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Mapping the essential soil nutrients status of smallholder farmers fields in the Wolaita area, southern Ethiopia

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Abstract

Soil properties can vary significantly within farmland or across landscapes due to a combination of physical, chemical, and biological processes. It is essential to understand this spatial variation to effectively manage soil nutrients and enhance crop yield sustainably. Thus, the purpose of this study was to investigate the spatial variability of essential plant nutrients in agricultural lands in Wolaita Zone, southern Ethiopia. A total of 789 soil samples were collected and analysed for macro- and micronutrients. Soil samples were analysed to determine the content of macronutrients [total nitrogen (TN), available phosphorous (P), sulphur (S), and calcium (Ca)] and micronutrients [boron (B), copper (Cu), iron (Fe), zinc (Zn), and manganese (Mn)]. The measured data were first subjected to descriptive statistics, and the digital soil map (DSM) that shows spatial variability was generated after geostatistical analysis. The result showed that there was low [S, Mn], moderate [TN], and high [P] variability in the nutrient concentrations among fields. The nutrient concentration varied between 0.02-0.47% (TN), 0.78-26.22 mg kg^{-1} (P), 6.45-17.50 mg kg^{-1} (S), 0.05-1.83 mg kg^{-1} (B), and 0.05-2.64 mg kg-1 (Cu). The contents of TN, P, S, B, and Cu were low. The DSM further exhibited the wide-ranging spatial variability structures in which, from the total area, 64.8% (TN), 100% (P), 100% (S), and 98% (both B and Cu) have indicated low status. In addition, Mg-induced K deficiency on 68% of studied area was suspected. Based on these findings, it is recommended that site-specific nutrient management practices be implemented on smallholder farms, and the nutrient requirements of major crops should be calibrated accordingly.

Keywords: Macronutrients, Micronutrients, Site-specific management, Spatial variability.

Introduction

Land is the principal resource that supports the livelihood of over 80% of the population in Ethiopia (UN, 2019). With the rapid growth of population in the country, there is increasing pressure on the land to produce more in order to meet the needs of families. However, this has led to a significant problem known as land degradation. Inappropriate land use and poor land management practices have resulted in the deterioration of agroecosystems and food production systems (Teklu et al., 2020; Tesfaye and Fanuel, 2019; Teklu et al., 2018). Land degradation and low agricultural productivity are major challenges in Ethiopia's rural highlands. These areas cover a significant portion of the cultivable land and are home to the majority of both human and livestock populations (Holden et al., 2005). Therefore, implementing effective soil management practices based on scientific knowledge has become crucial for ensuring sustainable and productive agriculture in these regions.

Soil properties affect crop yield and are spatially variable due to different processes (Fanuel et al., 2018a; Fanuel et al., 2018b; Nourzadeh et al., 2012; Tittonell et al., 2005). Managing soil despite its spatial variability leads to undesirable effects on the environment: it reduces the efficiency of farm input applications, increases production costs, and negatively affects crop productivity and soil health (Mary et al., 2016). The absence of a well-developed soil information system leads to inadequate strategies for soil fertility and fertilizer management. Therefore, understanding soil spatial variability and mapping digitally are imperative to assess the effects of agricultural activities on soil properties, plan appropriate soil management practices, and support site-specific farming practices (Fuentes et al., 2021; Guan et al., 2017). Site-specific farming helps farmers efficiently utilize agricultural inputs and achieve better soil health and sustainable production concerning soil spatial variation (Patil et al., 2011; Singh et al., 2010).

Soil parameters play a crucial role in determining the health and productivity of agricultural land. These parameters, such as nutrient content, pH level, organic matter, and moisture retention, are typically measured in laboratory settings. However, in many developing countries, like Ethiopia, access to soil testing facilities is limited. Owing to the characteristics of soil spatial dependence (Costa et al., 2015; Ozgoz et al., 2013; Cambardella et al., 1994), farmers are facing difficulties in knowing the fertilizer requirements of their land. These factors would affect soil health and efforts towards food security. These days, technological advances in geographic information systems (GIS), global positioning systems (GPS), remote and proximal soil sensing, and digital elevation models (DEM) provide more efficient ways of assessing the continuous spatial variability of soils (Fuentes et al., 2021). The soil spatial dependency analysis of georeferenced variables and digital soil mapping (DSM) is possibly evaluated using a geostatistical approach (Fanuel et al., 2018 a and b; Patil et al., 2011; Cambardella et al., 1994).

Digital soil mapping is a procedure for generating model-informed maps of soil variability and may be used for optimizing soil management and use (Fuentes et al., 2021). Researchers in different parts of the globe have used geo-statistics as a tool to predict the values of soil physical and chemical properties for larger areas where the soil samples are not actually collected and measured (Fuentes et al., 2021; Fanuel et al., 2018 a and b; Costa et al., 2015; Nourzadeh et al., 2012; Ewis, 2012; Tesfahunegn et al., 2011). Generally, DSM allows for the presentation of the continuous nature of soils, as inherent soil variability is captured through quantitative models that relate soil attributes to the spatial distribution of soil-forming factors (Gizachew et al., 2021; Fuentes et al., 2021).

In Ethiopia, spatial variability of soil properties has largely been ignored during soil management interventions (Birhanu and Chalsissa, 2019). This implies that uniform soil management under spatially variable fields aggravated the deficiency of macro- and micronutrients (Eyasu et al., 2019) and resulted in variable yield even within the same field receiving the same input and management (Birhanu and Chalsissa, 2019). It would also cause less nutrient use efficiency and fail to make proper allocations of scarce fertilizer resources. Thus, accurate soil information that supports producers in making farm-level decisions is needed for the sustainable management of existing soil resources (Gizachew et al., 2021). In this regard, the use of DSM comes in handy for land use decisions and would be an input to increase agricultural productivity and combat food insecurity (Gizachew et al., 2021; Fuentes et al., 2021). According to Fuentes et al. (2021), many producers and communities will adopt land management practices when provided with spatially explicit soil information. By mapping the soil's nutrient status, it will help identify potential nutrient deficiencies or excesses that may exist in the soil, which can have significant implications for crop productivity and farmers' income. This study aims to provide valuable information on the distribution and availability of essential soil nutrients in the selected area.

Materials and methods

Description of the study area

The study was conducted in Damot Gale, Damot Sore, and Sodo Zuria districts of the Wolaita zone, Southern Nations', Nationalities', and Peoples' Regional States (SNNPRS) of Ethiopia (Figure 1). The area is located between 037°35'30" and 037°58'36" E and 06°57'20" and 07°04'31" N. The study area covers about 84,000 hectares (ha) of land. A total of 82 *kebeles* (the smallest administrative unit in the government structure), 31 from Damot Gale, 18 from Damot Sore, and 33 from Sodo Zuria districts were surveyed. The mean annual precipitation was about 1355 mm with a bimodal rainfall pattern (Figure 2). The mean monthly temperature ranges from 17.7 to 21.7 °C, with an average of 19.7 °C. The elevation varies between 1473 and 2873 metres above sea level (m. a.s.l.) (Figure 3). As per traditional agro-ecological zone classification in Ethiopia, about 0.003%, 96%, and 3.7% of the total area are found under lowland, mid-highland, and highland agro-ecologies, respectively.

