SOIL MICRONUTRIENT CONTENT ANALYSIS AND MAPPING OF AGRICULTURAL SALT-AFFECTED SOILS AROUND ABAYA AND CHAMO LAKES, SOUTH ETHIOPIA RIFT VALLEY †

[ANÁLISIS DEL CONTENIDO DE MICRONUTRIENTES DEL SUELO Y MAPEO DE SUELOS AGRÍCOLAS AFECTADOS POR LA SAL ALREDEDOR DE LOS LAGOS ABAYA Y CHAMO, EN EL VALLE DEL RIFT DEL SUR DE ETIOPÍA]

Azmera Walche,[1, 2*] Wassie Haile,[2] Alemayehu Kiflu,[2] and Dereje Tsegaye[1]

[1] College of Agricultural Sciences, Arba Minch University, P.O. Box: 21, Arba Minch, Ethiopia. Email: azmera.walche@amu.edu.et
[2] College of Agriculture, Hawassa University, P.O. Box: 05, Hawassa, Ethiopia.
**Corresponding author*

SUMMARY

Background. Salt-affected soils cause a significant portion of land to become unproductive yearly; its impact is severe in sub-Saharan African nations, especially the arid and semiarid lowlands, and the Rift Valley regions of Ethiopia are typically host to naturally salt-affected areas. **Objective.** To analyze the micronutrient content and map the micronutrient fertility status of agricultural salt-affected soils around Abaya and Chamo Lakes South Ethiopia Rift Valley. **Methodology.** A systematic sampling technique was employed to obtain 300 soil samples for the investigation from two depths (0-20 and 20-40cm), with a 600m sampling interval, of which 30 were used. The research data was analyzed using the application of standardized analytical procedures for soil data and descriptive and geostatistical techniques. **Results.** According to the study, there is low zinc available in the soil but an ample amount of iron, manganese, and copper. In addition, the study's findings revealed that, whereas the remaining micronutrient regional variability is found at long distances, available iron exhibited a regional variation in soil quality at small distances. **Implications.** The study suggests applying organic matter for better soil structure, water retention, and nutrient availability. Moreover, the results recommend that soils affected by salt might recover using various materials. **Conclusions.** In the study areas, zinc fertilizer may still be needed for an optimal yield even though the research area has low amounts of zinc fertilizer. The study concluded with management recommendations to minimize the adverse effects of very high micronutrient content on human health and plant growth.
Key words: Kriging, nutrient variability; salt-affected soils; soil micronutrient; special dependency.

RESUMEN

Antecedentes. Los suelos afectados por la sal hacen que una porción importante de la tierra se vuelva improductiva cada año; su impacto es severo en las naciones del África subsahariana, especialmente en las tierras bajas áridas y semiáridas, y las regiones del Valle del Rift en Etiopía suelen albergar áreas naturalmente afectadas por la sal. **Objetivo.** Analizar el contenido de micronutrientes y mapear el estado de fertilidad de los micronutrientes de los suelos agrícolas afectados por la sal alrededor de los lagos Abaya y Chamo, el valle del Rift del sur de Etiopía. **Metodología**. Se empleó una técnica de muestreo sistemático para obtener 300 muestras de suelo para la investigación a dos profundidades (0-20 y 20-40 cm), con un intervalo de muestreo de 600 m, de las cuales se utilizaron 30. Los datos de la investigación se analizaron mediante la aplicación de procedimientos analíticos estandarizados para datos de suelos y técnicas descriptivas y geoestadísticas. **Resultados**. Según el estudio, hay poco zinc disponible en el suelo, pero una gran cantidad de hierro, manganeso y cobre. Además, los hallazgos del estudio revelaron que, mientras que la variabilidad regional de los micronutrientes restantes se encuentra a largas distancias, el hierro disponible exhibió una variación regional en la calidad del suelo a distancias pequeñas. **Implicaciones**. El estudio sugiere aplicar materia orgánica para una mejor estructura del suelo, retención de agua y disponibilidad de nutrientes. Además, los resultados sugieren que los suelos afectados por la sal podrían recuperarse utilizando diversos materiales. **Conclusiones.** En las áreas de estudio, es posible que aún se necesite fertilizante de zinc para obtener un rendimiento óptimo, aunque el área de investigación tenga cantidades bajas de fertilizante de zinc. El estudio concluyó con recomendaciones de gestión

† *Submitted January 25, 2024 – Accepted June 22, 2024.* http://doi.org/10.56369/tsaes.5424

ISSN: 1870-0462.

para minimizar los efectos adversos de un contenido muy alto de micronutrientes en la salud humana y el crecimiento de las plantas.
Palabras clave: Kriging; variabilidad de nutrientes; suelos afectados por la salinidad; micronutriente del suelo; dependencia especial.

