Assessing the Spatial Distribution, Condition, and Intensity of Soil Acidity for Informed Management Decisions in the Semen Aari District of Ari Zone, Southwestern Ethiopia

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Abstract:- Soil acidity poses a significant challenge to agricultural productivity in Ethiopia's highlands, particularly affecting the Semen Ari district in the Ari zone. The common practice of applying agricultural lime to mitigate soil acidity is hampered by a lack of detailed information on the extent, severity, and spatial distribution of acidic soils. This study aims to determine how soil acidity varies spatially by identifying and mapping the specific geographic patterns of soil acidity levels in the Semen Ari district. Seventy-one composite soil samples from the 0–20 cm layer were geo-referenced and analyzed. Using statistical analysis and ArcGIS software for spatial interpolation through ordinary kriging, soil pH ranged from 3.29 to 5.68, classifying 99% of the soils as strongly acidic. The root mean squared error (RMSE) of the interpolation was 0.30. Soil pH showed a significant negative correlation with exchangeable acidity but a non-significant negative correlation with organic carbon and total nitrogen. The results highlight the need for targeted soil management strategies, such as appropriate lime application rates and the cultivation of acid-tolerant crops, to enhance crop yields. Further research is recommended to include comprehensive soil property datasets to better understand the factors influencing soil pH variability, thus supporting more precise management of acidic soils in the region. The generated high-resolution soil acidity map serves as a valuable tool for agricultural planning and decision-making.

***Keywords:-** Soil Acidity, Spatial Variability, Geographic Pattern, Kriging Interpolation.*

I. INTRODUCTION

Soil acidity ranks among the most significant issues contributing to land degradation, affecting 50% of the world's potentially arable soils (Kochian et al., 2004). Particularly in the Ethiopian highlands Nitsols, soil acidity and its resultant nutrient deficiencies pose significant barriers to crop productivity (Gete et al., 2019). Preliminary estimates suggest that soil acidity impacts approximately 43% of Ethiopian agricultural land. Moreover, it has inflicted damage on Ethiopia's southern, western, and central highlands (Abebe,2007). This phenomenon is prevalent in temperate and tropical regions worldwide, where heavy precipitation significantly influences soil pedogenic development ((Brady & Weil, (2002); (Kochian et al., 2004)).

Soils naturally become acidic due to the leaching mechanism of carbonic acid (CO_2 dissolved in rainwater). Acidification continues until a balance is achieved between removal and replacement. Basic cations such as calcium (Ca) and magnesium (Mg) are lost through leaching and crop harvesting, but these bases are replenished through organic matter breakdown and mineral weathering (Abebe, 2007).

Typically, high soil acidification in the soil solution is indicated by pH levels lower than 5.5, high exchangeable acidity, and aluminum saturation (Al). When soil pH drops below 5, the active form of aluminum becomes soluble, leading to reduced nutrient uptake (Chimdi, 2015).

In acidic soils, plant growth is often hindered by aluminum toxicity, which significantly reduces shoot and root growth and inhibits effective phosphorus utilization in the soil. Poor root growth leads to decreased water and nutrient uptake, thereby constraining crops with limited nutrient and water availability, ultimately resulting in reduced growth and yield (Wang et al., 2013). Soil acidity is increasingly expanding in scope and magnitude in Ethiopia, severely limiting crop production. For instance, in some areas where barley, wheat, and faba beans are cultivated in the central and southern Ethiopian highlands, farmers have shifted to producing oats, which are more tolerant to soil acidity than wheat and barley (Wassie and Shiferaw (2009).

Spatial variability in soil acidity arises due to differences in soil formation and other environmental conditions across the landscape. Hence, accurate information on soil pH, extent, and spatial variability across the landscape is crucial for informed management decisions. However, the current dataset has limited application for detailed local and sub-regional land management decisions due to its inadequate

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spatial resolution. Digital soil pH and exchangeable acidity mapping, along with methods like ordinary kriging, offer effective means to assess spatial distribution and delineate areas based on soil pH units (Iticha & Takele, 2019)

To this end, descriptive analysis and geostatistical methods provide effective means to quantitatively assess soil acidity and map its spatial distribution. Therefore, this study aims to determine how soil acidity varies spatially by identifying and mapping the specific geographic patterns of soil acidity levels in the Semen Ari district, located in the Ari zone of Southwest Ethiopia.