Nitisols are the most prevalent soil (Tesfaye, 2003). Rain-fed-based agriculture at a subsistence scale is dominant. The major crops grown in the area include tef *(Eragrostis tef* (Zucc.) Trotter), maize *(Zea mays* L.*),* bread wheat (*Triticum aestivum* L.), haricot bean (*Phaseolus vulgaris* L.), field pea *(Pisum sativum* L.*),* potato *(Solanum tuberosum)*, sweet potato (*Ipomea batatas*), taro (*Colocasia esculenta*), *enset* (*Ensete ventricosum),* and coffee (*Coffea arabica).* In addition, the vegetation is dominated by eucalyptus trees (*Camaldulensis spp.*). Remnants of indigenous tree species such as croton *(Croton macrostachyus* Hochst. ex Rich.*),* cordia (*Cordia africana* Lam.*),* Erythrina spp., and podocarpus *(Podocarpus falcatus)* are also present.

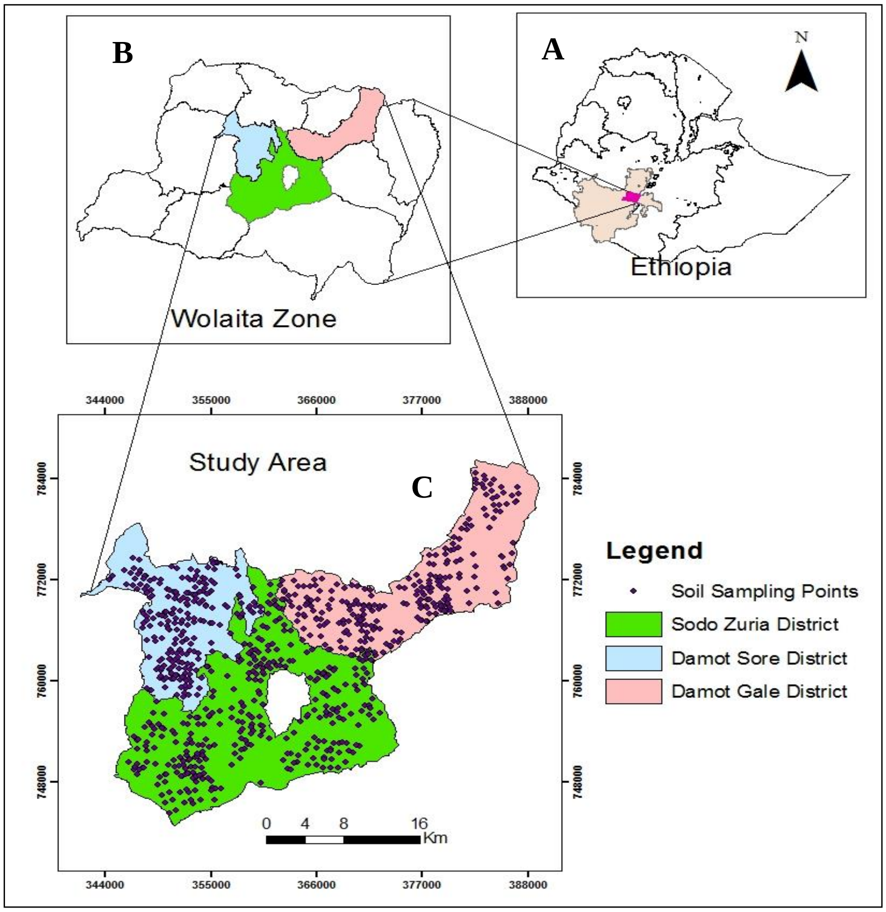

Figure 1: The location map of SNNPRS in Ethiopia and Wolaita Zone in SNNPR (A), study districts in Wolaita Zone (B), and soil sampling points in the study areas (C)

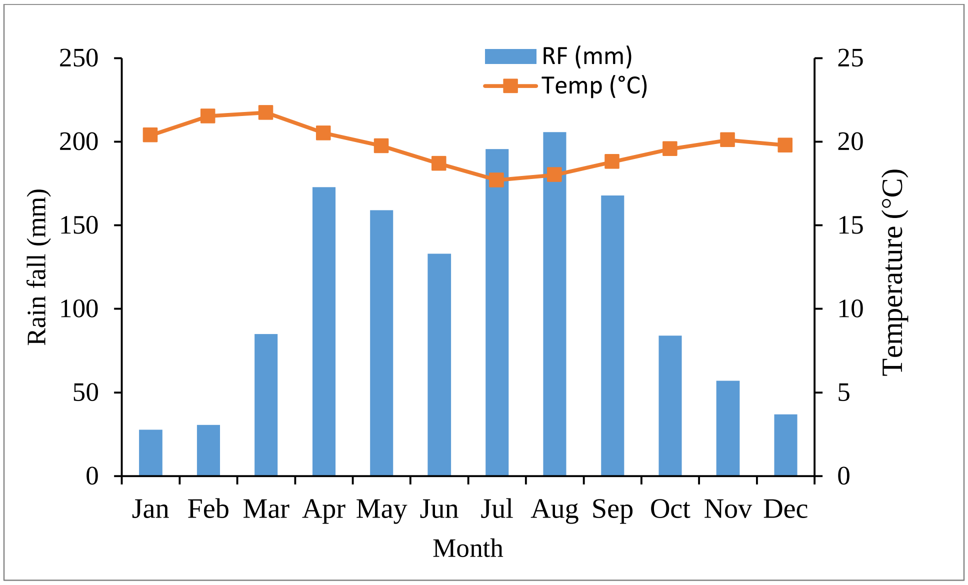

Figure 2: Ten years of monthly average rainfall and temperature in the study area.

