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Spatial prediction of soil acidity and nutrients for site-specific soil management in Bedele district, Southwestern Ethiopia

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Abstract

Background: Understanding the spatial variability of soil properties is useful to tailor site-specific agricultural inputs to enhance crop production on a sustainable basis. This study was aimed to assess and map the spatial patterns of soil acidity and nutrients using geostatistical methods and support site-specific lime and fertilizer recommendations in Bedele district, Southwestern Ethiopia.

Methods: Soil samples were collected from agricultural land at a depth of 20 cm using grid sampling technique. The semivariogram analysis was performed for accurate spatial prediction and the kriging technique was used for interpolation of soil parameters.

Results: Soil pH varied between 4.5 and 6.8. Soil organic carbon (OC) content ranged from 0.3 to 5.6% and the mean soil OC density was 0.81 kg m^{-2}. Available phosphorus (AvP) ranged from 0.8 to 38.6 mg kg^{-1} and nearly 80.23% of the soils exhibited very low to low AvP that could be due to fixation by strong acidity. Soils of the study area exhibited very high exchangeable potassium (K), but very low exchangeable calcium (Ca) and magnesium (Mg). The potassium to magnesium ratio (K:Mg) ranged from 0.2:1 to 10.9:1, while the values of calcium to magnesium ratio (Ca:Mg) varied between 0.3 and 3.4. Among the soil parameters, exchangeable Ca (CV = 54%) and K:Mg ratio (CV = 57.62%) were more variable than other soil parameters. Spatial variability was lowest for soil pH (CV = 10%).

Conclusions: Major portions of the study site were affected by strong acidity ($pH \leq 5.5$). Accordingly, about 89% of the soils require lime that varied between 0.09 and 3.6 tons ha^{-1}. In addition to soil acidity, deficiency of available P, Ca, and Mg were the major liming factors affecting crop production in the study area. Digital soil mapping was used to show the spatial variability of soil acidity and nutrients across agricultural land and applied for efficient lime and nutrients advisory works.

Keywords: Spatial variability, Geostatistics, Soil nutrient, Soil acidity, Soil management, Fertilizer, Lime

Background

Declining soil fertility has continued to be a major constraint to food production in many parts of the tropical region [1] and wider areas of sub-Saharan Africa [2–4]. Food production needs to increase to feed the projected 9.3 billion global population and 2.5 billion African population by 2050 [5, 6]. Agriculture plays a central role in both food availability and food quality and is also the main source of income and livelihood for 70–80% of people who currently suffer from hunger in developing countries [7]. In addition to rendering a broad range of other services, soils provide humanity with 98.8% of its food [8]. Many studies reported that the production of food is intrinsically linked to healthy soils and revealed that healthy soils are a prerequisite for sustainable food

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security [6]; healthy soils are the basis for healthy food production and healthy life [9, 10], and healthy soils boost economy [11]. Soil acidification, loss of nutrients, soil erosion, and chemical imbalances present within the soil may lead to crop failure and malnutrition, reducing both the quality and quantity of food available to the rapidly growing population [8, 12].

It is estimated that about 40% of the total arable land of Ethiopia is affected by soil acidity [13]. Of this land area, about 27.7% is moderately acidic (pH in KCl 4.5–5.5) and about 13.2% is strongly acidic (pH in KCl < 4.5). The problem of soil acidity is very severe in southwestern parts of Ethiopia, which receive high rainfall [14]. Soil acidity affects crop production by reducing the solubility of nutrients, toxicities of H, Al, Mn, Fe, and low activities of beneficial microorganisms [15]. Without addressing such soil-related issues, smallholder farmers cannot equitably benefit from yield gains offered by improved plant genetics and other associated agronomic practices [16]. Soil productivity is not only affected by soil-related issues, but also the traditionality of soil management practices, among others. This means that the traditional nutrient applications that did not consider site-specific soil nutrients and crop requirements is the major impediment to crop production. Smallholder farmers in developing countries including the study area apply fertilizers irrespective of the heterogeneity of soil nutrients across farmland [1, 17, 18]. Similarly, variable rate lime application for soils that vary according to soil pH values is rarely used in the region [19]. In this regard, prudent management decisions that entail applications of fertilizers and lime according to the spatial distribution of soil nutrients and pH across a field are vital to boost crop yield and ensure food security on a sustainable basis [20–23].

The current and future food security in sub-Saharan Africa requires the adoption of agricultural technologies that could bring high production from a limited area of land. Innovative forms of precision agriculture that consider the spatial heterogeneity and dynamics of soil systems are used to improve soil productivity [24]. Precision agriculture involves mapping and georeferencing soil information systems including variations in soil pH and soil nutrients. Geostatistics provides methods for mapping soil properties and site-specific nutrient and lime rates. Numerous studies have stated the importance of geostatistical analysis to characterize the spatial variability of different soil properties [25, 26]. Geospatial prediction is the analysis of spatial distribution and variability based on the spatial scale of the study area, the distance between sampling points and their patterns [27]. Among many geostatistical tools, kriging is widely used to map spatial variation of soil properties, and it yields better point estimates of soil properties than other interpolation techniques [28]. The kriging interpolation techniques are widely recognized as important spatial interpolation techniques used to evaluate spatial correlation in soils and to analyze the continuous variability of soil properties in space [29, 30]. Kriging interpolations require the determination of semivariograms, which must be calculated with 100 or more data points [26]. According to [25], geostatistics uses the technique of variogram to measure the spatial variability of a regionalized variable and provides the input parameters for the spatial interpolation of kriging. These technologies allow mapping fields accurately and computing complex spatial relationships between soil acidity and fertility parameters. They help to estimate and tailor agricultural inputs to fit the spatial requirements of soils and crops.

Knowledge about an up-to-date status of soil acidity and nutrients across landscapes and mapping their spatial distribution play a vital role in site-specific lime and fertilizer recommendations to enhance production and productivity of the agricultural sector on a sustainable basis. However, information on the status and spatial distribution of soil acidity and nutrients in the study area is limited. Therefore, the study was aimed to assess, predict and map the spatial patterns of soil acidity and nutrients to support site-specific lime and fertilizer advisory works.

Materials and methods

Study site

The study was conducted in the Bedele district of Oromia regional state situated in Southwestern Ethiopia. The district is located between 8°14′30″N and 8°37′53″N latitude and 36°13′17″E to 36°35′05″E longitude (Fig. 1). The elevation of the study area ranges from 1013 to 2390 m a.s.l. The mean annual precipitation is 1945 mm, while the mean annual minimum and maximum temperatures are 12.9 °C and 25.8 °C, respectively [31]. The study area is classified under the humid agro-ecological zone. The area is characterized by a rugged topography dominated by gentle slopes and localized steep slopes ranging from 2 to 45%. The predominant soil types are Dystric Nitisols in the plateau and side slopes and Leptosols on the steep slope [32]. Mixed farming is the main agricultural activity carried out in the area. The main livelihood strategies in the district include crop production, livestock rearing, and off-farm activities. The major crops grown in the district includes maize (*Zea-maize*), wheat