II. MATERIAL AND METHOD

➢ *Description of the Study Area*

The research was conducted in the highland district of Ari zone, specifically in Semen Ari. Geographically, Semen Ari is situated within the ranges of 6.07° to 6.27° N latitude and 36.526° to 36.75° E longitude (see Figure 1), with an altitude ranging from 811 to 3251 meters above sea level. It is located southwest of Jinka town, the principal city of the South Omo zone, at a distance of 96 km. The area experiences a mean annual rainfall of 1616mm, as recorded by the Bulki-mender meteorological station (refer to Figure 2).

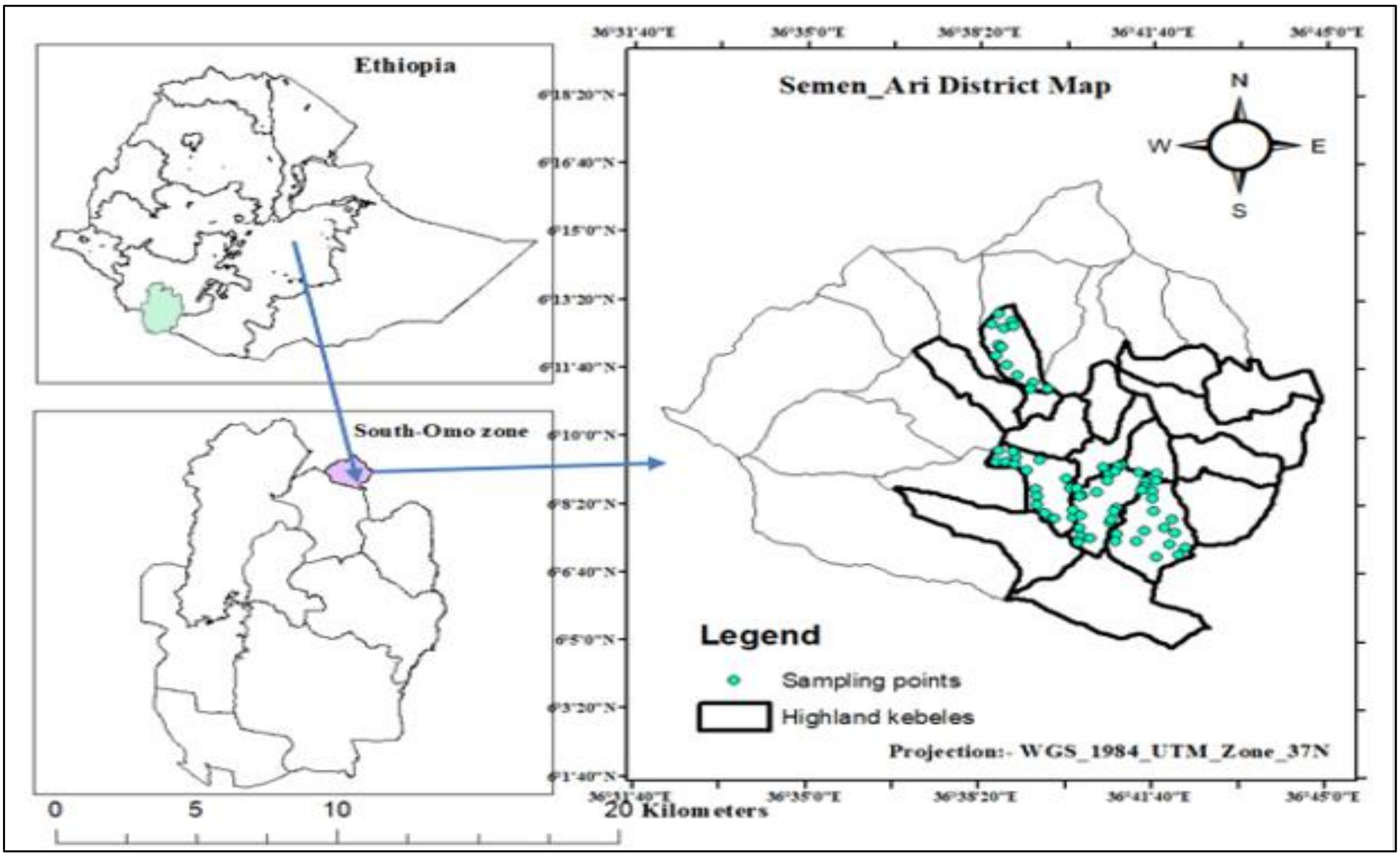