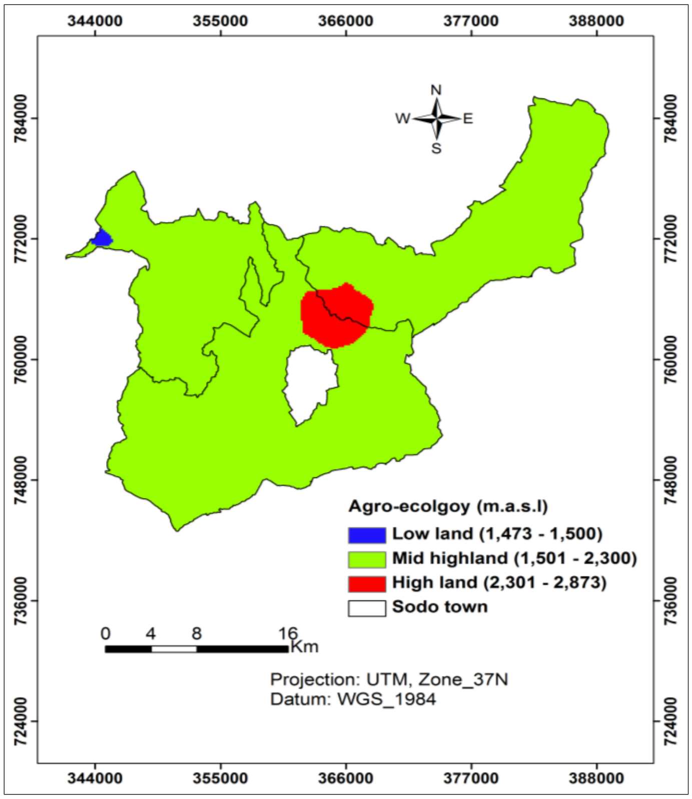

Figure 3: Agro-ecology of the study areas (source: own result)

Soil sampling procedure and laboratory analysis

Soil sampling procedure

ArcGIS software version 10 was used to randomly assign soil sampling locations. Then, a total of 789 pre-identified sampling points at an average separation distance of 512 metres were identified and displayed over the three districts. During survey work, the sample points were navigated, and the latitudes, longitudes, and elevations of the sampling field were recorded using a portable geographical positioning system (GPS) receiver (model Garmin GPSMAP 60Cx). Once the sampling point was navigated and reached, 10 to 15 surface soil sub-samples were taken based on the complexity of the topography and the heterogeneity of the soil type. The topsoil was chosen as plants and soil management practices most influence it (Gizachew et al., 2021). Samples were collected using a soil auger and then composited. Soil samples were taken to a depth of 0–20 cm for *tef*, haricot bean, wheat, maize, etc., while they extended up to 50 cm for perennial crops such as *enset* and coffee. A kilogram (kg) of soil was taken from each field with a labelled soil sample bag.

Sample preparation and soil analysis

The soil samples were air-dried at room temperature and then ground into a fine powder. Next, they were passed through a 2 mm mesh sieve to remove any large particles. For mid-infrared diffuse reflectance (MIR) spectral analysis, the samples were further sieved through a 0.5 mm mesh sieve. These soil samples were processed at the National Soil Testing Centre (NSTC) in Addis Ababa, Ethiopia. At the NSTC, the soil samples were analyzed for various parameters, including soil pH, total nitrogen (TN), and cation exchange capacity (CEC). In addition, the soil samples were also analyzed for available phosphorus (P) and sulphur (S), as well as exchangeable bases such as calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na). The analysis for available P and S, as well as exchangeable bases, was done at Altic B.V. in Dronten, Netherlands. Furthermore, the soil samples were analyzed for soil micronutrients, including iron (Fe), copper (Cu), manganese (Mn), zinc (Zn), and boron (B). The analysis for these extractable micronutrients was also conducted at Altic B.V. in Dronten, Netherlands.

Soil pH (1:2 soil:water suspension) with a glass electrode (model CP-501) was determined. The Mehlich-3 multi-nutrient extraction method was used to extract available phosphorus (P), available sulfur (S), exchangeable basic cations (calcium (Ca), potassium (K), magnesium (Mg), and sodium (Na)), and extractable micronutrients (iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B)) from the soil. The concentration of these extracted elements was measured using an inductively coupled plasma (ICP) spectrometer. To evaluate the soil manganese content, the manganese activity index (MnAI) method developed by Karltun et al. (2013) was used. MIR (mid-infrared) diffuse reflectance spectral analysis was employed to determine the amount of total nitrogen (TN) and cation exchange capacity (CEC) in the soil. This analysis utilizes the reflectance of infrared light to estimate the presence and quantity of these soil properties.

Mapping the soil nutrients

Ordinary kriging was performed to interpolate the values of parameters at unsampled locations and produce digital maps of soil properties (Singh et al., 2010). To check the existence of spatial variability, soil parameters were categorized using EthioSIS (2014), Landon (2014), and Maria and Yost (2006) ratings. EthioSIS (2014) was used to rate [TN, available P, S, B, Cu, Fe, Mn, and Zn], and CEC was categorized using Landon (2014). The Ca and Mg concentrations were interpreted based on the suggestions made by Maria and Yost (2006). During mapping, two map types that show overall status (describing the nutrient status) and a binary map (sufficient and deficient areas requiring management) are generated. The Universal Transverse Mercator (UTM), Zone 37N projection, and Datum of WGS_1984 were employed for map projection. All the tasks were done using GIS software (Arc Map version 10.1). The coefficient of variation (CV) values were rated as low (< 20%), moderate (20–50%), and highly variable (> 50%) (Amuyou et al., 2013).

Results

Macro nutrients

Total N ranged from 0.02 to 0.47%, with a mean ± SD of 0.14 ±0.05%. It showed moderate variability (Table 1). The spatial analysis revealed that 22.2, 42.6, 34.5, and 0.7% of the area exhibited very low (< 0.1%), low (0.1–0.15%), optimum (0.15–0.30), and high (0.30-0.50) TN (EthioSIS, 2014) (Figure 4). Data regarding available P revealed high variability where it stretched between 0.78 and 26.22 mg kg-1 with a mean ± SD value of 4.79 ± 3.56 mg kg^{-1}. Spatially, 97.5% of the total area was very low (< 15 mg kg^{-1}) and the remaining 2.5% was low (15–30 mg kg-1). (EthioSIS, 2014) (Figure 5).