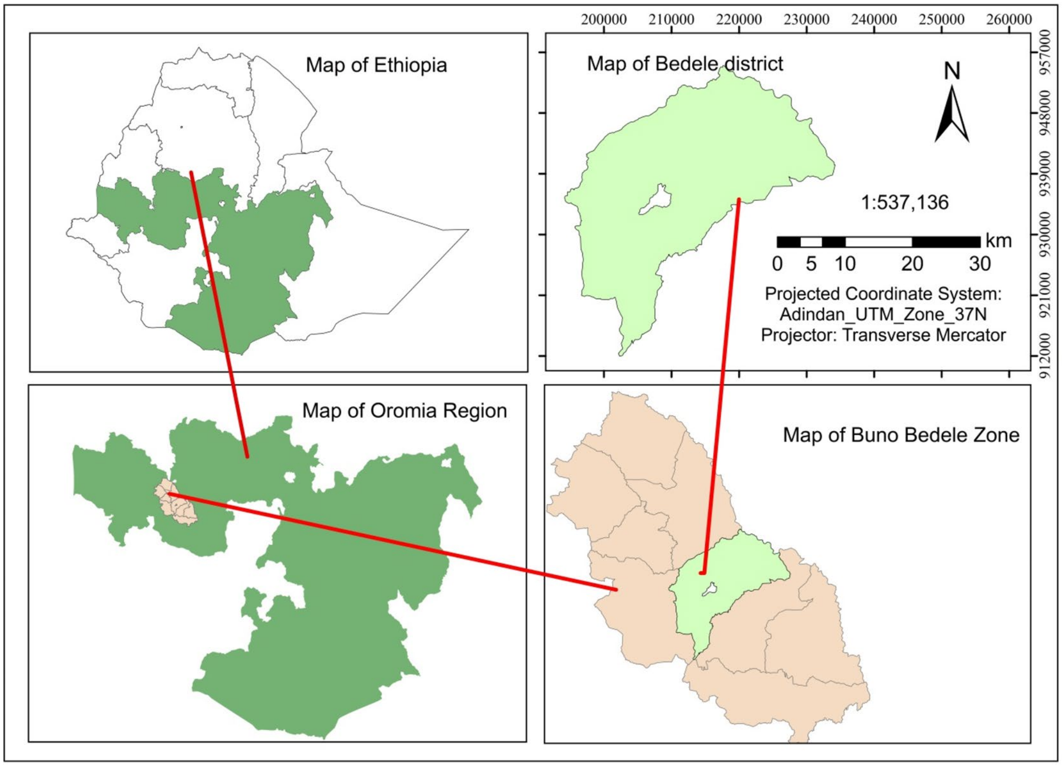

Fig. 1 Location map of the study area

(*Tritium aestivum*), sorghum (*Sorghum bicolor*), finger millet (*Eleusine coracana*), coffee (*Coffee arabica L.*), and teff (*Eragrotis abyssinica*). Pulse crops such as faba bean (*Vicia faba*) and field peas (*Cicer arieinum*) are also grown in selected areas. Generally, the study covered a total area of 74468.50 hectares of land. Bedele district has an estimated population density of 83.1 people per square kilometer [33].

Soil survey and sampling

A base map of the study area was prepared by overlaying a 30 × 30 m resolution LANDSAT and Google-Earth imagery. The tentative sampling points were distributed at 1.5 km × 1.5 km grid intervals throughout the district using ArcGIS 10.2 software and predefined sampling points were prepared on the base map with 1:50,000 scale. The tentative sampling points that fall out of agricultural lands were excluded and the predefined sampling points that fall in agricultural lands were surveyed. After locating the grid points by global positioning system (GPS), 15–20 subsamples were collected using an auger to a depth of 20 cm and mixed to make a composite sample for each grid point. Grid points were made flexible in case the predefined sampling points fall in inaccessible and non-representative areas. In this case, samples were systematically collected from representative areas and GPS coordinates of the sampling points were recorded. Accordingly, a total of 132 composite soil samples were collected from agricultural lands in the district (Fig. 2). Soil-landscape information such as texture, soil depth, geographical coordinates, topography, and waterlogging condition were described at each sampling plot. Soil samples were air dried and crushed to pass through a 2 mm sieve size according to the procedure outlined by [34].

Soil analysis

Particle size distribution was determined by the Bouyoucos hydrometer method [35]. Soil pH was measured potentiometrically in 1:1.25 soil to water suspensions [36]. Exchangeable acidity was determined by titration with sodium hydroxide (NaOH) [37]. Soil OC was determined using the wet oxidation method [38]. Total N was determined by Kjeldhal method [39], while available P was extracted by Olsen method [40]. Cation exchange capacity (CEC) was determined by ammonium acetate method [41]. Among exchangeable bases, Ca^{2+} and Mg^{2+} in the original ammonium acetate leachate were measured by atomic absorption

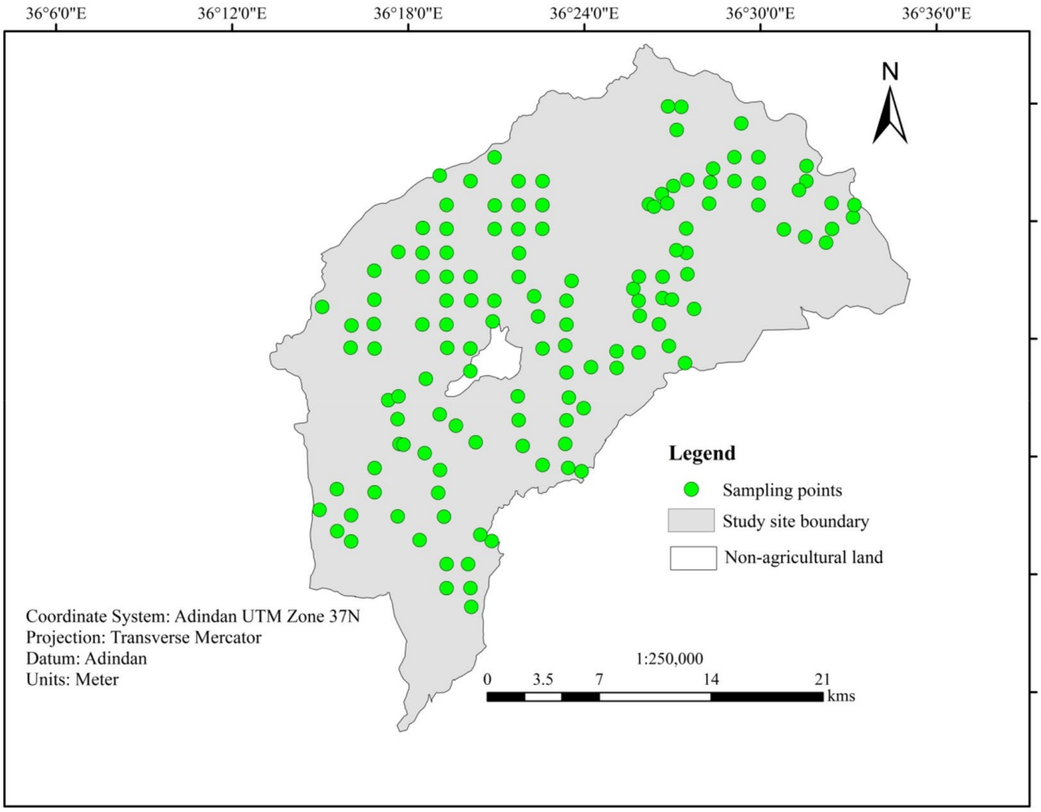

Fig. 2 Spatial distribution of the actual soil sampling points in the study site

spectrophotometer, whereas exchangeable K^+ and Na^+ were read using flame photometer [42].