Fig 1 Location map

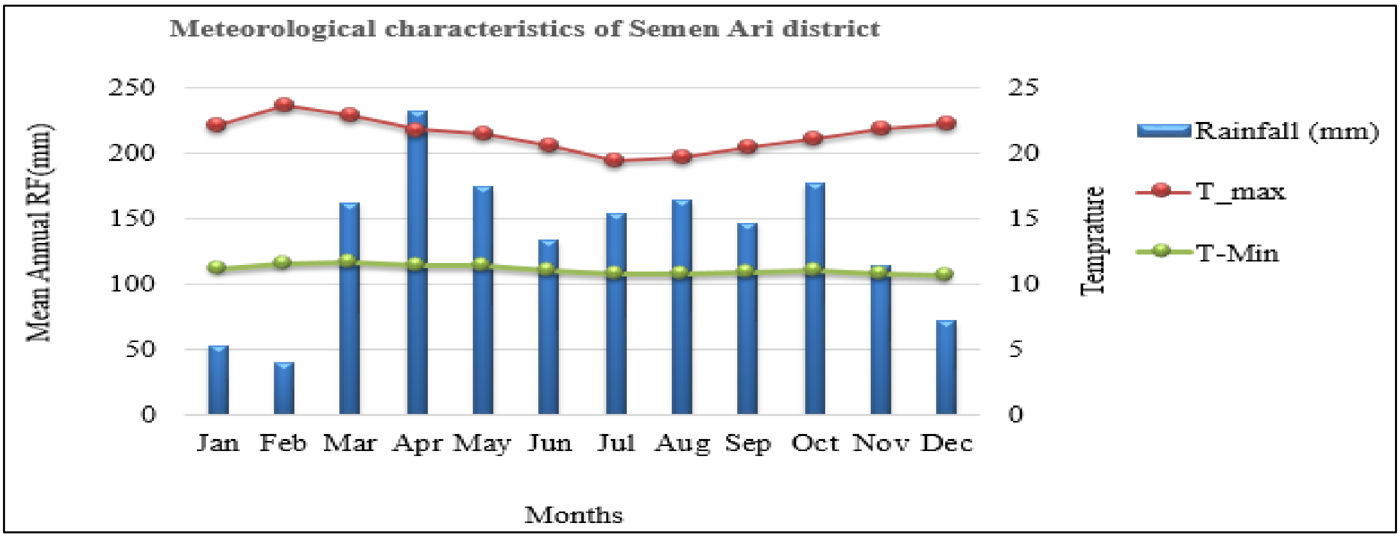

Fig 2 Meteorological Attributes of Study Area

➢ *Site Selection, Soil Survey and Sampling*

To identify the area of interest based on the specific objectives of the study, such as assessing soil fertility, texture, or contaminant levels, factors like topography, land use history, and expected soil acidity variability were considered. Representative kebeles were selected in consultation with the Woreda Agricultural office. Accordingly, four kebeles, namely Shama-bulket, Melt, Aymatol, and Ambi, were purposefully chosen to represent the entire highland kebeles of the district.