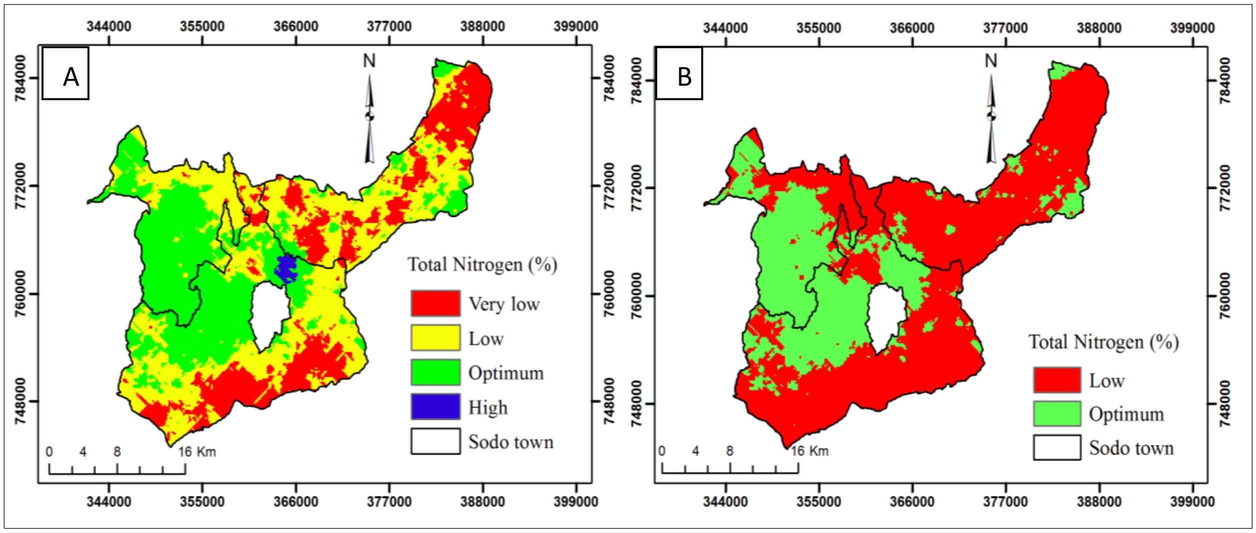

Figure 4: Total nitrogen (%) A) Status and B) Management-based Map of Damot Gale, Damot Sore, and Sodo Zuria Districts

Table 1**:** Descriptive statistics of predicted values of soil nutrients, PBS, and CEC for maps using geostatistical analysis

Soil properties	**Unit**	**Mean**	**SD**	**Min**	**Max**	**CV (%)**
pH	-	6.13	0.39	5.02	7.28	6
TN	%	0.14	0.05	0.02	0.47	36
P	mgkg^{-1}	4.79	3.56	0.78	26.22	74
S	mgkg^{-1}	10.56	1.57	6.45	17.50	15
Ca	Cmol(+)kg^{-1}	7.45	1.71	3.65	14.90	23
Mg	Cmol(+)kg^{-1}	1.88	0.43	0.70	6.00	23
K	Cmol(+)kg^{-1}	1.09	0.32	0.46	2.55	29
K:Mg	-	0.65	0.16	0.14	1.48	25
B	mgkg^{-1}	0.52	0.11	0.05	1.83	21
Cu	mgkg^{-1}	0.52	0.19	0.05	2.64	37
Fe	mgkg^{-1}	126.86	25.95	42.85	296.23	20
Mn	mgkg^{-1}	146.17	27.61	67.11	240.13	19
Zn	mgkg^{-1}	8.35	3.65	1.02	35.47	44
PBS	%	55.87	6.78	37.67	72.95	12
CEC	Cmol(+)kg^{-1}	20.97	2.44	11.18	45.13	12

CEC: Cation Exchange Capacity, PBS: Percent Base Saturation

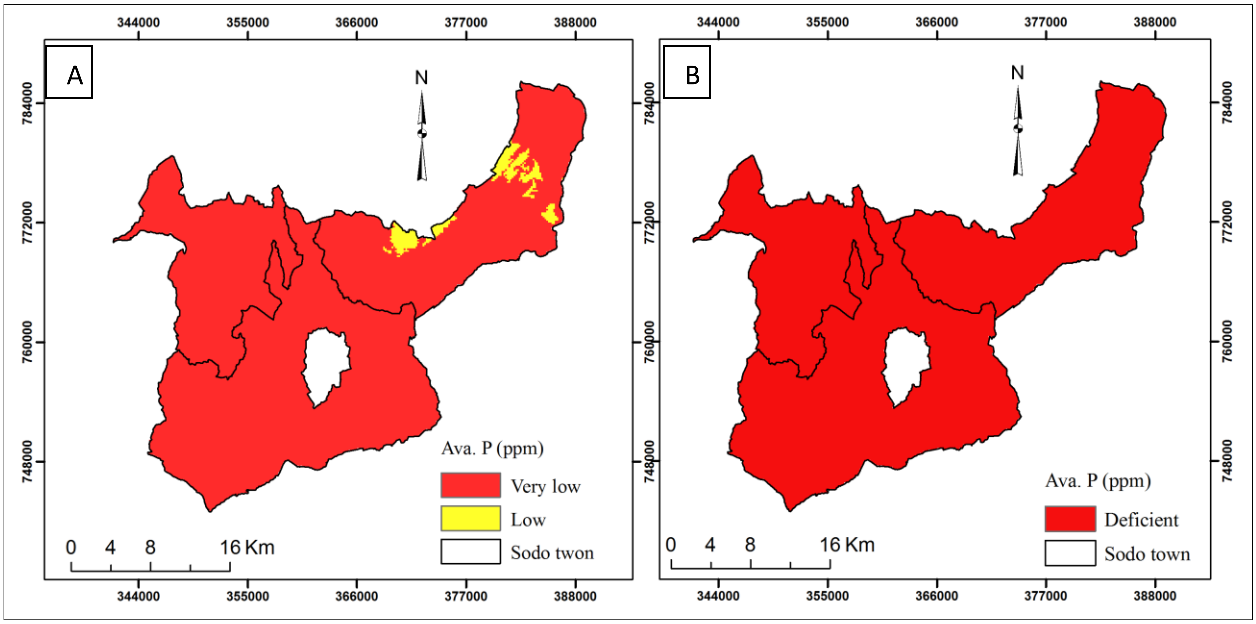

Figure 5: Soil available P A) Status and B) Management-Based Map of Damot Gale, Damot Sore, and Sodo Zuria Districts

Exchangeable Ca ranged from 3.65 to 14.9 Cmol (+) kg^{-1} with a mean value of 7.45 ± 1.74 (Figure 6). A digital soil map based on the rating of Maria and Yost (2006) indicated that 6, 87, and 7% of the total area had low (2–5), medium (5–10), and high (10–20) exchangeable Ca, respectively. The soil exchangeable Mg (Cmol (+) kg^{-1}) varied between low (0.7) and high (6) with a mean value of 1.88 ± 0.43 (data not included). About 14, 84, and 1% of the area had low, medium, and high status (Landon, 2014). Furthermore, the mean S content (mg kg^{-1}) was 10.56 ± 1.57, where it ranges from very low (6.45) to low (17.50) based on EthioSIS (2014) (Figure 7). It was also found to be moderately variable (Table 1) as a result of external and inherent factors. The CEC (Cmol (+) kg^{-1}) of the soils investigated was between 11.18 [low] and 45.13 [high], with a mean value of 20.97 ± 2.44 (Table 1). About 94.8% of the total area was found to have medium (15–25) CEC, based on Landon (2014) (Figure 8).