Lime rate estimation and soil nutrient diagnosis techniques

The lime requirement of the soils was estimated based on the logic of permissible acid saturation (PAS) interim of crops developed by [43] for Ethiopian soils. Besides, based on [44], a modified lime requirement factor of 1160 kg lime ha^{-1} $cmol_c{}^{-1}$ and PAS of 10% was applied for Ethiopian soils to estimate the lime requirement rate as follows:

$$LR = 1160\,(EA - (ECEC * PAS)), \tag{1}$$

where LR is the recommended lime rate (kg ha^{-1}), EA is the exchangeable acidity ($cmol_c$ kg^{-1}), ECEC is effective cation exchange capacity ($cmol_c$ kg^{-1}), and PAS is the permissible acid saturation specific for the type of crop in percent (%).

Critical values of soil parameters adopted by scholars were used to giving ratings and judge the acidity and fertility status of soils. The threshold values of soil nutrients were used as baselines for general nutrient or fertilizer recommendation works.

Statistical and geostatistical analyses

Descriptive statistics such as mean, minimum and maximum, standard deviation, coefficient of variation, skewness, and kurtosis were calculated for measured soil variables. Principal component analysis (PCA) was used to see the relationship between soil parameters (the components) using XLSTAT 2017 software. Pearson correlation coefficient among soil fertility parameters was calculated from soil sample data at a significance level of 0.05 using XLSTAT 2017 software. The semivariogram model of geostatistics was used to measure the spatial variability of a regionalized variable and to generate the input parameters for the ordinary kriging method of spatial interpolation. The semivariogram is half of the expected squared difference between paired data values Z(x) and Z(x + h) to the lag distance h by which locations are separated [25] and defined as:

$$\gamma(\mathrm{h}) = \frac{1}{2\mathrm{N(h)}} \sum_{i=1}^{N(h)} [(\mathrm{Zi}) - (\mathrm{Zi} + \mathrm{h})]^2, \tag{2}$$

where $\gamma(\mathrm{h})$ = Semivariance for interval distance class (h), $\mathrm{Z_i}$ = measured sample value at point *i*, Z_{i+h} = measured sample value at point $i+h$, and N (h) = total number of sample couples for the separation interval *h*.

The interpolation of data at unsampled locations was performed using the ordinary kriging interpolation method in ArcGIS 10.2 software [45] to obtain a probability map of the soil fertility parameters. The basic equation for interpolation by kriging at an unsampled location $\mathrm{S_0}$ is given by:

$$\hat{\mathrm{Z}}(\mathrm{S_O}) = \sum_{i=1}^{n} \lambda_\mathrm{i} \mathrm{Z}(\mathrm{S_i}), \tag{3}$$

where $\mathrm{Z(S_i)}$ is the measured value at the ith location, λ_i is an unknown weight for the measured value at the ith location, $\mathrm{S_0}$ is the prediction location and *n* is the number of measured values. Then, the spatial distribution maps were prepared at 1:50,000 resolutions.

Results

Descriptive statistics for soil acidity and nutrients

Data presented in Table 1 shows the measured value statistical summary for soil properties at sampled locations. The mean measured clay content was 44% with a maximum value as high as 72% (Table 1). This shows the soils were dominated by clay and clay loam. The mean measured value of soil pH at sampled locations was 5.3 with a standard deviation of 0.53, indicating a tight cluster of values around the mean (Table 1). The lowest coefficient variation (CV) was recorded for soil pH (Table 1). The minimum soil pH was 4.5, while the maximum pH value was 6.8. The minimum and maximum values of exchangeable acidity (EA) were 0.1 and 5.1 $\mathrm{cmol_c\ kg^{-1}}$, respectively, with a mean value of 1 $\mathrm{cmol_c\ kg^{-1}}$. Higher values of exchangeable acidity were recorded for samples containing lower soil pH.

The OC content of the soils ranged from 0.3 to 5.6%, with a mean value of 0.28%. The OC content showed a skewness value of − 0.58 and kurtosis of 3.20 (Table 1). The distribution of OC values was moderately skewed to the left. The total N content of the soils ranged between 0.03 and 0.48%. Available P content ranged from 0.8 to 38.6 mg $\mathrm{kg^{-1}}$. Its mean value was 6.2 mg $\mathrm{kg^{-1}}$. The CV of available P was 45.16%, showing high variability across agricultural soils of the study area. This indicates variable rate applications of P fertilizers according to the field variability of P nutrient could improve crop production.

Exchangeable Ca in soils of the study area ranged from 0.3 to 3.2 $\mathrm{cmol_c\ kg^{-1}}$, whereas the exchangeable Mg ranged from 0.2 to 2.2 $\mathrm{cmol_c\ kg^{-1}}$. Both exchangeable Ca and Mg showed high CV (Table 1). The minimum and maximum value of exchangeable K was 0.3

Table 1 Statistical values of selected soil acidity and fertility parameters (*n* = *132*)

Variables	Statistics						
	Min	Max	Mean	SD	CV (%)	Skewness	Kurtosis
Clay (%)	14	72	44	11.78	26.77	0.24	2.49
Silt (%)	8	34	20	5.04	25.20	− 0.14	3.11
Sand (%)	10	68	36	12.85	35.69	− 0.19	2.36
pH ($\mathrm{H_2O}$)	4.5	6.8	5.3	0.53	10	0.67	2.83
EA ($\mathrm{cmol_c\ kg^{-1}}$)	0.1	5.1	1	0.39	39	1.04	2.96
OC (%)	0.3	5.6	3.3	1.03	31.21	− 0.58	3.20
TN (%)	0.03	0.48	0.28	0.09	32.14	− 0.57	3.18
Av. P (mg $\mathrm{kg^{-1}}$)	0.8	38.6	6.2	2.80	45.16	1.07	3.78
Ex. Ca ($\mathrm{cmol_c\ kg^{-1}}$)	0.3	3.2	1	0.54	54	0.96	4.14
Ex. Mg ($\mathrm{cmol_c\ kg^{-1}}$)	0.2	2.2	0.9	0.37	41.11	0.76	3.77
Ex. K ($\mathrm{cmol_c\ kg^{-1}}$)	0.3	4.5	1.5	0.74	49.33	0.59	3.65
Ex. Na ($\mathrm{cmol_c\ kg^{-1}}$)	0	1.5	0.1	0.03	30	0.58	2.64
CEC ($\mathrm{cmol_c\ kg^{-1}}$)	2.6	35.3	14.2	5.42	38.17	0.63	4.42
Ca:Mg	0.3	3.4	1.3	0.43	33.08	0.76	2.68
K:Mg	0.2	10.9	2.1	1.21	57.62	1.00	3.72

Min minimum, *Max* maximum, *SD* standard deviation, *CV* coefficient of variation, *EA* exchangeable acidity, *OC* organic carbon, *TN* total nitrogen, *Av. P* available phosphorus, *Ex. Ca* exchangeable calcium, *Ex. Mg* exchangeable magnesium, *Ex. K* exchangeable potassium, *Ex. Na* exchangeable Na, *CEC* cation exchange capacity, *Ca:Mg* calcium to magnesium ratio, *K:Mg* potassium to magnesium ratio and 4.5 cmol$_c$ kg^{-1}, respectively. Exchangeable Na is not a plant nutrient. The values of exchangeable Na fall in the range of 0 to 1.5 cmol$_c$ kg^{-1}, indicating lower Na contents that have no adverse effect on the growth of crops and physical properties of the soil. The CEC of the soils ranged from 2.6 to 35.3 cmol$_c$ kg^{-1} (Table 1). The potassium to magnesium ratio (K:Mg) ranged from 0.2:1 to 10.9:1 (Table 1), but the values of calcium to magnesium ratio (Ca:Mg) varied between 0.3 and 3.4. The Ca:Mg ratio of the soils presented in Table 1 was less than the critical value of 4–6, suggesting the presence of Mg-induced Ca deficiency. The skewness values of all soil fertility parameters ranged between − 1 and + 1 as indicated in Table 1, except for EA and available P which showed very slight deviation.