In each kebele, annual and cereal crop farms were intensively sampled. Soil sampling from selected farm fields was conducted based on specific farmer management practices, with different soil types and varying topography (hills and flats) sampled separately to a depth of 0-20cm using an auger. Areas such as stock camps, fertilizer dump sites, swampy sites, gates, troughs, fence lines (old and new), sheds and roadways, poorly drained areas, wet conditions, and trees were avoided during sampling. In special cases, previously lime-applied lands were excluded from sampling.

The number of cores taken was crucial, so based on the landscape, composites were made from 20 cores taken from every 25 meters covering an area of 5-10 hectares, and then homogenized. These composites were centered in their radius and georeferenced using GPS (Garmin-72). After preliminary data screening, soil pH and other parameters for highland areas were represented by 71 composite soil samples for the study area.

➢ *Soil Sampling and Laboratory Analysis*

Soil samples collected were representative of the overall interpolation. Accessibility was a major limitation to soil sampling; therefore, to optimize the sampling strategy, the landform map was used to stratify clustered random sampling locations. The distance between soil sampling locations ranged from around 150m up to 1500m, although most were separated by a distance of between 400m and 1200m.

The soil samples collected from the surface were air-dried at room temperature and ground to pass through a 2mm sieve. Soil pH, exchangeable acidity (cmolc kg -1), total nitrogen (TN), organic matter (%OM), and organic carbon (%OC) were analyzed in accordance with their respective standards. Soil pH was measured potentiometrically with a digital pH meter in a supernatant suspension of 1:2.5 soils to water ratio (Baruah & Barthakur (1997). Total exchangeable acidity was determined by saturating the soil samples with a 1M KCl solution and titrated with 0.02M HCl as described by Rowell (1994). Organic carbon was determined by the Walkey and Black titration method, while total nitrogen was analyzed by Kjeldahl digestion and distillation.

➢ *Data Analysis*

The soil data were analyzed to assess spatial variability and create maps illustrating the distribution of different soil properties across the study area. Statistical techniques such as geostatistics, interpolation methods (e.g., kriging, inverse distance weighting), and geographic information system (GIS) tools were employed for this purpose. Descriptive statistics maximum, minimum, and standard deviation were carried out using the XLSTAT Version 2018 software. The mean values of soil parameters were compared with critical values. Besides, the autocorrelation among parameters was performed by SAS software V@9.1.

➢ *Data Pre-Processing and Analysis*

Following soil laboratory analysis, all data processing and analysis were conducted in ArcGIS 10.3.1. The coordinates of the soil sampling points and the associated measured soil pH data were converted to shapefiles with coordinates in the World Geodetic System 1984 (WGS 1984) zone 37 north. Preliminary screening of the measured soil pH data was performed by creating box plots, where outliers were visually identified as individually plotted points rather than part of the whiskers in the box plots. The histogram tool in ArcGIS was also utilized; any isolated bars from the main group of bars in the histogram were considered possible outliers and were excluded from further analysis. After this preliminary data screening, data for soil pH were represented by 71 soil samples. Summary statistics were then generated to provide a basic understanding of the characteristics of soil pH at the study site.

➢ *Geo-Statistical Analysis*

In this study, ordinary kriging (OK) was employed to generate the spatial distribution of each parameter (Johnston et al. 2001). Ordinary kriging (OK) was specifically used to evaluate the spatial distribution of soil pH, for which the variogram was fitted globally. Since OK relies on the assumption of stationarity, which requires that all data values come from distributions with the same variability, further examination of the data was conducted to determine the necessary data preprocessing for efficient model implementation.

The theory and principles of Ordinary Kriging have been described in detail by various authors (Kaur & Rishi, 2018). In summary, OK is considered an exact interpolator, meaning that interpolated values or their local averages coincide with values at the sampled locations.

The predicted soil pH $\hat{Z}(x_0)$, at an un-sampled location s using observations Z (x_i), *i* = 1... *n* was given by:

$$\hat{Z}(x0) = \sum_{i=0}^{n} \lambda i . Z(Xi)$$

Where, λ_i is the kriging weight,. Z(*s*) is the observed or measured variable,

The soil pH dataset was initially mapped using an appropriate color and classification scheme to identify any patterns associated with soil pH. The classification scheme comprised five classes: ultra-acidic (<4), extremely acidic (4.0–4.5), very strongly acid (4.5–5.0), strongly acidic (5.1-5.5), and moderately acidic (5.1–6.0) (Jones Benton. (2003).