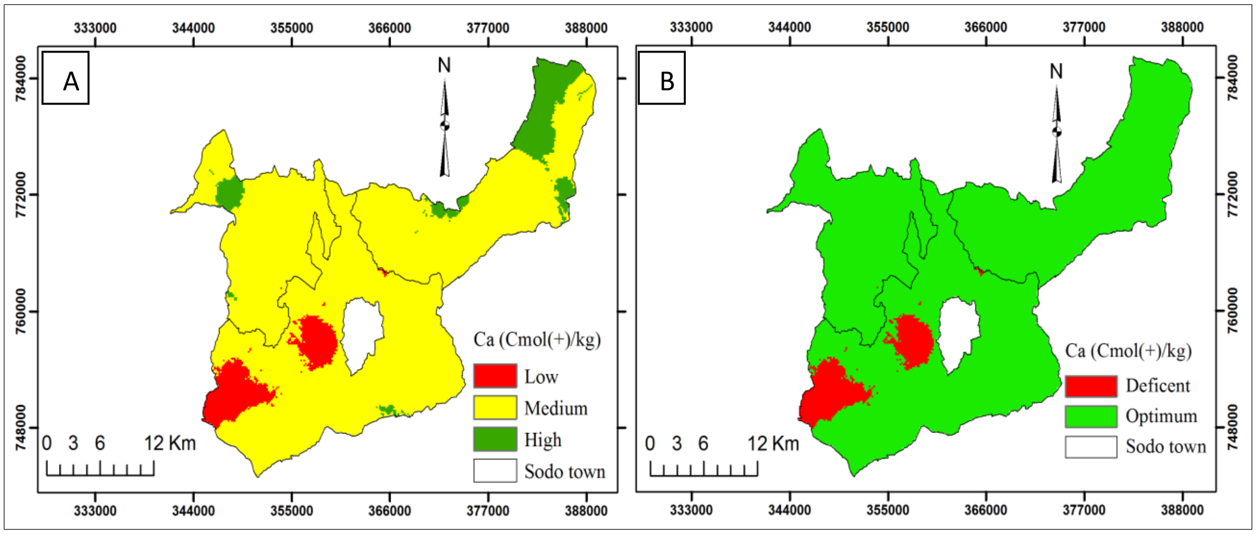

Figure 6: Soil exchangeable Ca A) Status and B) Management-Based Map of Damot Gale, Damot Sore, and Sodo Zuria Districts

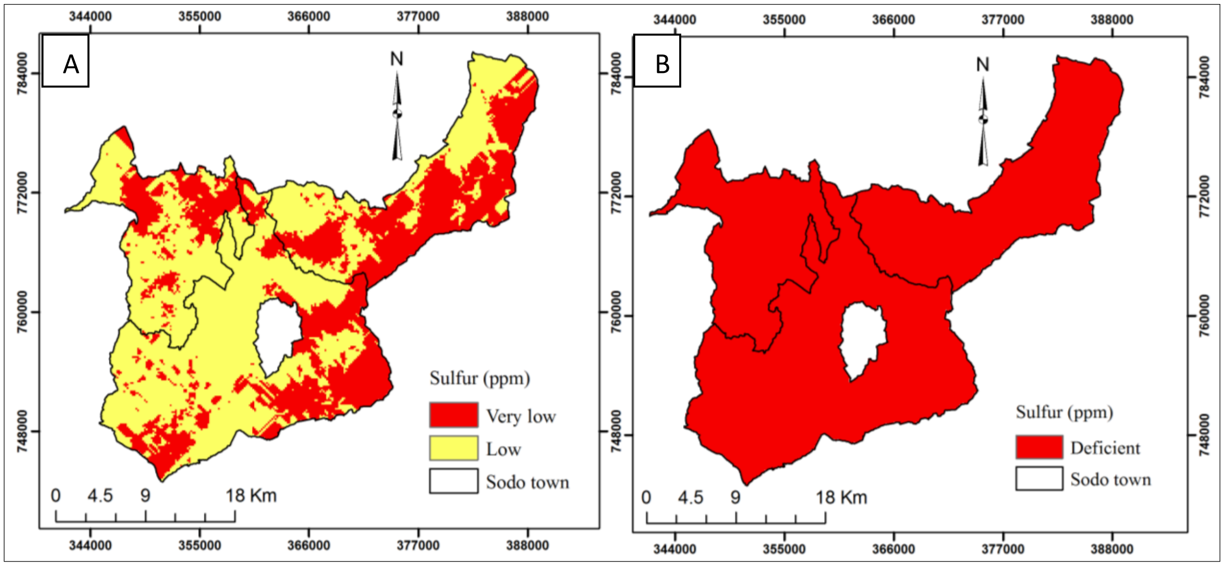

Figure 7: Sulfur A) Status and B) Management-Based Map of Damot Gale, Damot Sore, and Sodo Zuria Districts

