Digital Mapping to Explain Spatial Variability and Aid Accurate Management of Soil Acidity

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Abstract: Soil acidity is one of the major constraints to cropping systems in the vast highlands of Ethiopia. The study investigated the status of soil acidity, map the spatial variability of acidity across agricultural soils and model lime requirement to aid their management. The pH values ranged from 4.21 to 6.57 and 26.95% of the soils in the study site were strongly acidic (pH ≤ 5.5). The exchangeable acidity varied between 0.29 and 6.18 cmol kg⁻¹ for soils with pH values ≤ 5.5 and its mean value was 2.40 cmol kg⁻¹ soil. Coefficient of variation for exchangeable acidity was 51.88% but that of pH was 6.73% indicating that soil pH was less variable across landscape than exchangeable acidity. Overall analysis of lime requirement showed that 21.71, 20.63 and 5.11% of the agricultural soils in the district requires < 0.50, 0.50-1.00 and 1.00-1.78 t ha⁻¹ of lime, respectively. The mean lime requirement rate of the soils was about 0.89 t ha⁻¹. Our results showed that nearly 47.44% of the total study area requires agricultural lime, which otherwise hampers crop production. Furthermore, we suggest that use of organic methods such as charcoal, manures, compost and selection of acid tolerant crop varieties could reduce the lime requirement and ensure environmental sustainability.

Key words: Soil Acidity - Lime Requirement - Mapping - Management - Reclamation

INTRODUCTION

Soil acidity is a major constraint to cropping systems, especially in temperate and tropical regions of the world where high precipitation has put a dominant influence on the pedogenic development of the soils [1-3]. In Ethiopia, vast areas of land in the western, southern and even the central highlands of the country are thought to be affected by soil acidity [4]. Earlier study estimated that 41% of the total arable land of Ethiopia is affected by soil acidity [5]. In Ethiopia, soil acidity is expanding both in scope and magnitude severely limiting crop production [6, 7]. Soil acidity is a challenge to agricultural productivity posing deficiencies of nitrogen (N) by leaching, phosphorus (P) by fixation and low soil organic matter (OM) [8, 9]. Soil acidification cannot be quantitatively described by a single index or parameter, even though it is often assumed that soil pH is such a parameter [10]. Rather, soil acidification is a complex set of process resulting in toxicity of certain ions (such as Al, Mn) and unavailability of many nutrients such as P, Ca, Mg and Mo to the plant [11, 12]. An increase in the solubility of toxic metals such as Al and Mn may influence root growth, nutrient and water uptake and a change in microbial activities [13-16].

Depending on the variability of soil forming and other environmental factors across landscape, soil acidity also varies spatially. Information on the spatial variability of soil pH across the landscape is required for many ecological and environmental models [17]. Digital soil pH and exchangeable acidity mapping with variable rate application of lime is a current concern in precision soil acidity management [18, 19]. Hence, conventional geo-referenced soil sampling helps to identify the variability of soil properties within fields.
To minimize the adverse effects of extreme soil acidity, lime application is the most widely used strategy. However, soil pH values and lime requirements can vary within a field [20]. Therefore, prudent management decisions entail that lime should be applied according to spatial distribution of soil pH and exchangeable acidity in the area. To this effect, geostatistical methods provide effective ways for quantitatively mapping the spatial distribution of soil acidity and recommending accurate management measures. The data set available so far is of limited application for detailed land management decisions because it lacks the spatial resolution necessary to represent the variability of soil acidity at district and farm levels.

Therefore, the study was aimed at digitizing of the spatial variability of soil acidity and mapping its lime requirement rate at a detailed scale of 1:10,000 for accurate management decisions.

**MATERIALS AND METHODS**

**Study Site:** The study was conducted in Sibu Sire district of Oromia Regional State, western Ethiopia. Geographically, it is located between 36°35‘42.37” and 36°44‘ 28.29” East and 8°57‘16.26” and 9°22‘ 42.59” North. The elevation of the study area ranges from 1,240 to 3,140 meters above sea level. The area receives uni-modal rainfall pattern with an average annual rainfall of about 1348 mm. The mean annual minimum and maximum temperatures are 14.2 and 28.4 °C, respectively. The predominant soil type in southwest and western Ethiopia in general and the study area in particular is Nitisols according to the FAO [21] soil classification system. Its vernacular name is “Biye Dima” meaning red soil.

**Soil Survey and Sampling:** Soil sampling was conducted following 1.5 km x 1.5 km grid survey and distributed on the base map using ArcGIS Version 10.3 software. During sampling, the points identified as pre-defined sample location on the base map were navigated and the exact sampling points were determined by GPS. After locating the center of the sampling point, about 10-15 sub-samples were collected at each location within a radius of 20 m and homogenized, after which a composite soil sample was taken for each grid intersection points. Using the grid survey, nearly 149 composite samples were collected from the pre-defined sampling points that were physically located in the field using predetermined GPS coordinates on the base map. Soil samples were collected using an Edelman soil auger marked at 20 cm and 50 cm depth from the annual and perennial crops, respectively.