Furthermore, additional data evaluation was conducted using a histogram to analyze the distribution of the measured soil pH data. This exploration revealed that the soil pH data followed a normal distribution, and thus, no transformation was performed on it.

Finally, the trend analysis tool was utilized to check for the presence of any non-random trends in the soil pH data.

III. RESULT AND DISCUSSION

➢ *Soil pH and Exchangeable Acidity*

The results of the current study indicate that soils in the study area have pH values less than 7, indicating acidity (refer to Table 1, Table 2, and Table 3).

The soil sample analysis conducted in the highland agro-ecology of this district revealed that the pH values of surface soil in Semen Ari ranged from 3.33 to 5.69, with an interpolation mean of 4.7 and standard deviation (SD) ranging from ±0.13 to ±0.4 (refer to Table 1). These pH values categorize the soils as falling within the range of ultra-acidic to moderately acidic. The high standard deviation values indicate significant spatial variability in soil acidity. According to ATA (2014), the USDA Natural Resources Conservation Service, and (Jones Benton. (2003), the pH range places the soils within the moderately acidic to slightly acidic category.

Laboratory analysis of exchangeable acidity (cmolc kg-1) revealed that among the four kebeles sampled for representation, the highest value of exchangeable acidity, 7.20 (cmolc kg-1), was recorded in Melt kebele, where the lowest pH value, 3.33, was observed. Conversely, a low value of 4.94 (cmolc kg-1) was obtained at a point with a high pH value of 5.69 in Ambi kebele.

➢ *Data Pre-Processing and Analysis*

The coordinates of the soil sampling points and the associated measured soil pH data were converted to shapefiles with coordinates in the World Geodetic System 1984 (WGS 1984) zone 37 north. Preliminary screening of the measured soil pH data was conducted by creating box plots sorted into five groups: (<4- ultra-acid), (4-4.5-Extremely acidic), (4.5-5- Very strongly acid), (5.1-5.5-Strongly acidic), and (>5.5- Moderate acidity). Outliers were identified visually as individually plotted points rather than part of the whiskers in the box plots. The histogram tool in ArcGIS was also utilized; isolated bars from the main group of bars in the histogram were considered possible outliers and were excluded from further analysis. After this preliminary data screening, data for soil pH were represented by 71 soil samples. Summary statistics were then generated to provide a basic understanding of the characteristics of soil pH at the study site.

Table 1 Descriptive Statistics of Selected Soil Properties

Kebeles	***No of sample***	***pH (1: 2.5 H_2O)***				***Exchangeable acidity ($cmol_c$ kg^{-1})***			
		max	**min**	**mean**	**SD (±)**	**max**	**min**	**men**	**SD (±)**
Shama	13	5.42	4.22	4.94	0.40	5.28	0.16	1.14	1.31
Ambi	17	5.69	4.44	4.76	0.28	4.94	0.93	2.87	1.18
Aymato	22	5.03	4.48	4.71	0.13	6.4	1.60	4.14	1.39
Melt	19	4.70	3.33	4.09	0.42	7.2	1.36	3.89	1.63

➢ *Result of Geo-Statistical Analysis*

- *Spatial Variability of Soil Acidity*

One of the objectives of the current study is to understand the spatial variability of soil acidity. Soil samples analyzed were associated with their geo-references and subjected to ordinary kriging under the ArcGIS environment with the aid of the spatial analyst tool.

The result of kriging interpolation conducted over the highland agro-ecology of Semen Ari district revealed that the pH values of surface soil ranged from 3.29 to 5.68, with an interpolation mean of 4.7 (refer to Table 1). This pH range indicates that the soils fall within the ultra-acidic to moderately acidic category.