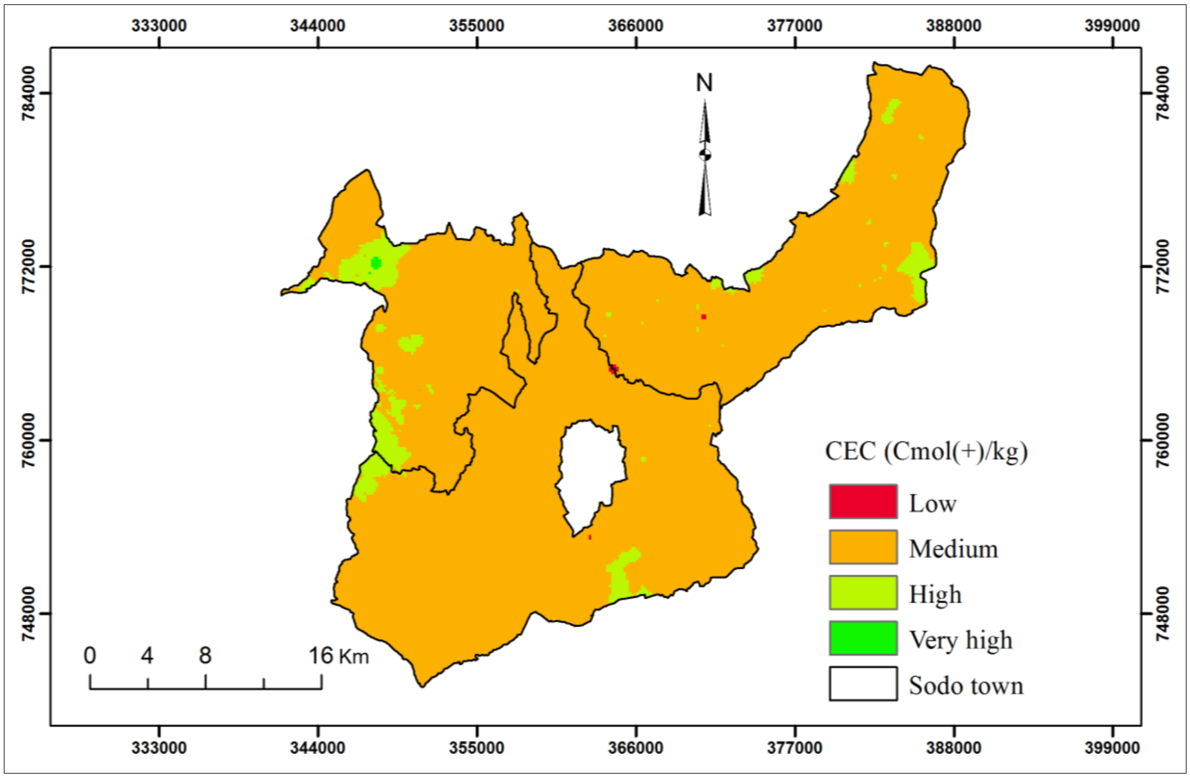

Figure 8: CEC Map of Damot Gale, Damot Sore, and Sodo Zuria Districts

Micronutrients

There was spatial variability among soil micronutrient concentrations (Table 1). Mn had low variability (CV< 20%), whereas B, Cu, Fe, and Zn exhibited moderate variability (20 < CV < 50%) (Table 1). The range and mean concentration (mg kg^{-1}) were: B (0.05-1.83, 0.52); Cu (0.05-2.64, 0.52); Fe (42.85-296.23, 126.86); Mn (67.1-140.1, 146.17); and Zn (1.02-35.47, 8.35) (Table 1). The spatial analysis result of B showed that 48, 50, and 2% of the study area (Figure 9) was mapped under very low (< 0.5 mg kg^{-1}), low (0.5–0.8 mg kg^{-1}) and optimum (0.8–2.0 mg kg^{-1}) B levels, respectively (EthioSIS, 2014). The Cu content on 98% of the total area (Figure 10) was less than 0.9 mg kg^{-1}, which is the limit adopted for Ethiopian soils (EthioSIS, 2014). The concentrations of Fe, Mn, and Zn in the entire area were above the critical levels of 80, 25, and 1.5 mg kg^{-1}, respectively, based on the rating suggested by EthioSIS (2014). Thus, the digital soil map also revealed that Fe, Mn, and Zn were not limiting (Figures 11, 12, and 13).

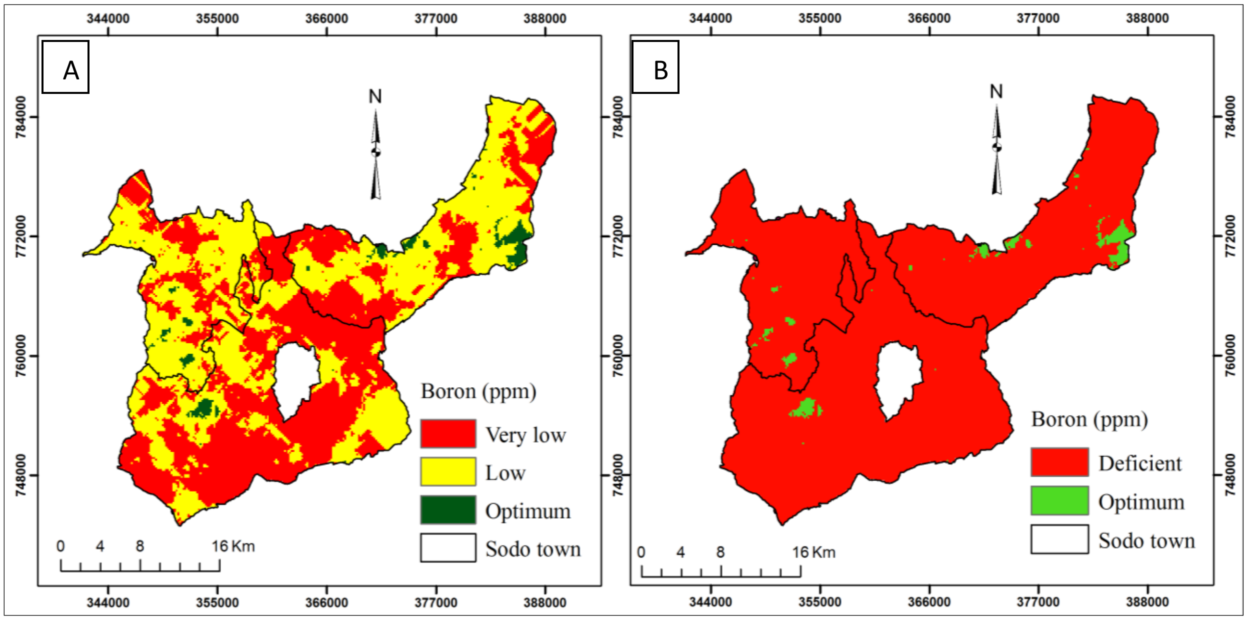

Figure 9: Boron A) Status and B) Management-Based Map of Damot Gale, Damot Sore, and Sodo Zuria Districts

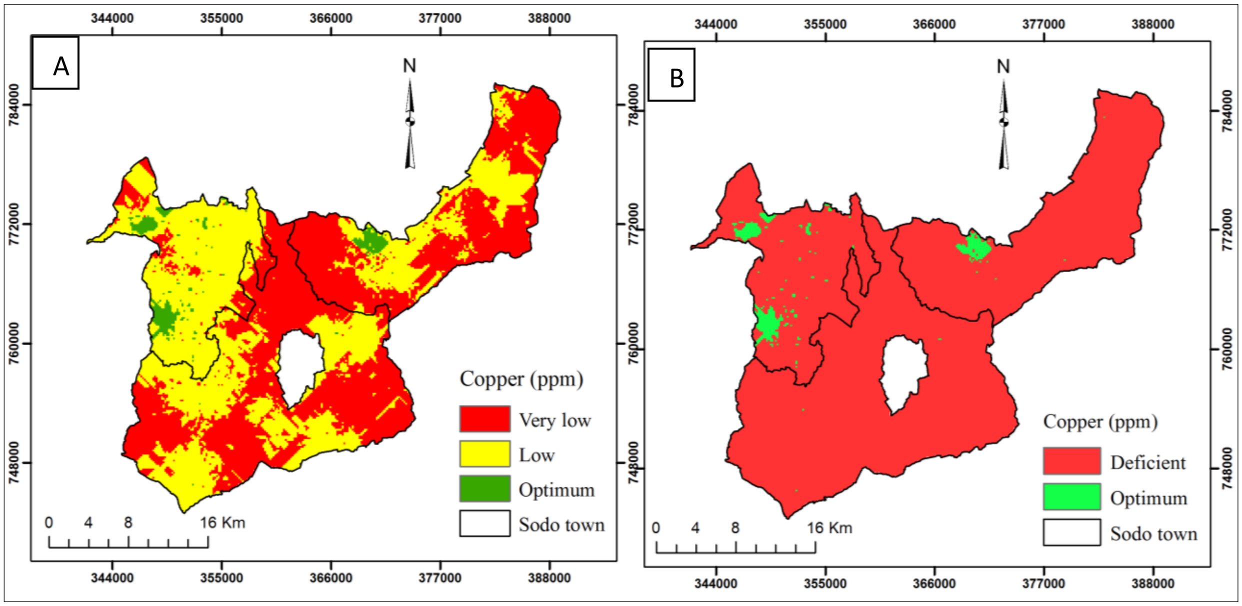

Figure 10: Copper A) Status and B) Management-Based Map of Damot Gale, Damot Sore, and Sodo Zuria Districts

