Soil fertility characterization in vertisols of southern Tigray, Ethiopia

Abstract

A fresh soil profile pit was opened and representative soil samples were collected from the profile and surface (0-15cm) soil of the experimental area to characterize the fertility status of the soils of the study area on the base of selected physicochemical properties. The soil textural class of the surface layer (0-25cm) of the profile and the mean composite surface (0-15cm) soil samples of the experimental field was clay loam while it was clay for the subsurface (25-150+cm) layers of the profile. The bulk density values of the layers in the profile varied consistently with depth ranging from 1.18 g cm⁻³ at the surface layer to 1.32 g cm⁻³ at the bottom layer while the average bulk densities of experimental field. The bulk and particle density values increased consistently with depth of the profile ranging from 1.18 to 1.32 and 2.51 to 2.85 g cm⁻³, respectively. The organic matter (0.05 to 4.39%), available P (0.86 to 22.50 mg kg⁻¹) and total N (0.03 to 0.23%) of the soil profile decreased consistently with depth. Both the profile and the composite surface soil sample indicated that the soil of the site was slightly acidic to moderately alkaline in reaction (6.5 to 8.20). The soil exchange complex was mainly dominated by Ca and mg where the order of occurrence was Ca > K > Mg > Na. The CEC values were very high ranging from 41.42 to 50.37 c mol (+) kg⁻¹. The results of the study revealed that the physical and chemical properties of the soils are highly variable to each other which disagrees the blanket rate of fertilizer recommendation throughout the country. The turning point to solve the problems should be restoring, maintaining and increasing the fertility status of the soils. These phenomena necessitate soil-crop specific fertilizer recommendation. Therefore, the existing soil fertility problems should be addressed sooner by introducing/developing resistant crop varieties, applying organic and inorganic fertilizers, and other soil fertility management options.

Keywords: soil profile, vertisols, soil fertility

Abbreviations: PBS, percent base saturation; BD, bulk density; PD, particle density; OM, organic matter; TP, total porosity; AP, available phosphorus; CEC, cation exchange capacity

Introduction

Declining soil fertility has continued to be a major constraint to food production in many parts of the tropical region. The low soil fertility in the tropics has been attributed to the low inherent soil fertility, loss of nutrients through erosion and crop harvests and little or no addition of external inputs in the form of organic or inorganic fertilizers. This is particularly evident in the intensively cultivated areas, traditionally called high potential areas that are mainly concentrated in the highlands of Ethiopia. These imply that the outflow of nutrients in most smallholder farms far exceeds inflows.

To address the problems of soil fertility, several technological interventions, especially those geared towards nutrient management and soil moisture conservation, have been suggested. Besides, the productivity of some soils is constrained by some other limiting factors even though they have high potential productivity or are naturally fertile. In this regard, Vertisols are important agricultural soils where primarily poor drainage and difficult workability limit nutrient availability and productivity, calling for proper soil fertility and water management practices.

In Ethiopia, Vertisols are widely and intensively utilized soil types covering 11% or 12.7 million hectares (ha) of the total land mass and is the fourth important major soil group. More than half (8.6 million ha) of the Vertisols are found in the central highlands with altitude of more than 1500 meters above sea level (masl). Generally, Vertisols have high montmorillonite clay known for its shrink-swell properties in response to changes in soil moisture content. Vertisols produce large cracks that are closed only after prolonged rewetting and thus become hard when dry and very sticky and plastic when wet. These soils are also characterized by the presence of gilgai micro-relief or subsoil showing sicken sides or spheroid structure due to contraction and expansion processes during drying and wetting. Vertisols generally have weak horizon differentiation, low hydraulic conductivity, low infiltration rate and high moisture retention capacity ranging from 60 to 70% at field capacity because of their high clay content. The pH of Vertisols in some highland areas of the country varies from slightly acidic to strongly alkaline, of course depending on different factors.