**Soil Analysis:** Particle size distribution was determined by the Bouyoucos hydrometer method [22]. The soil pH was measured potentiometrically with an ELMETRON pH-meter in the supernatant suspension of 1:2.5 soils to water ratio as outlined by Van Reeuwijk [23]. Total exchangeable acidity was determined by saturating the soil samples with 1M KCl solution and titrating with 0.02M HCl as described by Rowell [24]. Exchangeable basic cations (Ca, Mg, K and Na), were determined using Mehlich-III soil test extraction procedure [25]. Effective cation exchange capacity (ECEC) was derived as summation of exchangeable bases plus exchangeable acids.

**Determination of Lime Requirement:** For samples with pH ≤ 5.5, lime requirement (LR) was estimated based on the acid saturation method (Eq. 1). The acid saturation method was used in conjunction with optimal soil acidity levels tolerated by various crops. The following permissible acid saturation (PAS) interim norms were recommended by Farina and Chanon [26] for major crops grown in Ethiopia: Maize 20%, Wheat 10%, Barley 10%, Teff 40% and Sorghum 10%. But for this study, PAS of 10% was used to calculate lime requirement. Besides, a modified lime requirement factor of 1160 kg lime ha⁻¹ cmol⁻¹ developed by Taye [27] was used in the equation as follows:

\[
LR = 1160 \times (EA - (ECEC * PAS)) \tag{1}
\]

where LR is recommended lime rate (kg/ha), EA is exchangeable acidity (cmol kg⁻¹), ECEC is effective cation exchange capacity (cmol kg⁻¹) and PAS is permissible acid saturation for specific type of crop (%).

**Spatial Prediction of Soil Properties:** Point data of the target soil parameter was interpolated into spatial data using standard version of kriging, Ordinary Kriging (Eq 2). Additionally, the highest occurrence probability distribution at threshold (critical value) of the parameters was mapped to observe the direction of variation across the landscape in the study area. The basic equation for interpolation by kriging at an un-sampled location \( S_0 \) was given by:

\[
Z(s) = \mu + \epsilon(s) \tag{2}
\]

where \( Z(s) \) is the observed or measured variable, \( \mu \) is the constant stationary function (global mean) and \( \epsilon(s) \) is the spatially correlated stochastic part of the variation.
Statistical Analysis: Descriptive statistics and correlation analysis were carried out using the XLSTAT Version 2014 software. The mean values of soil parameters were compared with critical values.

RESULTS AND DISCUSSION

Soil pH and Exchangeable Acidity: The results revealed that the pH (H₂O) of the surface soil ranged from 4.21 to 6.57 (Table 1). The exchangeable acidity (Al + H), on the other hand, varied between 0.29 and 6.18 cmol kg⁻¹ for soils with pH values ≤ 5.5 and its mean value was 2.40 cmol kg⁻¹ soil. The pH range indicated that the soils fall under strongly acidic to moderately acidic category [28]. In the range of pH 5.5 to 7, hydroxyl aluminum polymers predominate among acids soil components, exchangeable acidity is virtually absent and only none exchangeable and titrable acidity are present in measurable quantities [29]. Our results indicated that soils of the study area have pH values less than 7 and, therefore, they are acidic. The low soil pH obtained from the entire study area might be due to weathering of acidic igneous granites and leaching of basic cations from the surface soil [30].

Considering the optimum pH for many plant species to be 5.5 to 6.8 [31] and absence of free exchangeable Al in this range, only 73.05% of the pH of the soils in study area could be considered as suitable for most crop production (Figure 1) whereas 26.95% of the soils of the study area fall under strongly acidic (pH ≤ 5.5) according to critical levels adopted by Tekalign and Haque [32]. Unless management measures are undertaken, such soils reduce solubility of nutrients and activity of soil microorganisms limiting plant growth and yield. Data presented in Table 1 indicates that exchangeable acidity is spatially more variable than soil pH as depicted from the figures of the standard deviation. Coefficient of variation for

Table 1: Descriptive statistics of selected soil properties

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>SD (±)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay (%)</td>
<td>20.00</td>
<td>79.20</td>
<td>49.50</td>
<td>12.23</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>2.70</td>
<td>50.14</td>
<td>22.44</td>
<td>7.29</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>2.81</td>
<td>66.25</td>
<td>28.08</td>
<td>12.24</td>
</tr>
<tr>
<td>pH</td>
<td>4.21</td>
<td>6.57</td>
<td>5.65</td>
<td>0.38</td>
</tr>
<tr>
<td>Exchangeable acidity (cmol kg⁻¹)</td>
<td>0.29</td>
<td>6.18</td>
<td>2.40</td>
<td>1.72</td>
</tr>
<tr>
<td>OM (%)</td>
<td>0.07</td>
<td>11.44</td>
<td>5.28</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Min: minimum value; Max: maximum value; SD (±): standard deviation; OM: organic matter

Fig. 1: Spatial variability of soil pH and exchangeable acidity (cmol kg⁻¹) across the study site
Fig. 2: Spatial variability of lime requirement (t ha\(^{-1}\)) for soils of the study site

exchangeable acidity was 51.88% but that of pH was 6.73%. This also proved that pH was less variable across landscape than exchangeable acidity.