There was positive and significant correlation between available P and pH ($r^2 = 0.57$, $p < 0.05$) (Table 2). This shows that at low pH values ($pH \leq 5.5$), there could be a reduction in available P due to fixation by aluminum (Al) and hydrogen (H) ions in acid soils. A very significant and positive correlation was observed between soil OC and total N ($r^2 = 0.99$ at $p < 0.05$). A significant, but negative correlation was seen between CEC and sand fractions in soils of the study area ($r = -0.32$ at $p < 0.05$) (Table 2).

Semivariogram modeling

The results of semivariogram modeling and the best fitted model for selected soil properties was presented in Fig. 3. In this study, the semivariogram models were developed from stable, spherical, exponential, and Gaussian functions. An analysis of the semivariance shows that the lowest range of spatial autocorrelation was obtained in the case of the Gaussian model for soil pH, TN, exchangeable Mg, and exchangeable Ca; spherical for OC and exchangeable K; stable for available P; and exponential for CEC (Table 3). The spherical nature of the fitted semivariogram suggests a constant pattern of variation for soil variables at the study site. The nugget to sill ratio for fitted semivariogram soil parameters was lowest for available P (zero) and the highest for exchangeable Mg (0.684) (Table 3). Nugget to sill ratio indicates what percent of the overall variance is found at a distance smaller than the smallest lag interval and gives a sense of how much variance is successfully accounted for in the model.

Mapping the spatial variability of soil pH and nutrients

The soil properties' spatial distribution maps that were generated based on the measured data and fitted semivariograms are shown below. A major portion (62.61%) of the soils of the study area exhibited strong acidity ($pH \leq 5.5$) (Table 4) and its spatial distribution is shown in Fig. 4. Only 11% of the soils showed pH in the range of being trouble-free for agricultural purposes (5.8–7.5), indicating more than 89% of the soils require acidity management practices (Table 4). Low soil pH values were observed at higher altitude where intensive cultivation was practiced, while higher values were observed at a lower altitude. The exchangeable acidity (Al + H) of the soils varied from 0.1 to 5.1 cmolc kg^{-1} for those soils with pH values ≤ 5.5 (Table 1). Our results indicated that soils with $pH > 5.5$ have no exchangeable acidity.

Nearly 54653.81 ha of land or 73.39% of the soils in the study site showed low (2–4%) OC content (Table 4) and its spatial distribution is shown

Table 2 Pearson correlation matrix among soil fertility parameters

Variables	Clay	Silt	Sand	pH	EA	OC	TN	P	CEC	Ex. Ca	Ex. Mg	Ex. K
Clay												
Silt	0.01											
Sand	**− 0.92**	**− 0.40**										
pH	**0.21**	**0.31**	**− 0.32**									
EA	− 0.03	**− 0.21**	0.11	**− 0.68**								
OC	**0.19**	0.11	**− 0.22**	0.02	0.17							
TN	**0.19**	0.11	**− 0.22**	0.02	0.17	**0.99**						
P	− 0.14	**0.30**	0.01	**0.57**	**-0.31**	− 0.01	− 0.01					
CEC	**0.23**	**0.30**	**− 0.32**	**0.26**	− 0.07	0.12	0.12	**0.25**				
Ex. Ca	**0.28**	**0.34**	**− 0.39**	**0.58**	**− 0.48**	0.02	0.02	**0.32**	**0.71**			
Ex. Mg	− 0.09	-0.13	0.13	− 0.06	0.12	− 0.08	− 0.07	0.02	**0.21**	**0.23**		
Ex. K	0.01	0.08	− 0.04	**0.39**	**− 0.45**	0.11	0.11	**0.35**	0.10	0.14	− 0.09	
Ex. Na	− 0.04	0.13	− 0.02	**0.26**	− 0.15	0.04	0.04	− 0.01	0.14	**0.31**	0.04	− 0.07

Values in bold are significantly correlated at significance level < 0.05

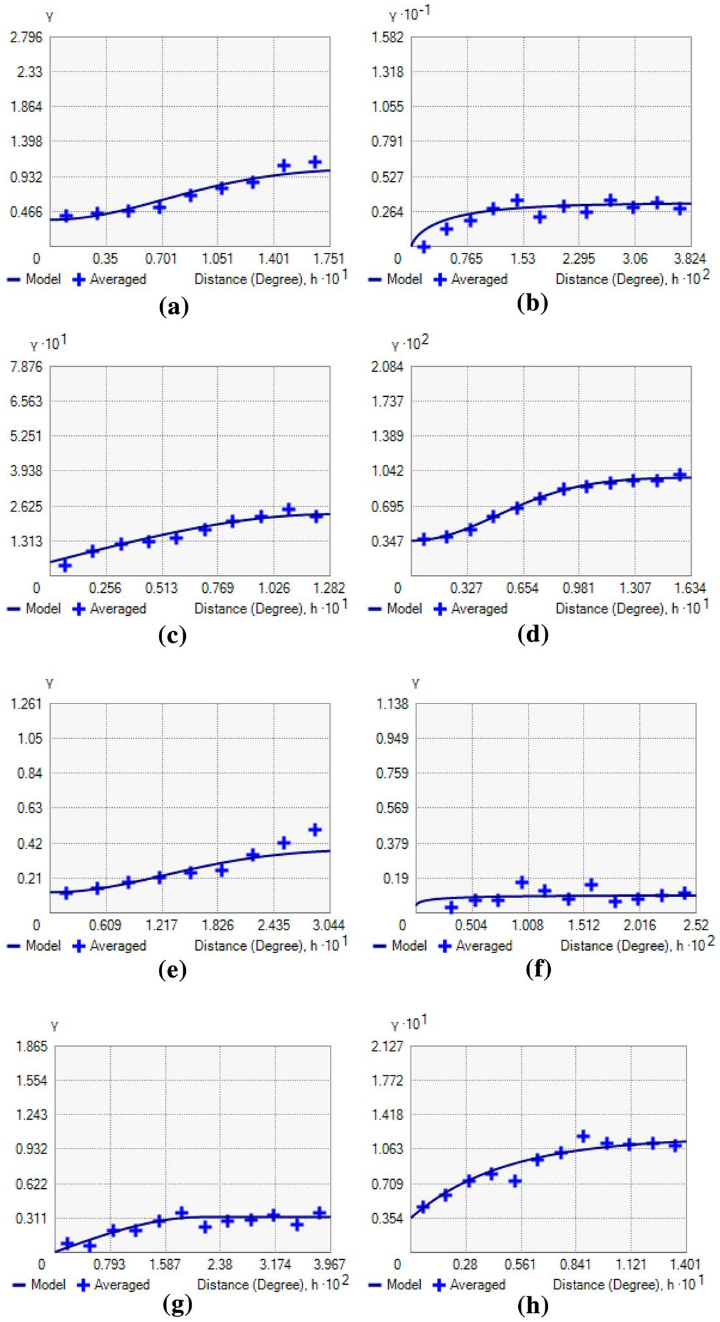

Fig. 3 Fitted semivariogram model for soil properties: **a** pH, **b** available P, **c** organic carbon, **d** total nitrogen, **e** exchangeable calcium, **f** exchangeable magnesium, **g** exchangeable potassium, and **h** cation exchange capacity (distance is according to degree)