INTRODUCTION

Salt-affected soils cause a significant portion of land to become unproductive every year. Soils affected by salt are found all throughout the world, and no continent is exempt from this problem (Basak *et al.*, 2022). Ethiopia's primary challenges are still soil salinity and sodicity in the lowlands and soil acidity in the highlands as a result of the country's reliance on rainfed agriculture (Regassa *et al.*, 2023). Particularly in arid and semiarid areas where irrigation is practiced, soil salinization is becoming more of a problem (Pulido-Bosch *et al.*, 2018). The environment, agricultural ecosystems, and human life are all at risk as a result of the alarming rate at which soil deterioration brought on by saltwater and sodicity is increasing (Prăvălie, 2021). According to reports, salt affects around 11 million hectares of Ethiopia's soil (Borena and Hassen, 2022; Habtamu and Wassie, 2022). The dry and semiarid lowlands as well as the Rift Valley regions of Ethiopia are typically host to naturally salt-affected areas, which are distinguished by increased evapotranspiration rates relative to precipitation (Challa *et al.*, 2022). This problem deleteriously impacts soil fertility, reducing soil productivity (Bisht and Chauhan, 2020). To find solutions for those problems, it is necessary to ascertain the current georeferenced soil micronutrients fertility status(Barman *et al.* 2021), irrigation water management techniques, and the chemical and physical characteristics of the soil that cause the problem of salt-affected soils and contribute to that problem (Choukr-Allah *et al.*, 2023; El-Ramady *et al.*, 2022).

Analysis and mapping of soil fertility are necessary to monitor the changes and reveal the state of soil fertility under different soil types and salt-affected soils (Worku *et al.*, 2015). Therefore, in order to better understand soil resources and predict and map soil patterns and distribution more precisely, it is essential to do comprehensive salt-affected soil analysis and mapping soil nutrients status (Brevik *et al.*, 2016). Crop productivity is determined by the status and management of soil nutrients as well as the concentration of nutrients in plant parts that are used for food and feed (El-Ramady *et al.*, 2022). As a result, the state of soil nutrients greatly affects human health. Approximately one-third of arable soils worldwide are deficient in micronutrients, especially zinc (Zn) (Steffan *et al.*, 2018), and human nutrition eventually gets affected by this. Globally, between two and three billion individuals deficiency certain micronutrients; this is particularly the case in developing countries, where at least half of the population is affected (Beal *et al.*, 2017) (Goudia and Hash 2015). In sub-Saharan Africa (SSA), the problem of soil micronutrient deficiencies, which frequently affect two to five micronutrients at a time, is pervasive (Ohanenye *et al.*, 2021). Decades of degradation of the soil and the inconsistent and inadequate use of fertilizers, namely nitrogen (N), phosphorus (P), and potassium (K), are the primary causes of this (Rajičić *et al.*, 2020). Although micronutrients have recently been shown to be important for crop productivity, but limited is known about how they relate to nutrition (Tripathi *et al.*, 2015). Plant yield can be affected by micronutrient toxicity and deficiencies (Chrysargyris *et al.*, 2022).

Due to the calcareous nature of the soils, high pH, poor organic matter, salt stress, prolonged drought, high bicarbonate concentration in irrigation water, and imbalances, inadequate nutrition is common in dry land soils (Hailu and Mehari, 2021). The last ten decades' salt-affected soils revealed that, currently, zinc (Zn) insufficiency is the micronutrient that has the greatest negative impact on crop yield (Chhabra and Chhabra, 2021b). A deficiency Fe, Zn, and Mn in the micronutrients that are needed to minimize the toxicity of B and Mo while also neutralizing the pH reaction in the salt-affected soils of Ethiopia's Central Rift Valley (Bedadi *et al.*, 2023). Micronutrient analysis and mapping in agricultural salt-affected soils in Sub-Saharan Africa is crucial for addressing micronutrient deficiencies, optimizing fertilizer use, improving food security and nutrition, enhancing climate resilience, and supporting sustainable land management (Dimkpa *et al.*, 2023; Kebede, 2023). These problems are widespread, exacerbated by salt-affected soils, and have limited resources for smallholder farmers (Sharma and Singh, 2017). Understanding the specific micronutrient limitations of different areas can help farmers apply fertilizers more efficiently, reduce costs, and reduce environmental impact (Bindraban *et al.*, 2020). By addressing these deficiencies, farmers can improve food security, reduce stunting, blindness, and maternal mortality, and build resilience to climate change (da Silva, 2019).