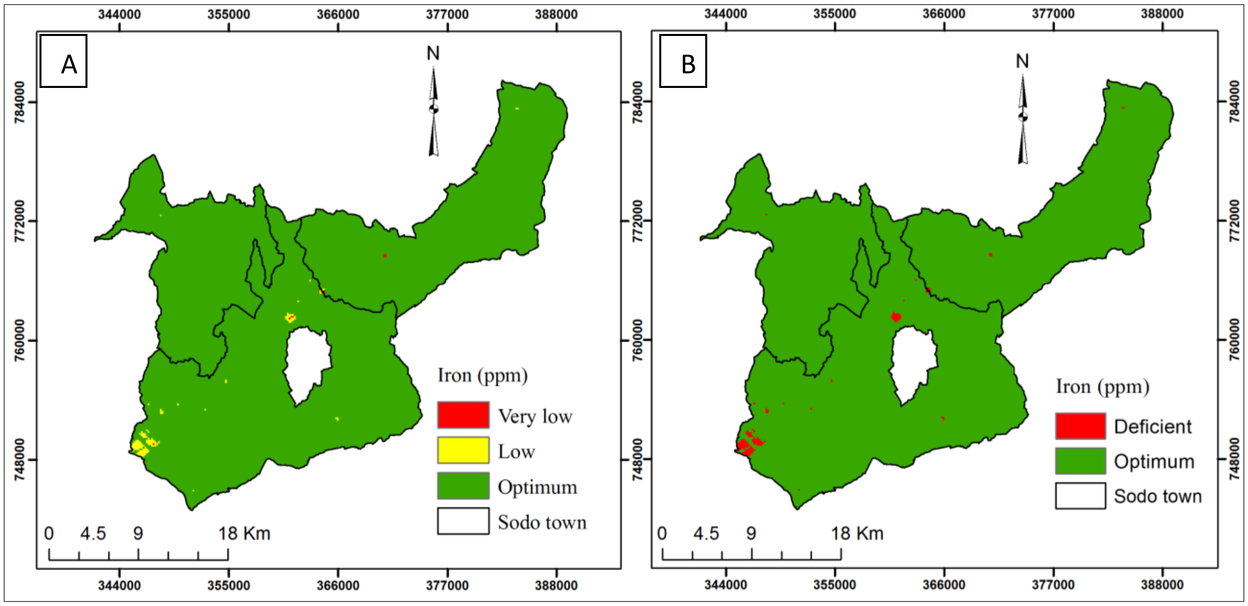

Figure 11: Soil Fe A) Status and B) Management-Based Map of Damot Gale, Damot Sore, and Sodo Zuria Districts