in Fig. 5a. We found a mean soil OC density of 0.81 kg m^{-2} within the upper plow layer (20 cm). In highland parts of the study site, a comparatively maximum OC density of 1.39 kg m^{-2} was recorded to a depth of 20 cm. The low level of soil OC in the soils was attributed to erosion and low addition of carbon sources to the soil systems. Coupled with natural processes, anthropogenic factors such as complete removal of crop residues and aboveground biomass (for energy, animal feed, construction) are the main causes for low soil OC in agricultural soils of Ethiopia. The reduced soil OC content might also be caused by

Table 3 Fitted semivariogram models for soil variables and estimates of model parameters

Soil variables	Model fit	Estimates of parameters			Nugget/sill ratio
		Nugget	Sill	Range	
pH	Gaussian	0.357	0.692	0.175	0.515
OC	Spherical	0.052	0.179	0.128	0.289
TN	Gaussian	0.003	0.006	0.121	0.500
AvP	Stable	0	3.292	0.024	0
Ex. Mg	Gaussian	0.039	0.057	0.015	0.684
Ex. K	Spherical	0.006	0.314	0.021	0.019
Ex. Ca	Gaussian	0.124	0.262	0.304	0.473
CEC	Exponential	0.036	0.083	0.140	0.434

Table 4 Areal extent of the different classes of soil properties in the study site

Soil parameters	Ratings	Area (ha)	Area (%)
Soil pH	4.5–5	28825.68	38.71
	5.0–5.5	17796.10	23.90
	5.5–6.0	22286.75	29.93
	6.0–6.8	5559.97	7.47
OC (%)	< 2	9333.30	12.53
	2–4	54653.81	73.39
	4–5	10481.39	14.07
TN (%)	< 0.15	6556.73	8.80
	0.15–0.25	9527.29	12.79
	> 0.25	58384.48	78.40
AvP (mg kg^{-1})	< 5	37893.48	50.89
	5–10	21852.12	29.34
	10–15	10251.43	13.77
	15–20	4037.45	5.42
	> 20	434.02	0.58
Ex. K ($cmol_c$ kg^{-1})	0.7–2.0	63409.09	85.15
	> 2.0	11059.41	14.85
Ex. Ca ($cmol_c$ kg^{-1})	0–2	67089.33	90.09
	2–4	7379.17	9.91
Ex. Mg ($cmol_c$ kg^{-1})	< 0.3	21.12	0.03
	0.3–1	49964.97	67.10
	1–3	24482.41	32.88

a warmer climate, which enhances the rapid rate of mineralization. However, when converted to soil carbon stock (tons), the wider areas of the cultivated land store a significant amount of carbon and needs to be carefully treated.

Nearly 91.2% of the area showed TN greater than or equal to 0.15% (Table 4 and Fig. 5b). This shows that only 8.8% of the soils in the study area exhibited low total N (< 0.15%). So, optimum N fertilizer rate could be recommended based on the critical value of total N in soils depicted during the present study and crop response to different rates of N fertilizers. The available P content of nearly 80.23% of the soils was in the very low (< 5%) and low (5–10%) categories. Only 6% of the soils exhibited high available P and the rest were in the medium range (Table 4). The spatial variability of Av.P is indicated in Fig. 6a. Relatively higher available P values were observed in areas where soil pH was relatively higher (slightly acidic) because most plant nutrients are fixed when the soil pH is less than 5.5. Available P was deficient and among the factors that were highly limiting the productivity of the soils in the study area. The low available P in soils of the district might be due to low soil organic matter (SOM) status. Similar to N, the P fertilizer application rates could depend on the critical values of soil test P and crop response to P fertilizer applications. Soil test-based formulation of blended and compound fertilizers would be ideal to correct such soils having a broad spectrum of nutrient deficiencies. All soils in the total study area exhibited high and very high values of exchangeable K (Table 4 and Fig. 6b). This implies that K was not the limiting nutrient in the study site.

About 90.09% of soils of the study area showed very low (< 2 $cmol_c$ kg^{-1}) exchangeable Ca, while the remaining portion of the study site showed 2–4 $cmol_c$ kg^{-1} (Table 4 and Fig. 7a). On the other hand, 67.12% of the study area showed low or deficiency of exchangeable Mg (Fig. 7b). Only 0.03% (21.12 ha) of soils in the study site exhibited < 0.3 $cmol_c$ kg^{-1} of exchangeable Mg. Except for exchangeable K, all exchangeable bases were comparatively low. This might be attributed to low OC content and removal of the exchangeable bases by erosion and leaching. Unless nutrient retention mechanisms are enhanced through the addition of organic materials, leaching loss of exchangeable cations could lead to further deficiencies.

Site-specific lime recommendation

Though some plant species tend to tolerate some levels of soil acidity, strongly acidic soils are usually managed using lime. Using a crop tolerance level of 10% for annual crops as recommended for Ethiopian soils, the lime rate presented in Fig. 8 was developed for soils of the study area. Lime requirements of the soils varied across the agricultural field. The estimated lime rate ranged from 0.09 to 3.6 tons ha^{-1}. Nearly 15.22% (11337.34 ha) of the study area required