The interpolation results further indicated that approximately 99% of the highlands in Semen Ari are categorized as strongly acidic (pH < 5.5), with less than 1% of the area having a pH above 5.5 (refer to Table 2 and Figure 3). According to critical levels adopted by (Mamo, T., & Haque, I. (1991), soils with pH levels below 5.5 can reduce the solubility of nutrients and the activity of soil microorganisms, thereby limiting plant growth and yield. Considering the optimum pH for many plant species to be between 5.5 and 6.8, and in the absence of free extractable aluminum in this range, soils with pH values within this range could be considered suitable for most crop production (Amacher et al., 2007).

Table 2 Soil Acidity Classes and their Area Coverage from the Highland Kebeles of Semen Ari

Soil PH ranges	**Denomination**	**Area (hectare)**	**Coverage in %**
(<4)	Ultra-acid	1371.85	11.85
(4-4.5)	Extremely acidic	1328.60	11.47
(4.5-5)	Very strongly acid	7983.45	68.95
(5.1-5.5)	Strongly acidic	882.92	7.63
(>5.5)	Moderate acidity	12.30	0.11
		11592.1	100%

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- *Soil pH ranges based on: Jones, J. Benton (2003) and ATA, (2014) and the USDA Natural Resources Conservation Service, formerly Soil Conservation Service (SWS)*