In salt-affected arid and semiarid environments, micronutrient requirements are critical for plant growth. Mangoes need zinc, boron, manganese, and copper for healthy flowering, fruit set, and quality (Chhabra and Chhabra, 2021b). Saline soils can decrease zinc availability, so foliar application or soil amendments rich in zinc may be necessary. Bananas need good levels of zinc, B, Fe, and Mn for growth, disease resistance, and fruit quality (Shahrajabian *et al.*, 2022). Maize needs Zn, Mn, and Fe for enzyme function, photosynthesis, and pollen development. Sweet potatoes need these micronutrients for root development and yield. Cotton requires balanced levels for fiber quality and yield *(*Pasala *et al.*, 2022). Different vegetables have varying micronutrient needs, and saline soils can affect these micronutrients (Shukla *et al.*, 2018). The Abaya and Chamo Lakes area in the south Ethiopia rift valley is a central agricultural region. However, the soils in this area are highly susceptible to salt accumulation, which can significantly impact crop production. Salt-affected soils can cause several problems for crops. The study of salt-affected soils is a complex and challenging field. Still, it is essential for ensuring sustainable agricultural production in the study area and other regions worldwide. Analyzing and mapping the micronutrient fertility status of the salt-affected soils in this area is essential to developing management options that can decrease salt accumulation and improve the production of crops. The critical and thorough investigation, assessment, and mapping of the micronutrient fertility status of the salt-affected soils in the designated area is essential to the management and exploitation of soil potential. However, baseline information on the nutritional status of the agriculturally salinized soils in the research area must be provided.Therefore, to sustainably produce crops and carry out land use planning, the study's present objective is to investigate the micronutrient levels and map the micronutrient fertility status of agricultural salt-affected soils.

MATERIALS AND METHODS

Descriptions of the study location and climate

The Abaya-Chamo sub-basin of the South Ethiopia Rift Valley that splits Ethiopia down the middle in a north-south direction. The basin comprises two lower-lying lakes, Abaya Lake and Chamo Lake (Tiruneh 2005; Walche et al. 2023). The latitude of the study area falls between 5^o 50'00"N and 6^0 10' 0"N, and the Longitude of the study area falls between 37^o 26'0" E and 37^o 40'0" E. The altitude of the study area ranges from 1107 m around Chamo Lake to 1191 m at around Abaya Lake range. Besides this, the altitude of the Institutional University Cooperation (IUC) Project area ranges from 972 m around Abaya and Chamo lakes shores to 3464 m in the highland mountain range (Figure 1). The total area of the four watersheds is 807 km^2: Elgo (249 km^2), Sile (227 km^2), Baso (167 km^2), and Shafe (164 km^2). Elgo and Sile catchments drain Lake Chamo, whereas Baso and Shafe drain Lake Abaya. Of all Abaya-Chamo Lake watersheds, the area around two lower lying lakes, Abaya and Chamo Lakes, are selected for this specific study based on accessibility and the productive potential of the site for crop production and covered a 2019sq.km area (Figure 1).

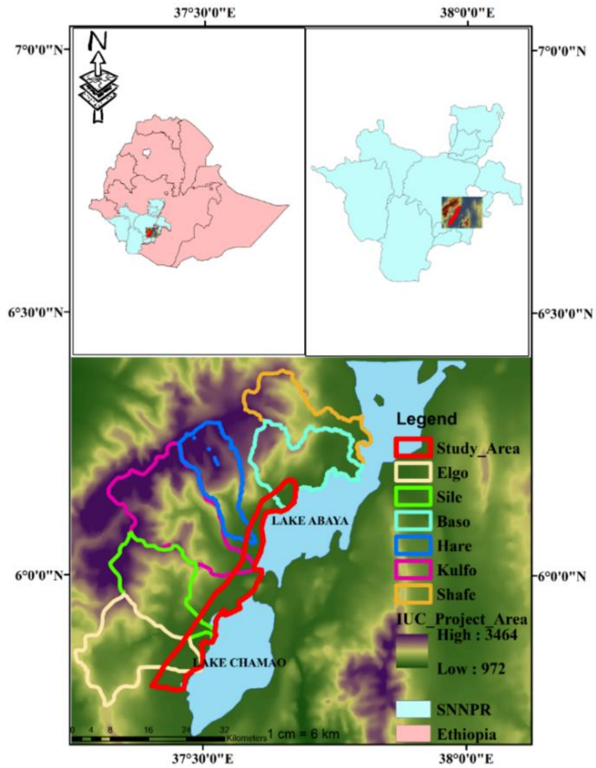

Figure 1. Location map of the project area and the study area.