Many soils in the highlands of Ethiopia are inherently poor in available plant nutrients and organic matter (OM) content. Tekalign et al., also reported that the Ethiopian highland Vertisols tend to exhibit low total nitrogen (N) and OM contents, and application of N fertilizer is considered essential to improve cereal crops production on these soils. However, cereal-dominated cropping systems, aimed at meeting farmers subsistence requirements, coupled with low usage of chemical fertilizers have led to a widespread depletion of soil nutrients in the major cereal crops growing regions of the country. Heavy rains during the part of the main cropping season (June to August) also cause substantial soil nutrient losses due to intense...
leaching and erosion on Nitisols and denitrification on the frequently water-logged Vertisols.

Soil degradation and depletion of soil nutrients are among the major factors threatening sustainable cereal production in the Ethiopian highlands. However, although knowledge on soil fertility status plays a vital role in enhancing production and productivity of the agricultural sector on sustainable basis, little information is available in Southern parts of Tigray in general and the specific study area in particular. Therefore, this study was proposed to characterize the fertility status of the Vertisols in the study area based on selected soil physiochemical properties.

Materials and methods

General description of the study area

Ofa District, one of the six districts of the Southern Zone, is located about 620km north of Addis Ababa and about 150km south of Mekelle city. The study District has about 133, 296 ha of land area and the altitude vary between 1700 and 2800m asl whilst the slope ranges around 2 to 35%.

The study area is characterized by a bimodal rainfall pattern with the main wet season (kiremt) extending from July to September and the small wet season (Belg) which extends from March to May. The area is characterized by heavy and erratic rainfall distribution. The ten years (2002-2011) mean annual rainfall is 980.5 while the annual rainfall in 2011 was 1050mm. Similarly, the mean maximum and minimum temperatures were 22.28 and 7.69°C, respectively. Vertisols are the dominant soil types in the area. The area has crop-dominated mixed crop-livestock farming system. The dominant crops growing around the experimental area are wheat (Triticum aestivum L.), maize (Zea mays L.), barley (Hordeum vulgare), teff (Eragrostis tef) and some species of legume crops.

Soil sampling, sample preparation and analysis

Surface soil and profile sampling and sample preparation: A fresh soil profile pit with 1m width, 2m length and 1.5m depth was excavated at a point representative for the adjacent sites of A and B. The soil profile was described morphologically under field condition and sampled depth-wise (layers) for characterization of some selected physicochemical properties. Moreover, surface soil samples (0-15cm depth) were collected using auger from eight to ten spots from each block to form one composite soil sample per block for soil fertility evaluation. Undisturbed (core) soil samples were also collected using core samplers for soil bulk density determination.

The composite surface soil and soil profile samples collected were air dried in wooden material, ground and sieved to pass through a 2mm sieve in preparation for laboratory analysis. Finally, the fertility status of the soil of the study area was evaluated using descriptive statistics.

Results and discussion

Characterization of the soil of the study area

Physical properties of the soil

Texture: Apparently, particle size distribution in soil water movement, aeration, root extension, oxidation-reduction processes and nutrient and OM contents as well as composition. In the present study, the texture of the surface layer (0-25cm) of the profile and the average of the composite surface (0-15cm) soil samples of site A and B were clay loam. However, the texture changed to clay in the subsurface layers of the soil profile opened adjacent to the experimental plots. Generally, the soil profile contained more than 30% clay throughout (>50% clay below the plow layer) and had intersecting slickenside’s and cracks which open and close periodically suggesting the presence of Vertical horizon. The proportions of clay and silt within the profile ranged from 32 to 52% and from 23 to 35%, respectively, whereby the silt fraction and the silt to clay ratio decreased consistently with increasing soil depth (Table 1). On the other hand, the sand content at the surface layer of the soil profile was the highest (33%) followed by the bottom layer, which contained 27% sand.

