturbation (in Vertisols). Increased levels of soil variables like SO_4-S, K^+ & Na^+ with depth may indicate their relative better mobility in the soil system. Overall, the soil properties that exhibited the relative abundances in the active-rooting depth may indicate, the major role the biomass-recycling might have played in their vertical distributions. Coefficient of correlations among soil properties also found to vary with depth. On the whole, for those nutrients that are reasonably abundant in subsoil than the overlying horizons, deep-tillage operations are recommended to bring their available forms to top layers for shallow root plants uptake and recycling. Similarly, deep capture of nutrients by trees (e.g., in the agroforestry system) can also recycle nutrients leached to subsoil improving the nutrient use efficiency and also reducing potential environmental impacts. In line with this, root distribution patterns of plants and nutrient acquisition strategies of tree-roots can further be explored.

Competing Interests

The author(s) declare that they have no competing interests.

Acknowledgements

EIAR and Pawe research centers allowed and supported the study. Kulumsa, Debre Zeit and Holleta research centers under the EIAR hosted the overall field study and provided all needed supports. All farmers in Arsi, East Shewa, and West Shewa zones who allowed their precious lands for the overall experimentations or study, free of charge are acknowledged.

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