The climate around the Abaya and Chamo Lakes basin region is tropical, hot, and semi-arid (Abdi and Gebrekristos, 2022). The bimodal rainfall system in the Abaya-Chamo watersheds seems to be assisted by a humid breeze coming from the Indian Ocean, which is brought in by the inter-tropical convergence zone (ITCZ). Altitude plays a role in the distribution of rainfall. The region experiences short rains in spring (belg) and long rains in summer (kremt), resulting in a bimodal rainfall distribution in most parts of the watershed (Mengistu et al., 2019). In the study area, the rainfall peaks during April and May. On the other hand, the lowest rainfall is recorded during January and February. The temperature is high for three months in the study area. For instance, around Chamo Lake, the temperature increases in February, March, and April, while around Abaya Lakes, the temperature is high during January, February, and March. The mean annual rainfall in the area ranges from 500 to 1100 mm, and the average yearly air temperature is 17–39 °C. According to the AMU-IUC Project 4 (Figure 2), the mean soil temperature ranges from 22 to 35 °C depending on the depth. Agriculture seems to be dominant in the area, with crops such as banana, mango, papaya, maize, cotton, sweet potato, tomato, onion, and haricot beans being cultivated. However, it seems that soil salinity and sodicity are also present in the area. These phenomena are brought on by factors of nature such nearby or nearby water tables, weathering rocks and minerals, low rainfall and high evaporation rates. Unfortunately, these problems are made worse by human actions including inadequate irrigation, deforestation, and overgrazing of livestock (Tessema *et al.*, 2023).

Method of Sampling and Sample Collection

A reconnaissance study was carried out prior to the collection of samples in order to determine the degree of soil variability or homogeneity based on differences in physiography, land use, and visually detectable soil properties (soil texture, drainage condition, and salt crust at the soil surface, among other things). It was decided what sampling technique and sample size were needed to adequately represent the study area. The research area's topographic map (scale 1:50,000) and reconnaissance survey data were used to identify sampling places and points, which were then categorized into five map units. In order to prepare composite soil samples from the obtained soil samples, three representative soil sampling regions were chosen from each map unit and homogenized. For this investigation, 300 auger soil samples were obtained, as 10 auger soil samples were needed to make one composite soil sample. Rearranging the sampling depth will lead to surface (0–20 cm) and sub-surface (>20 cm) samples for saline or saline-alkali soils (Wogi *et al.*, 2021). Then, with two depths (0-20cm and 20-40cm) using a systematic sampling technique, with a 600m sampling interval, 30 soil samples were used to analyze soil micronutrient status and mapping since the study area is salt-affected according to Walche *et al.* (2023). The soil micronutrient state in the research area was mapped using just the analytical results from surface soil samples. The auger took enough subsamples, depending on the location of each sampling unit and the level of micro-variability present. Any alien items, such stones and plant leftovers, were thrown away while collecting samples. We won't sample in areas that are close to trees or that have certain characteristics like compost pits, moist areas, or old manures. Every sampling place had a georeferenced, and the dates of the samples were accurately recorded. Each composite soil sample weighed about one kilogram before being packaged, labeled, and delivered to the laboratory for analysis.

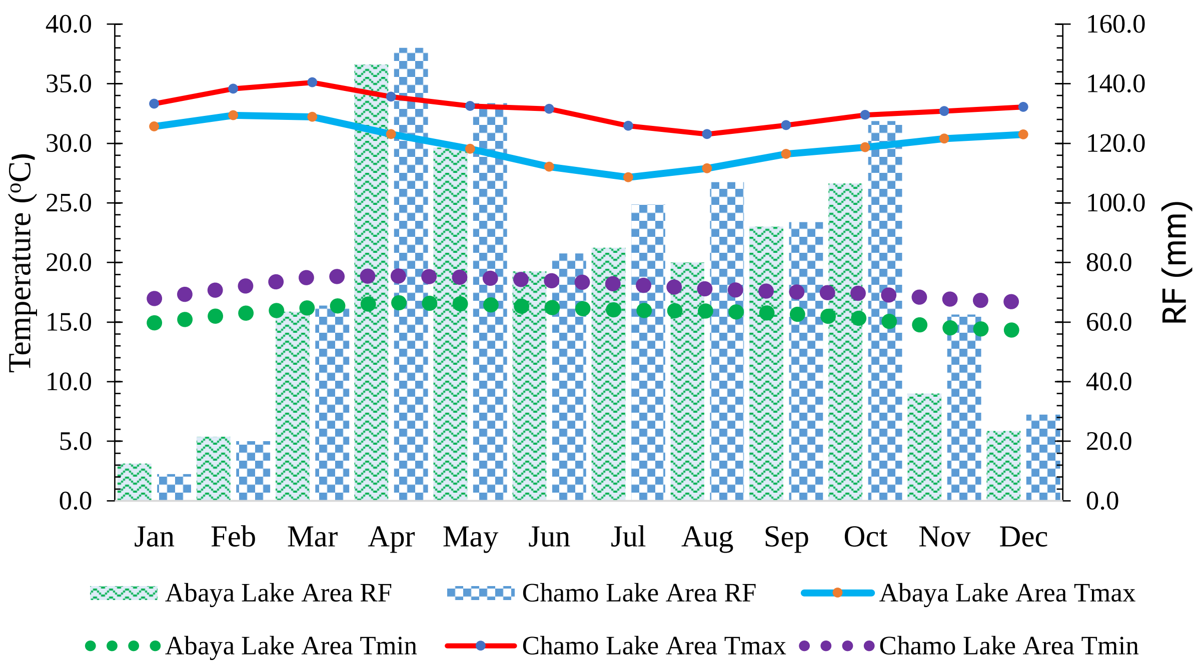

Figure 2. Annual climate data around Abaya and Chamo lakes (1983–2020 average) where rain falls (RF) in millimetre (mm) and temperature (T) in degrees Celsius (°C) (source: AMU-IUC project 4 meteorology station).