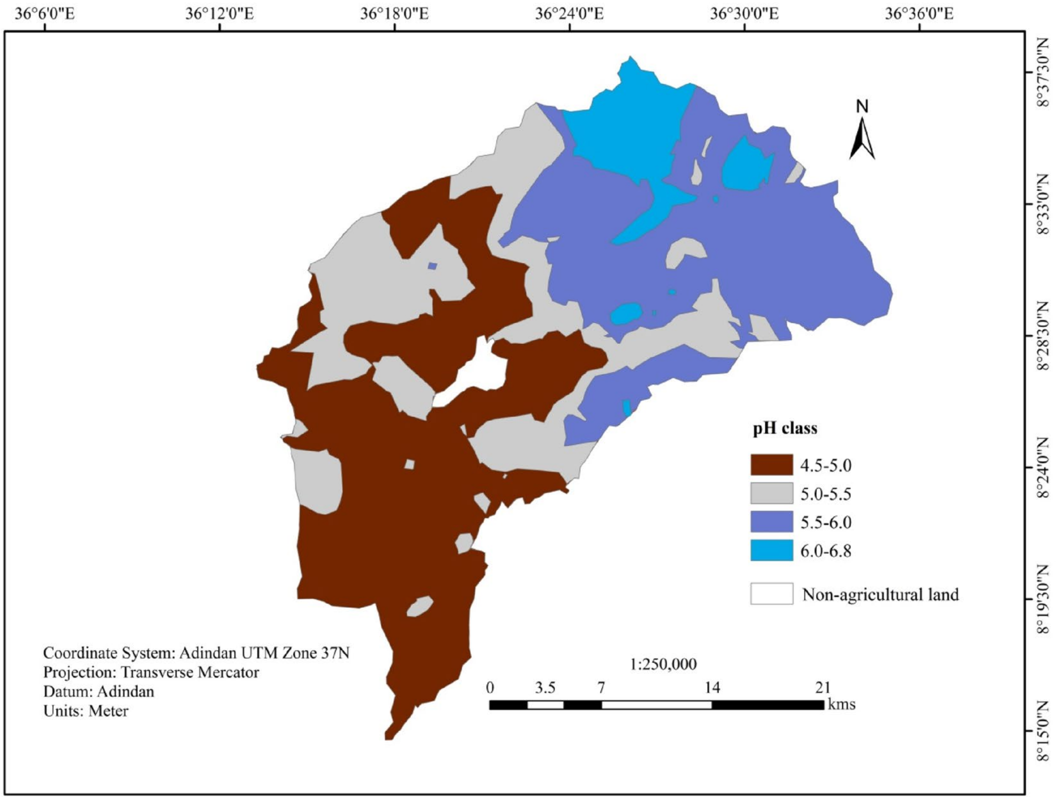

Fig. 4 Spatial patterns of surface soil pH in the study area

more than 2 tons ha^{-1} lime. A major portion of the study area (61.03%) or 45446.13 ha needs less than 1 ton ha^{-1} lime. The remaining portion of the study area (23.75%) needs 1–2 tons ha^{-1} lime. The lime rate increased when soil pH decreases as observed from the relation between pH map (Fig. 4) and lime rate map (Fig. 8). The highest estimated lime rate of 3.6 tons ha^{-1} was recommended for areas exhibiting the highest values of exchangeable acidity (5.10 $cmol_c$ kg^{-1}), indicating all farmers residing in this area are needed to apply 3.6 tons ha^{-1} of lime, at this moment.

However, the level of soil acidity may fluctuate with time depending on the management practices and environmental factors and thus alters the lime requirement of the area at other times. Otherwise, it should be known that farmers residing in areas where exchangeable acidity was high are generally in a risk zone for low pH and they are advised to test the soil by collecting reference samples and lime according to the test result in the future. Agricultural officers and extension agents are also advised to allocate more amount of lime for these farmers, whereas farmers residing in areas where exchangeable acidity was 0.08 $cmol_c$ kg^{-1} can optimize crop yield by growing acid-tolerant crop varieties without lime.

The exchangeable Ca value of the soils was below the critical level of 5 $cmol_c$ kg^{-1}—a value that is considered to be adequate for the nutrition of most crops. Magnesium deficiency was the other problem in the soils of the study area. This indicates that more Ca and Mg are required as a production input and the response to Ca and Mg application in the form of lime more likely increases productivity. In general, spatial variability of soil acidity and nutrients across the agricultural field of the study area suggested the need for variable rate lime and fertilizer applications.

Discussion

Based on acidity classes established by [46], the soils of the study area ranged from slightly acidic to very strongly acidic. This could be due to very low exchangeable bases (Ca, Mg, K, Na) caused by the leaching and weathering of acidic igneous granites [47]. Considering the optimum pH for many plant species was 5.5 to 6.8 [48] and the absence of free

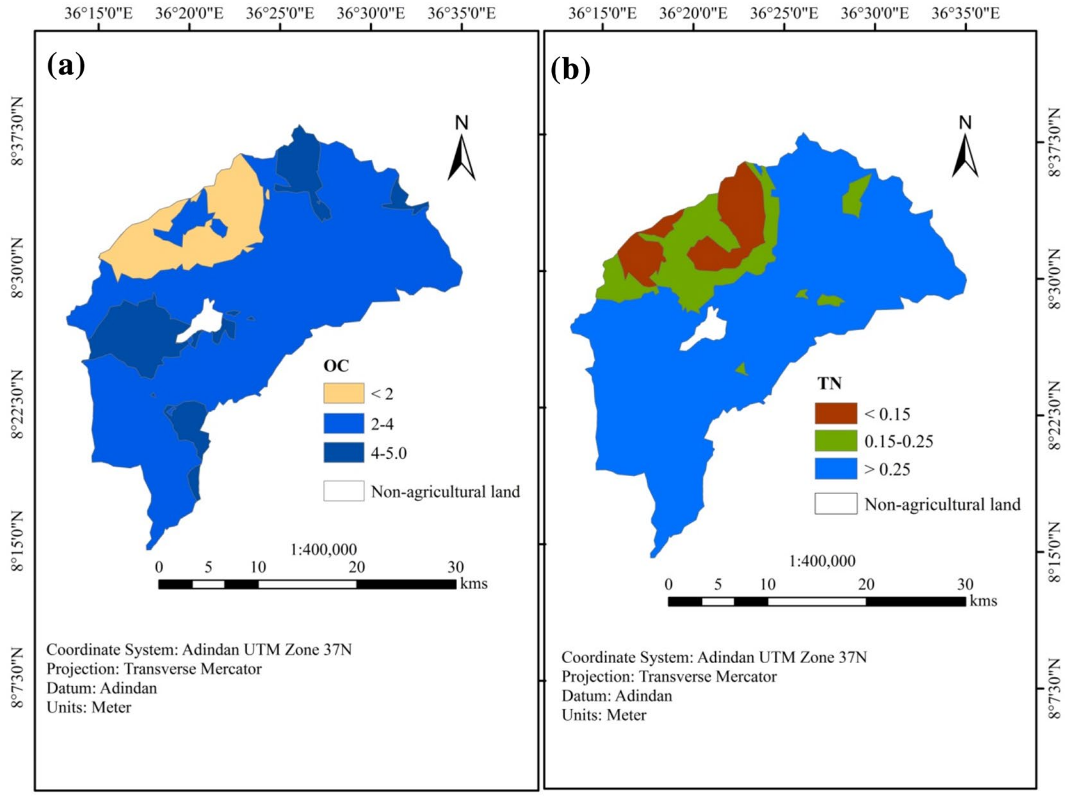

Fig. 5 Spatial patterns of **a** soil organic carbon (%) and **b** total nitrogen (%) across agricultural lands in the study area

exchangeable aluminum (Al) was in this range, only 31% of the pH of the soils in the study area was suitable for most crop production. This has multiple implications for plant growth and other soil fertility issues including reduced response to ammonium phosphate and urea fertilizers, stunted root and plant growth due to nutrient deficiency (yields frequently reduced), increased incidence of disease, and Mn toxicity (e.g., black spots and streaks observed on the leaves). The problems of acid soils are high acidity and low amount of exchangeable cations, especially calcium that would reduce soil fertility and in turn affect crop productivity [49]. The productivity of slightly acidic soils might be improved by the application of chemical amendments, but still they could be cultivated only by growing relatively more acid-tolerant crop varieties. Crops that have a high crop tolerance level reduce lime requirement [50, 51]. Improving the organic matter content of soils may also help to reduce the amount of lime required to neutralize exchangeable acids, because organic materials act as chelators and form stable organo complexes with H^+ and Al^{3+} ions decreasing their release to the soil solution.