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The silt to clay ratio of the soil ranged from 0.46 to 1.09 for the profile and from 0.38 to 1 to 1.16 and 1.43 to 1.56 for the composite surface soil samples of site A and B, respectively. This ratio is one of the indices used to assess the rate of weathering and determine the relative stage of development of a given soil. According to Young, a ratio of silt to clay below 0.15 is considered as low and indicative of an advanced stage of weathering and/or soil development while greater than 0.15 indicates that the soil is young containing easily weatherable minerals. Hence, the silt to clay ratio of the soil observed in the present study is generally high (greater than 0.15) both for the profile and the composite surface soils (Table 1) suggesting low degree of weathering and young soil development stage.

Particle and bulk density: The bulk density values of the layers in the profile varied consistently with depth ranging from 1.18g cm\(^{-3}\) at the surface layer to 1.32g cm\(^{-3}\) at the bottom layer while the average bulk densities of site A and B were 1.19 and 1.20g cm\(^{-3}\), respectively. These values are closer to the average range of bulk density for mineral soils which is 1.30-1.40g cm\(^{-3}\) as indicated by Bohn et al. The relatively lower bulk density values observed at the surface layer could be due to the relatively high OM contents (Table 1) which resulted in high total porosity (>52%). On the other hand, the relatively high bulk density values in the layers below the plow depth (0-25) could be due to the rapid decline in OM content as well as reduced root penetration and compaction caused by the weight of the overlying soil material.

The particle density values of the layers in the profile increased consistently with depth ranging from 2.51g cm\(^{-3}\) at the surface (0-25cm) layer to 2.85g cm\(^{-3}\) at the bottom layer (98-150+cm) while the average particle density of site A and B were 2.52 and 2.53g cm\(^{-3}\), respectively (Table 1). For many mineral soils, the particle density ranges from 2.60 to 2.70g cm\(^{-3}\) and it does not vary a great deal for different soils unless there is considerable variation in OM content and mineralogical composition of the soil. Therefore, the particle densities of the soils where the current study was conducted are closer to the average range of particle density for mineral soils. However, the particle density values of the surface layers of the profile and the mean of the composite surface soil samples of site A and B were relatively lower than the underlying subsurface layers of the profile. This is probably attributed to the rapid decline in OM with increasing soil depth from 4.39% at the plow depth to 0.05% at the bottom of the subsoil (Table 2).

Total porosity: Total porosity of the soil profile decreased consistently with depth from 52.99% at the surface layer to 49.43% at the bottom layer. In accordance with the total porosity of the surface layer of the profile characterized representing both sites where the average volumes of total soil porosity of site A and B were 52.85 and 52.51%, respectively (Table 1). The relatively higher values of total porosity observed at the surface layer of the profile and the composite surface soil samples across site A and B correspond to the higher OM content and the resultant lower bulk density values (Tables 1) (Table 2). The range of total porosity observed in the soils considered in this study falls within the range of 46 to 64% reported by Abayneh for the soils of the Karya valley.

Chemical properties of the soil

Soil reaction (pH): The data in Table 2 indicates that the soil pH values within the soil profile linearly increased with increasing profile depth. According to the soil pH rating established by Tekalign, the results of soil analysis in this study showed that the pH of the soil profile varied from slightly acidic (pH=6.3) at the surface layer (0-25cm depth) to strongly alkaline (pH=8.2) at the bottom (98-150+cm) layer. Similarly, the mean pH values of the composite surface soil samples from site A (6.5) and site B (6.6) were categorized under the slightly acidic soil reaction class as per the same rating provided.

According to Eylachew, the pH of Vertisols characterized in different parts of the country was within the range of 6.3 to 7.6 on the surface layer and within 6.8 to 8.5 in the underlying layers. Therefore, the soil pH values recorded for the profile and the composite surface soil samples of both sites of the present study fully agree with these findings. The increase in pH consistently with increasing soil profile depth may be due to the marked increase observed in the basic cations particularly exchangeable Ca along with depth (Table 2). The increase in basic cation concentrations with soil depth, in turn, may suggest the existence of downward movement of these constituents from the surface layer to the subsurface layers within the profile.