Soil Sample Preparation and Laboratory Analysis

Soil samples from the field were air-dried at a suitable laboratory temperature of 24°C. After drying, the soil samples were crushed using a mortar and pestle and passed through a 2-mm mesh sieve for laboratory analysis. Subsequently, the soil samples underwent standard laboratory procedures to determine micronutrient content.The Ethiopia Design and Water Works soil laboratory performed laboratory analyses. The Diethylene Triamine Penta Acetic acid (DTPA) method was used for analyzing the soils' DTPA extractable micronutrient content (Fe, Mn, Zn, and Cu) (Lindsay and Norvell, 1978). Five grams of air-dried soil were centrifuged for 15 minutes at 3000 rpm after being mixed for three hours with 20 ml of DTPA, Tri-Ethanol-Amine, and calcium chloride combination solution. Whitman No. 42 paper was used to filter the supernatant into a 50 ml volumetric flask. An atomic absorption spectrophotometer was then used to measure the amount of available micronutrients in the filtrate (Lindsay and Norvell, 1978).

Geostatistical analysis and Mapping of Soil Micronutrients

When samples were taken, GPS pinpointed their exact locations. Following that, the research area was defined and divided into mapping units. The whole area of the study location as well as the Easting and Northing coordinates of each map unit were carefully recorded. The combination and final computation of intermediate surfaces based on the combination decision rule and basic questions were performed using the Raster Algebra analysis capabilities of the Spatial Analyst extension. Based on the findings and ratings of soil laboratory analyses, the area of each map unit was also rated (very low, low, medium, high, and very high). Lastly, a map of the research area's soil micromutrients status was created. The accuracy of the interpolation techniques was evaluated via cross-validation using mean error (ME), root mean square standardized error (RMSSE), and root means square error (RMSE) (Arétouyap *et al.*, 2016). Selecting the best-fitted semivariogram model for an interpolation map could be made easier by values of the mean error (ME) and root mean square standardized error (RMSSE) being closer to 0 and 1, respectively, indicating that the prediction values were close to the measured values (Ferreira *et al.*, 2015).

Data Analysis

Descriptive statistics data were analyzed using SAS software, version 9.4 (Blanca Mena *et al.*, 2017). The rating of determined values was based on a guide to standardized analytical methodologies for soil data (Wogi *et al.*, 2021). Nutrient variability was determined using the coefficient of variation. The variability is low when the CV is < 10%, moderate between 10 and 100%, and strong when > 100% (Terefe *et al.*, 2021). The laboratory results were imported into a GIS environment to determine the geographical distribution of soil micronutreint status in the investigated area. The data were entered into Microsoft Excel with their corresponding coordinates (Latitude and Longitude). Spatial prediction and mapping of the un-sampled surface from laboratory point data were done in a GIS environment using interpolation techniques. From laboratory point data, the un-sampled surface was predicted and mapped using the standard kriging method in Arc GIS 10.81 software.