The carbon content of the present study soils can be considered low based on [52] ratings. The mean soil OC density estimated for arable soils during the present study was smaller than that of the Kocaeli–Kartepe district in Turkey (3.85 kg m^{-2} to a depth of 20 cm) reported by [53]. The mean soil OC of 5.1 kg m^{-2} reported for conventionally cultivated land at 20 cm depth in Inner Mongolia of North China [54] is also higher than the value obtained during the present study. Limited crop rotation practices, use of crop residues for energy, animal feed, construction, etc., and slash and burn, which are the common practices in Ethiopia, contributed to the depletion of soil OC [55]. The mono-cropping system in the study area also resulted in apparently low soil OC similar to the findings of [56]. So, we suggest that the OC sequestration condition of the soils can be improved by using manures, cover crops, and green manures, and avoiding slash and burn practices. Besides, controlled grazing and subsequent incorporation of crop residues into the soils could also increase the carbon content of the soils. Such carbon management practices should not be only seen as a means of improving soil

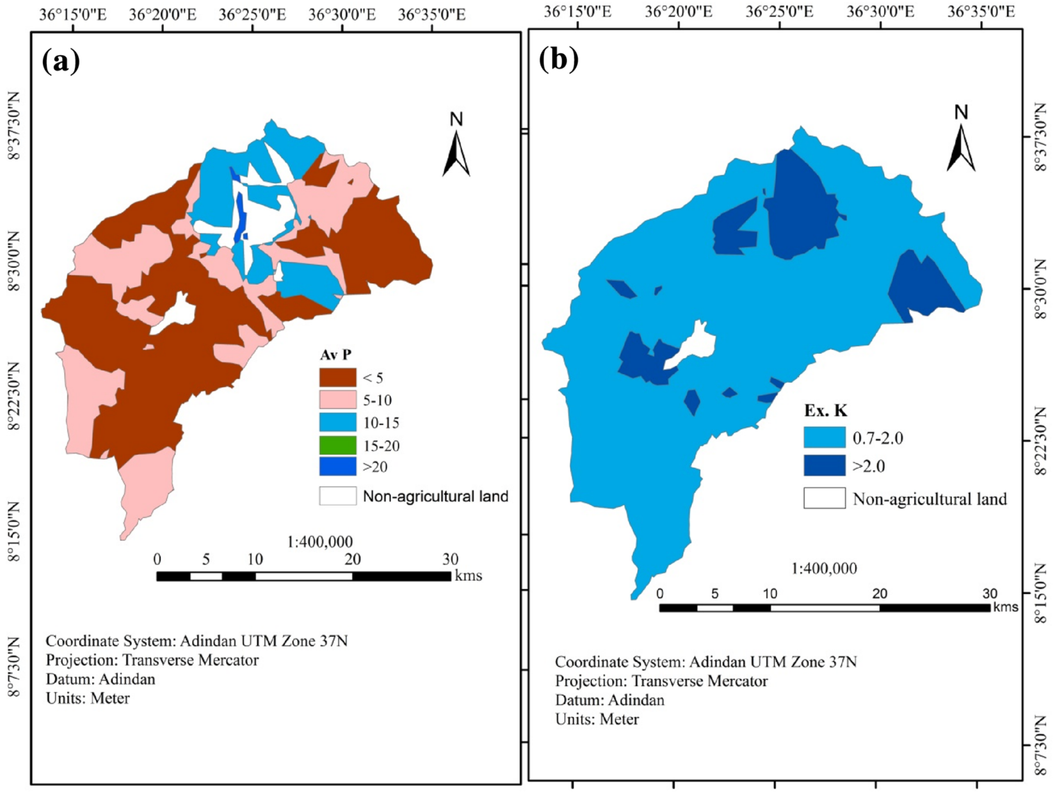

Fig. 6 Spatial distribution of **a** available phosphorus (mg kg^{-1}) and **b** exchangeable potassium (cmol$_c$ kg^{-1}) across agricultural field

property, but also reducing carbon emission to the atmosphere. More than 90% of the soils in the study area apparently had total N (> 0.15%) and thus considered above optimum according to a critical value set by [57].

Available P was the major limiting nutrient in soils of the study area. Based on the threshold level set by [57], more than 89% of the soils were deficit in available P. In agreement with this observation, researchers including [58, 59] have reported that soil P deficiency is a widespread phenomenon and it is believed to be the second most important soil fertility problem throughout the world next to N and often the first limiting element in acid tropical soils. Research reports in Ethiopia showed SOM as the main source of available P [60] and the availability of P in most soils of Ethiopia declined by the impacts of fixation, soil disturbance, and low soil OC caused by abundant crop harvest and erosion [61].

According to [62], the exchangeable K was rated as high to very high. However, exchangeable Ca was entirely low leading to Ca deficiency and imbalance between Ca and Mg. Exchangeable Mg of greater than 1 cmol$_c$ kg^{-1} is believed to be adequate for plant nutrition [62]. Plants produce higher yields at Ca:Mg ratio closer to 4–6:1 [63] and K:Mg ratio of 0.7:1 in acidic soils [64]. The K:Mg ratio less than 0.7:1 indicates the presence of Mg-induced K deficiency based on the rating of [64] and [65]. This can be corrected by K fertilizer application to bring the K to Mg ratio closer to 0.7:1. There was also K-induced Mg deficiency in the study area where K:Mg ratio was greater than 0.7:1, indicating the need for Mg in the soils. Generally, soil K information alone may not be adequate to predict K response. Nearly 37% of the soils in the study area showed low CEC (< 12 cmol$_c$ kg^{-1})—below a critical value set by [66]. Though the soils were dominated by clay fractions, only 4.5% of the soils exhibited high CEC. This could be due to the leaching of bases and low SOM content. Generally, the acidic nature of soils in the study area led to complex nutritional disorders.

The semivariogram measures the suitability of a given model to run kriging. The nugget to sill ratio was used as a criterion for classifying the spatial dependence of soil properties. The variable has strong spatial dependence if it has a low nugget to sill ratio (< 25%) indicating a large part of the variance is