Organic matter: The organic matter (OM) content of the profile decreased consistently with depth ranging from 4.39% at the surface layer (0-25cm) to 0.05% at the bottom (98-150+cm) layer (Table 2). On the other hand, the composite surface soil samples collected from both sites had mean OM contents of 3.71 and 2.26%, respectively. According to the rating of soil OM content established by Tekalign, the surface layer of the profile had medium while the composite surface soil samples of both sites had medium and low OM contents, respectively.

The reasons for the low to medium OM levels observed in the soils of the present study areas could be intensive cultivation of the land which encourages oxidation reaction and the total removal of crop residues for animal feed and source of energy. Moreover, there is no practice of organic fertilizers addition, such as animal (farmyard) manure and/or green manure that could have contributed to the soil OM pool in the study area. In other soils of Ethiopia, variability of soil OM has also been related to land use history and the associated management practices. Accordingly, OM content is generally low in cultivated soils than soils under grazing lands and in soils of grazing land soils compared to soils of forest land. Moreover, medium OM content of 3.07 and 2.07% were reported for soil samples collected from the plow layer of cultivated lands from Gojjam and Amareasa areas, respectively.

Total nitrogen: The total N contents of the soil profile varied from 0.03% at the bottom layer (98-150+cm) to 0.23% at the surface (0-25cm) layer (Table 2). The total N content of the surface layer of the profile (0.23%) and the mean total N contents of the composite surface soil samples of site a (0.17%) and site B (0.13%) of the study area are rated as medium based on its classification provided by Black. Apparently, the highest value of total N (0.23%) corresponds to the layer of the profile containing the highest OM content (4.39%) and the lowest amount of total N (0.03%) was recorded in the bottom layer which contained the lowest OM content (0.05%) (Table 2).

In line with the OM contents of the profile, the contents of the total N also decreased consistently with depth suggesting the strong correlation between the two soil parameters. The medium total N contents indicate that the soils of the study area are deficient in N to support proper growth and development of crops for expressing their genetic yield potential which suggest that the soils require fertilization with external N inputs and gradual build of its OM levels to ensure sustainable productivity.

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Table 1 Selected physical properties of the profile and composite surface soil samples of the study area

| Depth (cm) | Particle size (%) | Textural class | Silt/clay ratio | BD (g cm\(^{-3}\)) | PD (g cm\(^{-3}\)) | TP (%) |
|-----------|-------------------|----------------|-----------------|---------------------|---------------------|---------|
| 0–25      | 33 35 32          | Clay loam      | 1.09            | 1.18                | 2.51                | 52.99   |
| 25–98     | 23 25 52          | Clay           | 0.48            | 1.29                | 2.61                | 50.57   |
| 98–150'   | 27 23 50          | Clay           | 0.46            | 1.32                | 2.85                | 49.43   |

Composite surface (0-15) soil samples of site A

| Block 1  | 31 19 50 | Clay | 0.38  | 1.17  | 2.52  | 53.57   |
| Block 2  | 31 37 32 | Clay loam | 1.16  | 1.16  | 2.46  | 52.85   |
| Block 3  | 31 37 32 | Clay loam | 1.16  | 1.23  | 2.57  | 52.14   |
| Mean     | 31 31 38 | Clay loam | 0.90  | 1.19  | 2.52  | 52.85   |

Composite surface (0-15) soil samples of site B

| Block 1  | 23 47 30 | Clay loam | 1.56  | 1.24  | 2.56  | 51.56   |
| Block 2  | 27 43 30 | Clay loam | 1.43  | 1.19  | 2.50  | 52.40   |
| Block 3  | 25 45 30 | Clay loam | 1.50  | 1.17  | 2.52  | 53.57   |
| Mean     | 25 45 30 | Clay loam | 1.50  | 1.20  | 2.53  | 52.51   |