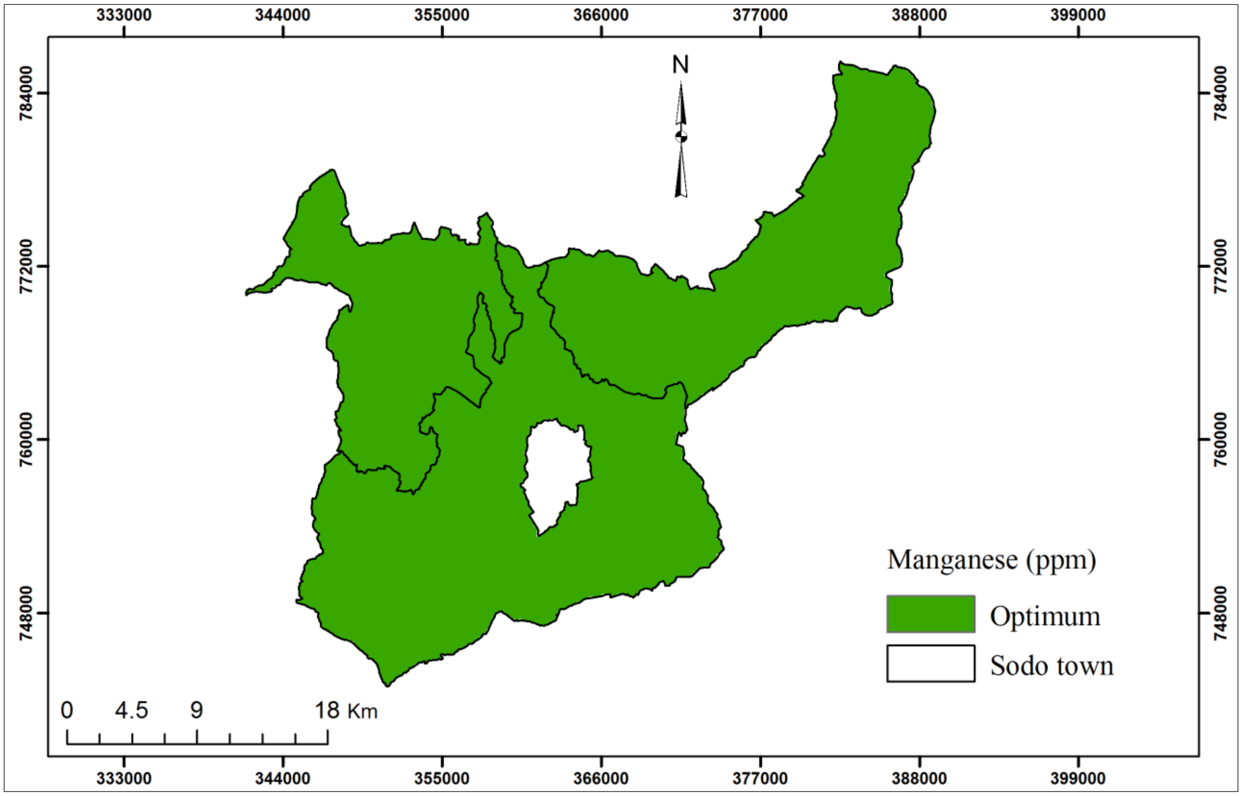

Figure 12: MnAI map of Damot Gale, Damot Sore and Sodo Zuria Districts

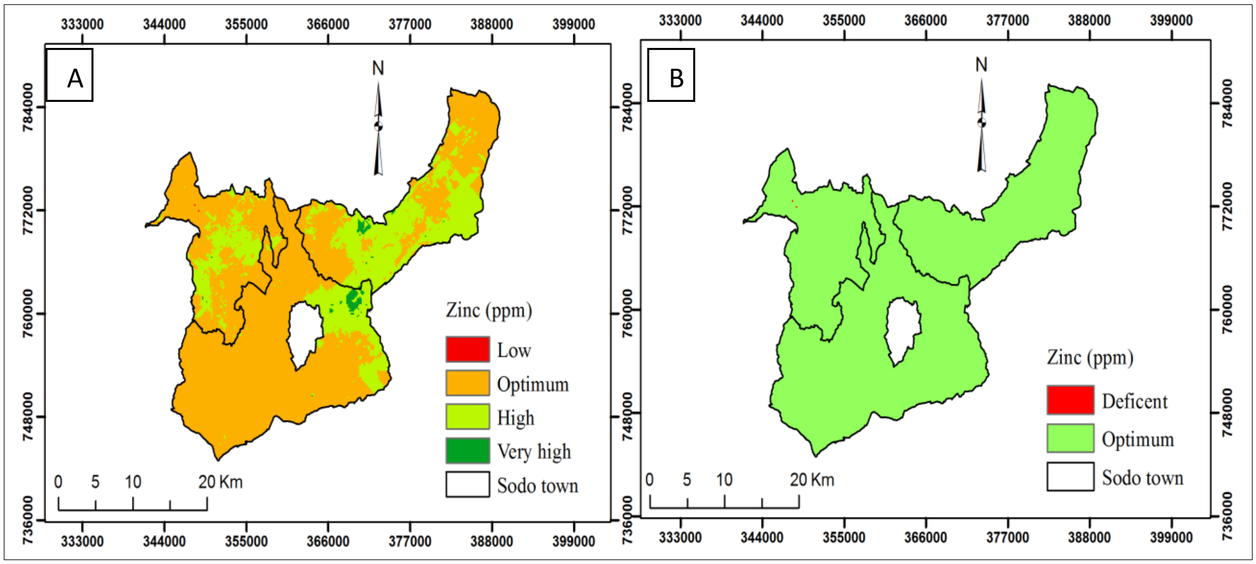

Figure 13: Zinc A) Status and B) Management-Based Map of Damot Gale, Damot Sore, and Sodo Zuria Districts

Discussion

Soil total N includes inorganic and organic N, where the latter is more in proportion. Yet, plants use the inorganic part of N. This implies that the optimum TN cannot be taken as a guarantee from the perspective of plant production. Generally, the lower soil OC content, inadequate and non-balanced use of fertilizers, intensive cropping systems, and N losses through leaching might have resulted in the low level of TN (Fanuel *et al*., 2016a; Patil *et al.*, 2011). Similarly, nutrient mining and low levels of OM application, which were common practices in the study area, might have contributed to the lower TN level (Akhter *et al*., 2010). Differences in soil management might have resulted in high variability in the P concentration. Additionally, deficient levels of P in the soils might be attributed to low levels of P application, uptake through abundant crop harvest, low return of crop residues, and soil erosion (Akhter *et al*., 2010; Fanuel *et al*., 2016a; Birhanu and Chalsissa, 2019). Besides, P availability may be negatively affected on strongly acidic soils due to fixation (Anon, 2003; Birhanu and Chalsissa, 2019). Hence, to secure high crop production, P application in the form of inorganic fertilizers, manure, crop residues, and lime on strongly acidic soils (Table 1) has to be considered in order to supplement the deficient levels of P in the soils.

Apart from N and P deficiencies, the possibilities of Mg-induced K deficiency on 68% of the total area was suspected using K/Mg threshold ratio of < 0.7 (data not included). Similar cases in Ethiopia have been discussed in Hillette *et al*. (2015). The positive response of wheat to K fertilizer application in Wolaita Zone where the soils were suspected of having Mg-induced K deficient has been reported (Mesele, 2019; Tigist *et al*., 2021). Furthermore, the experiment done by Megistu et al. (2021) in Sodo Zuria Woreda of Wolaita Zone also indicated the highest total and marketable carrot root yield of 30.5 t/ha and 24.6 t/ha, respectively from the combined application of 150 kg NPS/ha and 213 kg/ha KCl fertilizers. Thus, considering K along with other limiting nutrients could result yield advantage.

In the exchange site, the basic cations were in the order of Ca > Mg > K. The medium-to-high level of exchangeable Ca can be attributed to the high percentage of clay particles. According to Hazelton and Murphy (2007), about 11% and 64% of the total soil samples (n = 789) had high (40–50%) and very high clay (> 50%) content, respectively. Hence, as the percentage of soil colloids increases, the capacity of the soils to contain exchangeable Ca increases as well (Loide, 2004). The low exchangeable Ca content may be associated with a high level of leaching and a lower soil pH. Hence, the application of Ca fertilizers should be considered in deficient areas. Exchangeable Mg was not a limiting nutrient to crop production, but the moderate status seems to justify that Mg could be a potential problem in the future. Meanwhile, the low S content might be attributed to low soil OM, non-use of S-containing fertilizer, and continuous removal of S by crops (Fanuel et al., 2018a; Fanuel et al., 2016a and b; Pulakeshi et al., 2012). In order to rectify these shortages, the application of S-containing fertilizers is suggested. Besides, the application of OM and the maintenance of crop residues should be integrated.

The CEC ranged from low to high, with the majority being categorized as moderate (Table 1). Spatially, it was found under a moderate variable, which might be attributed to external and inherent factors. In areas where soil OM content is low, the CEC might be controlled by the nature and amount of clay minerals present in the soil (Birhanu and Chalsissa, 2019). Relatively, the moderate to higher percentage of clay particles might have resulted in a medium level of CEC.

The low level of B and Cu in the soil might be attributed to nutrient mining by crops, non-use of B and Cu-containing fertilizers, lower soil OC, and low organic fertilizer application (Fanuel et al., 2018a; Fanuel et al., 2016a). According to Aref (2011), soils low in soil OM are more often deficient in B than soils with high OM content. The presence of Fe-rich parent materials and high dissociation of Fe in acidic soils might be responsible for optimum soil Fe contents. Analogously, Kibet (2013) revealed that the higher Fe content might be linked with parent materials (hematite). Furthermore, Fe deficiency is very unlikely in acid soils (Oyinlola and Chude, 2010), as it is known to be soluble under relatively acidic and reducing conditions. The most probable reason for the high Mn content could be related to the soil's acidic nature, as Mn bioavailability is affected by pH and redox conditions (Karltun et al., 2013). Besides, Zn deficiency is mostly not expected on acidic soil (Aref, 2011).

Conclusion

The results of the study showed that there were low levels of total nitrogen (N), phosphorus (P), potassium (K), sulphur (S), boron (B), and copper (Cu) in the soil, but the spatial content varied across the area. By using digital soil mapping, the area was categorized into different soil management zones. This means that smallholder farmers' fields need specific nutrient interventions tailored to the characteristics of their soil. Thus, implementing site-specific nutrient interventions can help save agricultural inputs and reduce production costs. However, further research is suggested to determine the crop- and variety-specific nutrient application rates for major crops.

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Conflict of interest

The author declares that there is no conflict of interest.

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