The results indicated that soils of the study area were dominated by clay fractions with mean value of 49.50% (Table 1). Clay is the most active fractions of soils. It greatly determines the ability of the soils to hold H and Al ions on their colloidal surface. Soil colloids such as clays and organic matter have surface charges and serve very much as a modern bank. They are the sites within the soil where ions are held and protected from excessive loss by leaching. Hence, soils containing high clay fractions have relatively high concentration of exchangeable acids (Al + H) and low soil pH.

The role clay soil on determining the physical, chemical and biological properties of soils was also addressed by [33]. In contrast, ions do not adsorbed to sandy soils, for they have no surface charge. Sandy soils are prone to leaching and hold less exchangeable acids. The mean organic matter (OM) content of soils in the study area was generally low. Decrease in OM content reduces the buffering capacity of the soils and finally elevates the exchangeable acids (H + Al) in the soils. Soils containing high OM are less subjected to pH changes [34]. This might be due to chelating of H ions with organo-complexes which reduced the likely release of free H into the soil solution. Coupled with other factors, the low OM content in agricultural soils of the study site was resulted in lower pH values. Apart from regulating soil pH, the importance of OM in improving soil quality such as aggregate stability, microbial diversity and nutrient availability was reported by [35].

Causes of Soil Acidification in the Area: The main causes of soil acidification in the study area includes leaching, frequent tillage that resulted in decomposition of OM, intensive weathering resulted in dominance of kaolinite clay fractions, soil degradation, removal of crop residues and monocropping systems. In the study area, farmers have been continuously applying UREA and DAP as a main sources of N and P. UREA and DAP are applied nationally in Ethiopia to all crops with blanket recommendation without determining the chemical nature of the soil [36]. Frequent application of N and P fertilizers would enhance soil acidity in the long term, especially when residue or organic incorporation was low [37]. Nitrogen containing fertilizers such as urea releases H\(^+\) by the nitrification process, decreasing soil pH [11, 37]. The rate of UREA and DAP application was increasing over time as soils have become less responsive to the business-as-usual application. But it is further accelerating formation of strong acidity. Continuous cultivation over a long term also caused decrease in soil pH as reported by [38].

Modeling Lime Requirement: Overall analysis of lime requirement showed that 21.71, 20.63 and 5.11% of agricultural soils in the district requires < 0.50, 0.50-1.00 and 1.00-1.78 t ha\(^{-1}\) of lime, respectively (Figure 2).
Currently, the remaining portion of the area (52.56%) did not require lime. The mean value of lime requirement of the district was about 0.89 t ha\(^{-1}\). Nearly 47.44% of the total study area requires lime application, which otherwise hampers crop production. There was a strongly and highly significant correlation (\(r = 0.962^{**}\)) between lime rate and exchangeable acidity. A farm that contains higher amount of exchangeable acidity requires more lime to neutralize exchangeable acids. So, lime requirement varied across landscape depending on variability of exchangeable acidity. Hence, knowing the amount of exchangeable acids is a prerequisite to develop a simple lime requirement model.

According to Murphy and Hazelton and Desalegn et al. [39, 40], lime requirement is needed for sensitive crops like wheat when pH ≤ 5.5. Different lime rates are typically needed to neutralize acid soils sufficiently for crop production; depending on the soil types and levels of acidity [41]. However, one need to know that addition of lime to acid soils alone cannot ensure high crop yield. An increase in the liberation of plant nutrients in the organic matter may increases yield. Such increases in yields may be more economically obtained by adequate fertilization [42].

**Organic Methods of Acid Soil Management:** Green manure, animal manure, charcoal, farmyard manure and compost are other methods used to improve soil quality and regulate soil acidity by building soil OM content [43-45]. For instance, application of farmyard manure enhances organic matter, microbial biomass and contains significant amount of calcium that capable to arrest soil acidification [36]. These organic materials are useful to control fluctuations in the soil pH by increasing buffering capacity of acid soils. Besides, they form complex chelate with H and Al ions and minimize release of exchangeable acids to the soil solution. Nevertheless, in the context of acid soils of tropical Africa, utilization of lime, manure and other organic fertilizer sources have their own technical and or socio economic constraints. The use of tolerant crop varieties is considered to be the best complement to non-genetic management option for combating Al-toxicity problem [46, 47].

**CONCLUSION**

Extensive area of land in Ethiopia has a problem of soil acidity and Al-toxicity. The soils of the area were dominated by clay fractions. The soil has low organic matter content. The soils were moderately to strongly acidic dictating the need for application of lime, which otherwise hampers crop production. Acid soils affect soil productivity by limiting solubility and availability of nutrients, activity of micro-organisms and direct toxicity to plant roots. Nearly half of the total study area requires agricultural lime. The average lime requirement rate for the soils of the study area was 0.89 t ha\(^{-1}\). In addition to lime, use organic amendments such as charcoal, compost and manure also helps to reduce soil acidity. Moreover, a sustainable strategy that accommodates all resource poor farmers is use of acid tolerant crop varieties.

**REFERENCES**