RESULTS AND DISCUSSION

Geostatistical analysis and Mapping of Soil Micronutients status

Table 1 displays the findings of the soil spatial analysis. The ratio of nuggets to sill or spatial dependence Co/(Co + C) is the spatial property definition. When the value of Co/(Co + C) is less than 0.25, the variable is said to have a strong spatial dependency; when it is between 0.25 and 0.75, it is considered to have a moderate geographic dependence; and when it exceeds 0.75, it is considered to have a weak spatial dependence (Addis *et al.*, 2015; Cambardella *et al.*, 1994; Sani *et al.*, 2023). The semivariogram produced by the geostatistical analysis is displayed in Table 1 and provides various models of the soil characteristics' spatial distribution and degrees of spatial dependency. Semivariance demonstrated that the spatial dependence of soil parameters was the same (Cambardella et al., 1994; López-Granados *et al.*, 2002) (Table 1). According to Cambardella *et al.* (1994), for all soil micronutrient characteristics investigated, a considerable geographical dependence was seen in the nugget/sill ratio (C0/C0 + C) <25%, which reveals strong spatial dependence. The model explained the distribution's results by demonstrating how natural factors mostly of a geological nature affect the data. This may be primarily caused by intrinsic or inherent causes of variability (e.g., terrain, parent materials, and variations in soil texture) (Addise *et al.*, 2022; Stritih, 2021). Similarly, Saleh (2018) and Corwin and Yemoto (2020) also reported that strong spatial dependence of soil properties is associated with intrinsic structural factors like parent material, texture, climate, and topography; weak spatial dependency is associated with extrinsic factors that are random, like soil management practices like fertilization and plowing (Gülser *et al.*, 2016); conversely, a moderate degree of spatial dependence is probably influenced by both extrinsic and intrinsic factors (Swafo and Dlamini, 2023). For soil Fe, the nugget effect was commonly higher (Table 1). This suggested that regional heterogeneity in soil qualities existed at short distances. The spatial variability at smaller distances than the minimum separation between measurements is associated with the nugget effect (Yao *et al.*, 2020).The Spherical model was the highest accuracy among the other experimental semivariogram models for estimating all of the studied soil micronutrients for the agricultural salt-affected soils around Abaya and Chamo Lakes, South Ethiopia Rift Valley. The spatial range values for all investigated soil properties ranged from 4,615 m to 20,924 m, as shown in Table 1. Since this range is larger than the average sampling distance of 600 m, the sampling interval used in this study was adequate to capture the spatial variability in the investigated soil properties.

Available Iron

Iron is a crucial micronutrient for plants' various metabolic processes throughout their life cycle (Rout and Sahoo, 2015; Tripathi *et al.*, 2015). The South Ethiopian Rift Valley's agriculturally salt-affected soils near Abaya and Chamo Lakes have very high levels of available iron. In the surface soil (0–20 cm depth), the amount of iron was 14.54–176.02 mg kg^{-1}; in the subsurface soil (20–40 cm depth), it was 13.99–57.51 mg kg^{-1}. The mean quantity of available iron in the soil is 61.78 mg kg^{-1} in surface soil and 25.79 mg kg^{-1} in subsurface soil (Table 2). This goes above the very high threshold set by Wogi *et al.* (2021) of 50 mg kg^{-1} (Figure 3). These soils' high pH may be responsible for their high available iron level (Shanshan *et al.*, 2021). Alkaline soils, frequently affected by salt, can bind iron in the soil and reduce its availability to plants. However, iron availability in these soils doesn't seem to be the high pH (Martínez-Cortijo and Ruiz-Canales, 2018). The nature of salt-affected soil has waterlogging and can increase the available iron content in salt-affected sodic soils (Chhabra and Chhabra, 2021). This is because waterlogging can displace the sodium ions that are bound to the iron in the soil, making the iron more available to plants. Waterlogging can displace the sodium ions from the soil, freeing up the iron. This makes the iron more available to plants, which can help to improve their iron status (Rengel, 2023). Generally, an important factor influencing the amount of soluble Fe in the soil solution is the oxidation-reduction process. But in the case of waterlogged fallow it has less influence since lowering redox reaction increases Fe^{2+} solubility (Wang, 2022). In soils, there is very low Fe^{3+} in the solution. The concentration of Fe^{2+} in solution is lower in well-drained, oxidized soils than it is in the dominating Fe^{3+} species in solution. Soluble Fe^{2+} increase significantly when the soil become waterlogged (Hewitt et al., 2021; Kögel-Knabner et al., 2010). The available iron coefficient of variation was rated strong surface soil due to CV% greater than 100CV% while moderate for subsurface soils since it is between the 10 to 100 CV% range. The high level of iron present in the soil of the study area is great news for the farmers in the region. This indicates that their crops will have access to sufficient iron, which is essential for their growth and development. However, it's important to note that too much iron can also be harmful to plants. Therefore, it's advisable for farmers to periodically test their soil to ensure that the iron level is optimal for their crops (Rehman *et al.*, 2021; Rout and Sahoo, 2015; White and Broadley, 2009; Willy *et al.*, 2019).

Available Manganese

Manganese is a vital micronutrient for plants, playing a key role in many metabolic processes as an antioxidant cofactor for enzymes and in photosynthetic processes (Kwakye and Kadyampakeni, 2022). The available Manganese ranged from 17.95 to 79.44 mg kg^{-1} in the surface soil (0-20 cm depth) and from 13.98 to 45.37 mg kg^{-1} in the subsurface soil (20-40 cm depth) (Table 2). The available manganese level in the agricultural salt-affected soils near Abaya and Chamo Lakes in South Ethiopia Rift Valley is very high. The mean available manganese level in the surface soil is 32.08 mg kg^{-1} and in the subsurface soil is 23.53 mg kg^{-1} (Table 2). The high level of available manganese in these soils is likely due to the high salinity of the soils. Salinity can

Table 1. Semivariogram models and model parameters for soil micronutrients.