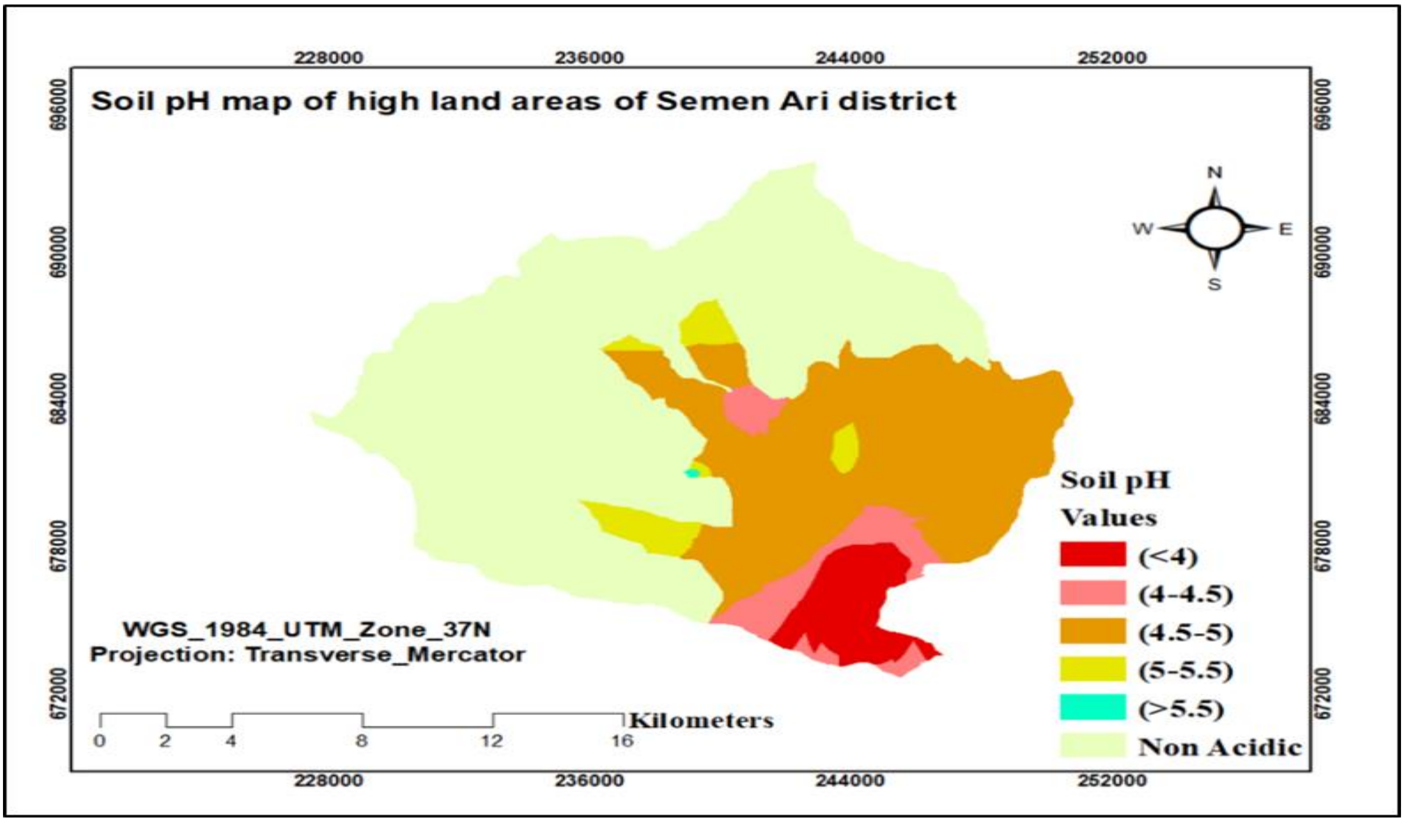

Fig 3 Spatial variability of Predicted Soil pH in Highlands of Semen Ari District