Table 2 Selected chemical properties of the profile and composite surface samples of wheat and teff experimental area. OM, organic matter; AP, available phosphorus; CEC, cation exchange capacity; PBS, percentage base saturation

| Depth (cm) | pH (H\(_2\)O) | OM (%) | Total N (%) | AP (mg kg\(^{-1}\)) | Exchangeable bases and CEC (coml. (+) kg\(^{-1}\)) | PBS |
|-----------|--------------|--------|-------------|---------------------|-------------------------------------------------|-----|
| 0–25      | 6.3          | 4.39   | 0.23        | 20.50               | 0.26 0.73 9.14 29.14 41.42 94.81                    |
| 25–98     | 7.5          | 0.10   | 0.06        | 2.20                | 0.43 0.42 10.99 35.44 50.37 93.87                    |
| 98–150'   | 8.2          | 0.05   | 0.03        | 0.86                | 0.76 0.51 11.48 31.89 49.33 90.49                    |

Composite surface (0-15) soil samples of site A

| Block 1  | 6.6          | 3.56   | 0.16        | 22.30               | 0.20 0.58 10.80 22.14 40.19 83.90                    |
| Block 2  | 6.4          | 3.72   | 0.18        | 19.34               | 0.17 0.58 9.41 22.57 42.77 81.44                    |
| Block 3  | 6.4          | 3.86   | 0.17        | 21.78               | 0.22 0.58 11.78 21.00 41.44 81.03                    |
| Mean     | 6.5          | 3.71   | 0.17        | 21.14               | 0.19 0.58 10.66 21.90 41.47 82.12                    |

Composite surface (0-15) soil samples of site B

| Block 1  | 6.6          | 2.20   | 0.19        | 13.68               | 0.18 0.57 10.00 22.00 41.20 79.49                    |
| Block 2  | 6.5          | 2.33   | 0.10        | 13.52               | 0.22 0.75 12.00 21.71 40.45 85.74                    |
| Block 3  | 6.6          | 2.24   | 0.10        | 15.80               | 0.19 0.59 11.00 22.54 42.80 80.19                    |
| Mean     | 6.6          | 2.26   | 0.13        | 14.33               | 0.19 0.64 11.00 22.08 41.48 81.81                    |

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Available soil phosphorus: The available P content of the profile ranged from 0.86mg kg⁻¹ at the bottom layer to 20.50mg kg⁻¹ at the surface layer. Similarly, the mean available P contents of the composite surface soil samples of site A and B were 21.14 and 14.33mg kg⁻¹, respectively (Table 2). According to Olsen et al., rating, the average available P contents of the composite surface soil samples of both sites and the surface layer of the profile fall under the high P status implying that response of crops to P fertilization at such P level may not be very high.

On the other hand, Tekalign et al., reported that 8.5mg P kg⁻¹ of soil was the critical level for some crops such as faba bean on major and/or agriculturally important soils of Ethiopia when assessed by the Olsen P extraction method. Finck et al., also revealed that for cereals, the critical limit below which responses to applied P could be expected on Vertisols is about 8mg kg⁻¹ soil of Olsen extractable P. Considering these critical levels of soil P, the amount of available P observed in the soils of the present study remains to be high.

The content of P showed a decreasing trend with soil depth (Table 2). This is in agreement with the findings of Tekalign et al., who reported that topsoil available P is usually greater than that in the subsoil due to sorption of the artificially added P on the soil surface and its gradual desorption, greater biological activity and higher addition and accumulation of organic materials on the surface soil than in the subsoils. Mulugeta Also indicated a decrease in P content with increasing depth due to its fixation by clay and Ca in the subsurface soil which was found to increase with profile depth.