Soil Property	Fitted Model	Nugget (Co)	Partial Sill (C)	Sill (Co + C)	Range (m)	SPD (Co/Co+C)*100	SPD Level	Estimated Error	
								ME	RMSSE
Fe	Sph	0.01	1.11	1.12	5594	0.99	Strong	0.02	0.15
Mn	Sph	0.00	1.10	1.10	5137	0.09	Strong	0.02	0.15
Cu	Sph	0.00	1.07	1.07	20924	0.09	Strong	0.01	0.07
Zn	Sph	0.00	1.13	1.13	4615	0.11	Strong	0.01	0.15

Table 2. Soil micronutrients status of agricultural salt-affected soils around Abaya and Chamo Lakes.

Depth	Des. S	Fe, mg kg^{-1}	Mn, mg kg^{-1}	Cu, mg kg^{-1}	Zn, mg kg^{-1}
0 - 20cm	Mean	61.78	32.08	5.22	0.80
	SD	68.74	26.54	3.21	0.17
	Minimum	14.54	17.95	3.19	0.63
	Maximum	176.02	79.44	10.88	1.04
	CV%	111.25	82.73	61.63	21.19
20 - 40cm	Mean	25.79	23.53	3.82	0.55
	SD	17.88	12.47	1.77	0.32
	Minimum	13.99	13.98	2.21	0.08
	Maximum	57.51	45.37	6.85	0.99
	CV%	69.32	52.99	46.33	58.61

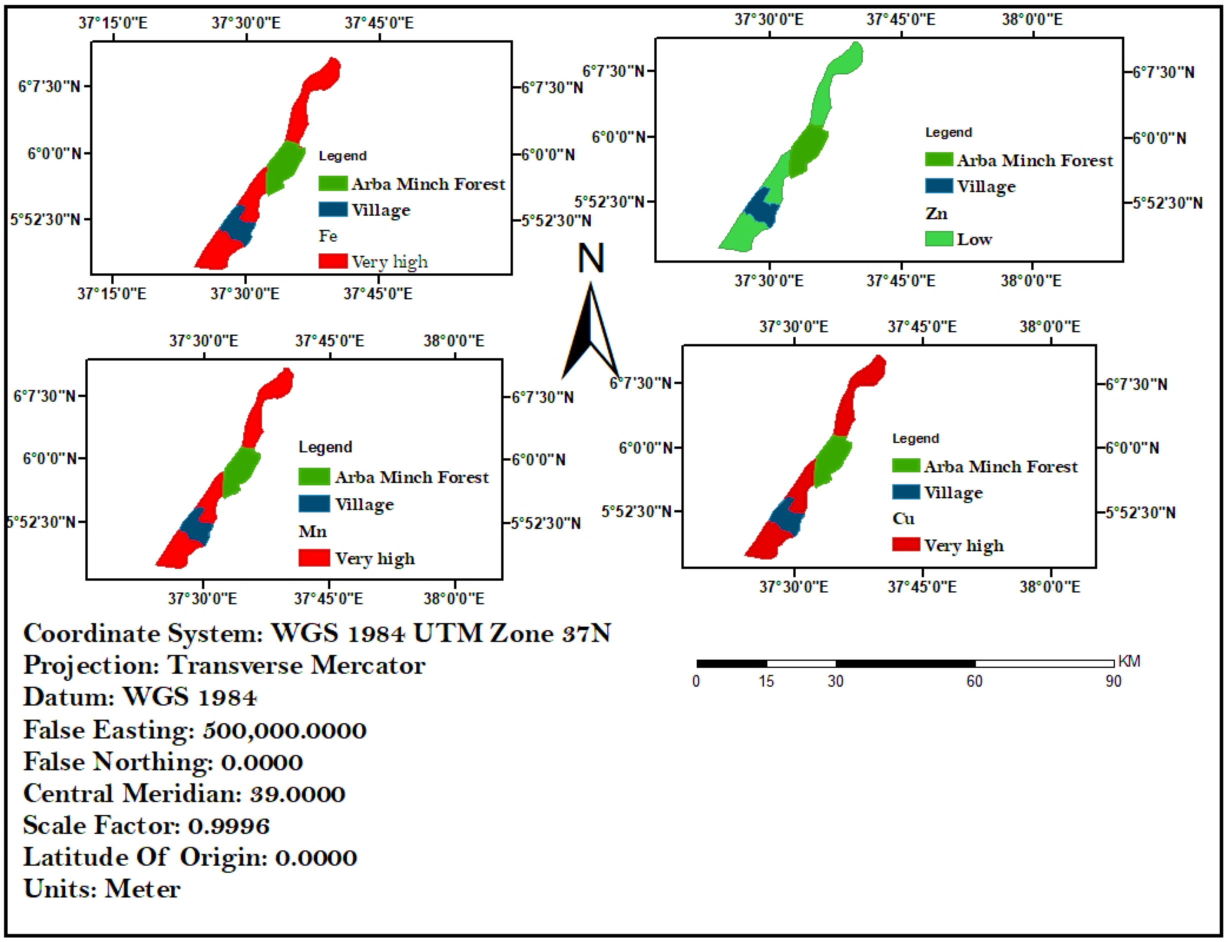

Figure 3. Soil micromutrients status and map of agricultural salt-affected soils around Abaya and Chamo Lakes.