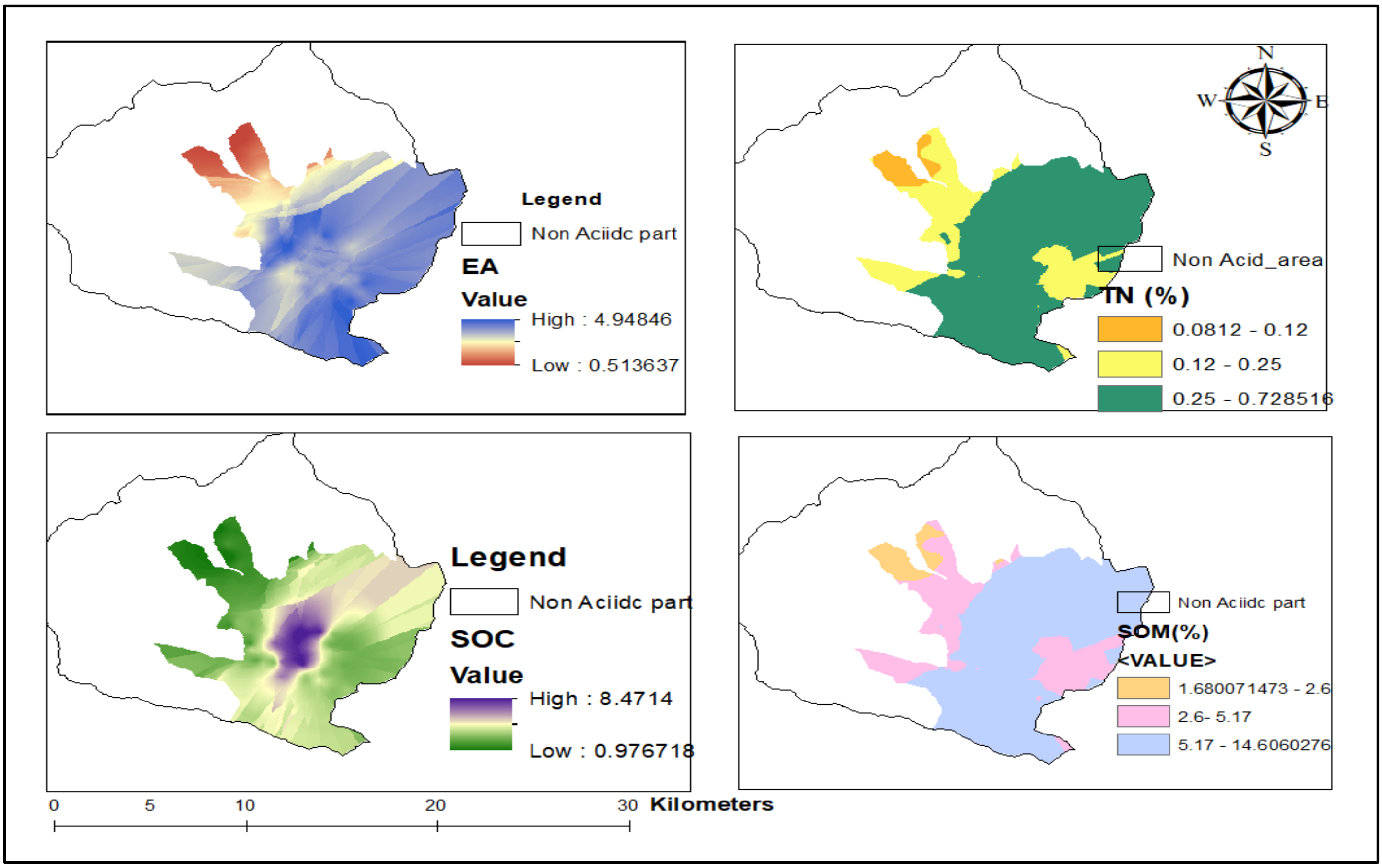

Fig 4 Spatial variability of Soil EA, TN, SOM and SOC in Highlands of Semen Ari District

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- *The Relationship between Soil pH and some Parameters*

Table 3 Pearson's simple correlation coefficient (r) of soil parameters

	PH	OC	OM	TN	EA
PH	1				
OC	-0.0144NS	1			
TN	-0.0143NS	0.9999***	0.9999***	1	
EA	-0.3349**	0.4097***	0.4097***	0.4119***	1

- **Note:** NS = Not Significant, *p < 0.05, **p < 0.01, ***p < 0.001

The correlation coefficient (r) in Table 3 indicates the strength and direction of the linear relationship between soil pH and other parameters: Organic Carbon (OC), Organic Matter (OM), Total Nitrogen (TN), and Exchangeable Acidity (EA). To find insights into the interrelationships among soil properties, which can inform soil management practices and agricultural productivity in the study area.

The correlation coefficient between soil pH and OC is -0.0144, which indicates a very weak and non-significant negative correlation (NS). This suggests that there is no meaningful linear relationship between soil pH and OC in the study area. Similarly to the relationship with OC, there is no significant linear relationship between soil pH and OM.

- *Soil pH and Total Nitrogen (TN):*

The correlation coefficient between soil pH and TN is not provided, but it is mentioned as 0.9999***. This indicates a very strong positive correlation between soil pH and TN, with a high level of statistical significance ($p < 0.001$). The strong positive correlation suggests that as soil pH increases, the concentration of TN also increases, or vice versa.

- *Soil pH and Exchangeable Acidity (EA):*

The correlation coefficient between soil pH and EA is -0.3349**, indicating a moderately strong negative correlation ($p < 0.01$). This suggests that there is a significant inverse relationship between soil pH and EA, where higher soil pH is associated with lower exchangeable acidity.

Overall, the correlation analysis reveals interesting relationships between soil pH and various parameters. While there is no significant correlation between soil pH and OC or OM, there is a strong positive correlation between soil pH and TN, and a moderately strong negative correlation between soil pH and EA.

IV. CONCLUSION

Soil acidity is a serious problem in high rainfall areas of southwestern Ethiopia including current research site. Assessment of soil acidity extent, magnitude and spatial variability was conducted in highland kebeles of Semen Ari district. The pH of the soils of Semen Ari are ranged from (3.29 to 5.68), indicting wide variation with status of ultra-acidic (99%) to only (<1%) moderately acidic. However, all the soils collected from sample highland kebeles were acidic. Therefore, appropriate rate of lime needs to be applied or cultivating acid tolerant crops is recommended for both strongly acidic and moderately acidic soils of the study woreda to obtain optimum crop yields. Besides, the generated soil pH map can be used as guide for various uses, including identifying lime application rates according to spatial variability of soil acidity. However, to more precisely understand what is driving soil pH variability in this system, further research should be done on characterization of soil properties which is required for effective management of acid soils, for more efficient crop production, including lime application for amelioration which is an established practice.

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