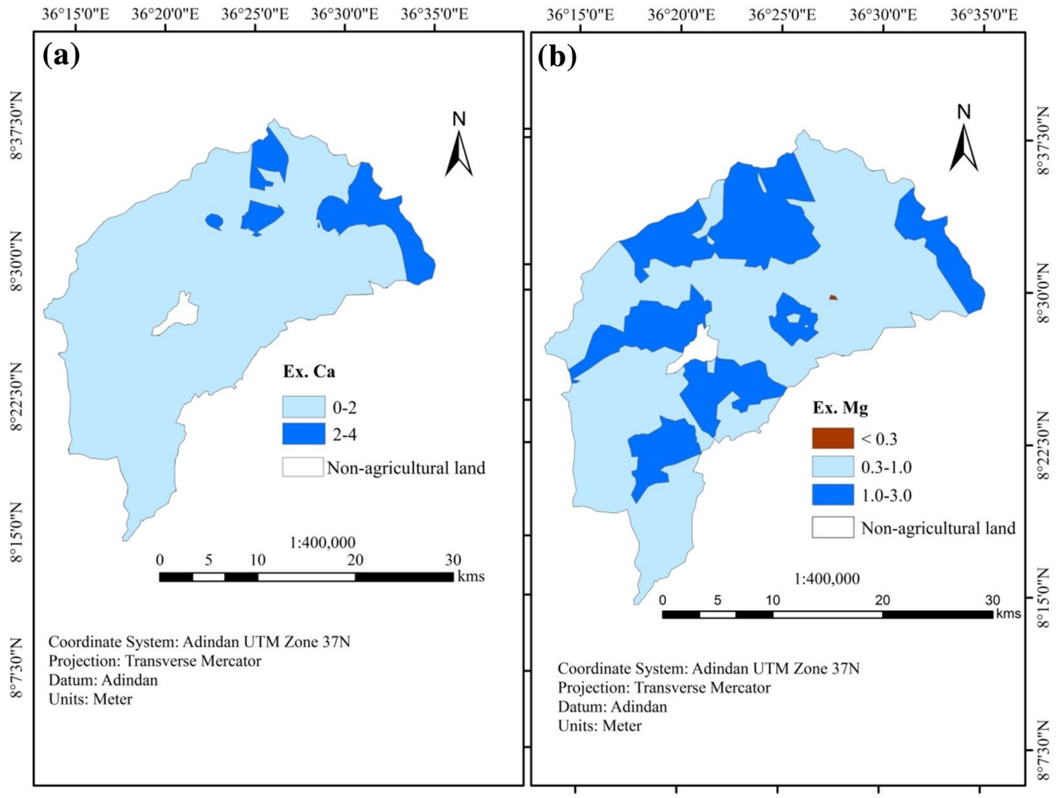

Fig. 7 Spatial patterns of **a** exchangeable calcium and **b** magnesium across agricultural field

introduced spatially: between 25 and 75% indicates that the variable has moderate spatial dependence and a high ratio (> 75%) often indicates weak spatial dependency [67]. A value close to 0% indicates that the variable has a strong spatial auto-relationship, while that close to 100% indicates spatial heterogeneity is dominated by randomness or nugget effect [68]. Based on nugget/sill ratio, the spatial structure and degree of spatial correlation are strong for available P and K, but moderate for pH, TN, OC, Ca, Mg and CEC; therefore, the predicted maps have acceptable accuracy [69].

Conclusions

The spatial patterns of soil acidity and nutrients are useful for site-specific decision-making in lime and fertilizer management. Nearly 62.61% of the soils in the study site exhibited strong acidity ($\mathrm{pH} \leq 5.5$). Meanwhile, 89% of the soils require lime that varied between 0.09 and 3.6 tons ha^{-1}. Deficiency of available P, Ca, and Mg was also a major limiting factors affecting crop production in the study area. The OC density in the soils of the study area was very low. These all led to unfertile soils negatively affecting crop production and food security in the region. Geospatial models helped to estimate and tailor agricultural inputs based on spatial variability and site-specific requirement of soils. This technique could avoid unnecessary and uniform applications of inputs over farmlands and thus minimize farm costs. The productivity of acid soils with broad nutrient deficiencies could be improved by applying the right type and amount of lime and blended fertilizers. Our research findings suggest precision agriculture whereby every soil management decision depends on the spatial variability of soils.

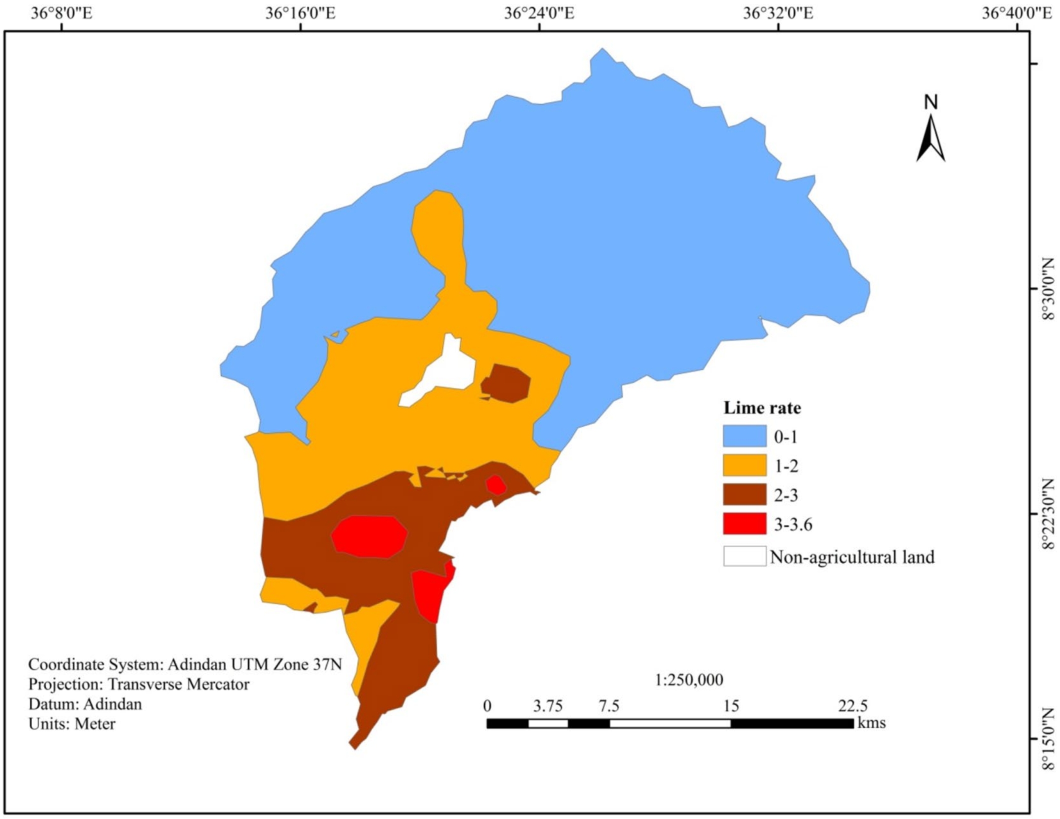

Fig. 8 Map of site-specific lime requirement rates (tons/ha) for soils of the study area

Abbreviations

CV: Coefficient of variation; EA: Exchangeable acidity; ECEC: Effective cation exchange capacity; GPS: Global positioning system; LR: Lime requirement; OC: Organic carbon; PAS: Permissible acid saturation; PCA: Principal component analysis; SD: Standard deviation; SOM: Soil organic matter; UTM: Universal transverse mercator.

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Authors' contributions

GS: conceived and designed the research; performed the experiments; analyzed and interpreted the data; and wrote the paper. BI: performed the experiments; interpreted the data; and wrote the paper. CT: performed the experiments; analyzed and interpreted the data; and wrote the paper. All authors have read and approved the final manuscript.

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Availability of data and materials

All data generated during this research work are included in this article.

Declarations

Ethics approval and consent to participate

Not applicable to this manuscript.

Consent for publication

All data and information were generated and organized by the authors.

Competing interests

The authors declare that they have no competing interests.

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