On the other hand, Mohammed et al., observed low levels of available P in the surface horizons of the cultivated soils of the Chercher highlands in Eastern Ethiopia. In general, existence of low contents of available P is a common characteristic of most of the soils in Ethiopia and some of the exchangeable cations (Mg and Na) which increased with depth. This is in line with the findings of Mebit who reported very high CEC on Eutric Vertisols and that varied with soil depth.

Available soil phosphorus:

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The CEC to clay ratios were over 0.97 reaching 1.29 in the surface horizon. Therefore, the range suggests the presence of 2:1 clay minerals and can be expected to have more nutrient reserves. Mohammed et al. Also indicated that the CEC to clay ratios of the soils of Jelo catchment were over 0.67 reaching 2.05 in some horizons which predicted the presence of smectite (montmorillonite) clay mineralogy of high inherent CEC in all of the soil horizons. This shows that inorganic material (colloidal clay) is the predominant contributing clay mineralogy to the very high CEC observed in the soils. Moreover, the high CEC values imply that the soil has high buffering capacity against the induced changes.

According to the rating by Hazelton and Murphy, the percent base saturation (PBS) of the surface layer of the soil profile was rated as very high. Similarly, the mean values of the composite surface soil sample of both sites were also very high ranging from 81.03 to 83.90 in site A and from 79.49 to 85.74% in site B (Table 2). Unlike CEC and some of the exchangeable cations (Mg and Na) which increased with soil depth, PBS decreased consistently with depth (Table 2).

Conclusion

A fresh soil profile pit was opened and described, and samples were collected depth-wise moreover, composite surface soil (0-15cm) samples were collected from site A and B to characterize the fertility status of the soils of the study area on the bases of selected physicochemical properties. The soil profile opened was 150 cm deep. The soil texture class of the surface layer (0-25cm) of the
profile and the mean composite surface (0-15cm) soil samples of both sites were clay loam while it was clay for the underlying subsurface layers of the profile. The bulk and particle density values of the layers in the profile varied consistently with depth ranging from 1.18 and 2.51g cm$^{-3}$ at the surface layer to 1.32 and 2.85g cm$^{-3}$ at the bottom layer of the profile, respectively.

The pH of the soil profile decreased consistently with increasing soil depth from 6.3 (slightly acidic) at the surface horizon to 8.2 (strongly acidic) at the bottom of the subsoil. The total N and OM contents of the surface layer of the profile and the mean total N content of the composite surface soil samples of both sites were rated as medium while the composite surface soil samples of site A and B had medium and low OM levels, respectively. The available P content of the soil profile at the surface layer (20.5mg P kg$^{-1}$ soil) and the composite surface soil samples of site A (21.14mg P kg$^{-1}$ soil) and site B (14.33mg P kg$^{-1}$ soil) were in the range of the high available P status.

The soil exchange complex of both the profile and composite surface soil samples of both sites were predominantly occupied by divalent basic cations (exchangeable Ca followed by Mg). The CEC values of the plow layer of the soils in the study area as determined in the profile and the composite surface soil samples were rated as very high. The CEC values of the profile increased inconsistently with increasing soil profile depth from 41.42c mol (+) kg$^{-1}$ at the surface horizon to 50.37c mol (+) kg$^{-1}$ at the upper subsurface (25-98cm) depth of the profile which was also rated as very high throughout its depth. Among the exchangeable cations, all except Na were rated as high to very high and all except K increased with depth consistently.

The results of the study revealed that the physical and chemical properties of the soils are highly variable to each other which disagrees the blanket rate of fertilizer recommendation throughout the country. The turning point to solve the problems should be restoring, maintaining and increasing the fertility status of the soils. These phenomena necessitate soil-crop specific fertilizer recommendation. The nutrient supplying powers of the soils and demanding levels of the plants need further correlation and calibration works to come out with site-soil-crop specific fertilizer recommendation. Therefore, the existing soil fertility problems should be addressed sooner by introducing/developing resistant crop varieties, applying organic and inorganic fertilizers, and other soil fertility management options.

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**Conflict of interest**

The author declares no conflict of interest.

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