increase the availability of manganese by displacing it from the soil particles. This can lead to manganese toxicity in plants, which can manifest as stunted growth, chlorosis, and necrosis (Bhatla *et al.*, 2018).The soil quality standards and interpreting guidelines developed by Wogi *et al.* (2021) define a very high level of available manganese as > 6mg kg^{-1} (Figure 3). Its coefficient of variation was rated moderate for both surface and subsurface soils since it is between the 10 to 100 CV% range (Table 2). These are most likely manganese under waterlogged salt-affected soil, typical fermentation byproducts. This microbial metabolic process occurs when oxygen levels are very low and degrades humus into simpler organic compounds while producing H_2 and CO_2. In the soil solution, the reported concentrations of acetate (millimolar) and H_2 gas (micromolar) are typical of active fermentation (Nivethadevi *et al.*, 2021; Steger et al., 2017; Thampatti, 2022). The accumulation of these fermentation products during the initial stages of incubation is followed by their depletion as Mn (II) levels rise or methane production starts, indicating consumption by the microbial community during these stages *(*Huan *et al.,* 2018). Soil waterlogging will reduce O_2 and reduce redox potential, increasing soluble Mn^{2+}. Mn availability can be increased by poor aeration in compacted soils and by local accumulation of CO_2 around roots and other soil microsites (Jennings, 2007). The resulting low redox condition will render Mn more available without appreciably affecting the redox potential of the pH of the bulk soil. So, the general manganese level in these soils is not quite at the toxic level, but it is getting close (Maguffin *et al.,* 2020). The high level of readily available manganese must be recognized, and measures must be taken to reduce the possibility of toxicity. The two potential remedies are altering the crop variety to one that can tolerate manganese toxicity or adding chelating agents to the soil to bind the manganese (Dhaliwal *et al.*, 2023; Neal and Zheng, 2015).

Available Zinc

Zinc deficiency is an important micronutrient barrier to food production in every region of the world, and its application has been successful in almost all crops (Younas *et al.,* 2023). The amount of readily available zinc in the surface soil (0–20 cm depth) ranged from 0.63–1.04 mg kg^{-1}, and in the subsurface soil (20–40 cm depth), it ranged from 0.08–0.99 mg kg^{-1} (Table 2). There is low readily available zinc in the agricultural salt-affected soils close to Abaya and Chamo Lakes in the South Ethiopia Rift Valley. The mean concentration of available zinc in soil is 0.80 mg kg^{-1} in surface soil and 0.55 mg kg^{-1} in subsurface soil. According to Mantovi *et al.* (2003), the normal range for zinc in the soil is 1.5 to 6 mg kg^{-1}. These soils' high salinity is probably the reason for their low concentration of readily available zinc. Zinc can form insoluble compounds by reacting with carbonate and hydroxide ions in soils with high pH levels. This can lead to a reduction in plant availability of zinc. Soil salinity can also limit zinc availability by decreasing microbial activity, which is responsible for releasing zinc from organic matter (Andrunik *et al.,* 2020; Baruah, 2018; Suganya *et al.*, 2020). By attaching zinc to soil particles, salinity can reduce zinc availability (Acosta et al., 2011). Zn^{2+} and soil organic matter (OM) components also form stable complexes. Zn availability will be decreased during immobilization reactions; this happens in soils with humic peat deficiencies. These may be why a soil with a healthy amount of organic matter has a zinc deficiency (Laurent *et al.,* 2020; Suganya *et al.,* 2020). On the other hand, keeping Zn^{2+} in solution will improve availability by forming soluble chelated Zn compounds. Freshly applied organic matter and its constituents can chelate Zn^{2+}, though this ability is not always reflected in improved Zn uptake by plants. Plants lacking zinc can suffer from stunted growth, yellowing of the leaves, and decreased yields (Alloway, 2013; Kayranli, 2021). According to the soil quality standards and interpretation guidelines developed by Wogi *et al.* (2021), a low level of available zinc is less than 1.0 mg kg^{-1}, hence the study area rated low (Figure 3). Therefore, these soils have a significantly lower level of zinc availability than is advised. It is critical to be aware of the limited zinc supply and to take precautions against deficiency. This might involve applying fertilizer with zinc to the soil or using a cover crop that resolves zinc (Mustafa *et al.,* 2022). The coefficient of variation of available zinc was rated moderate for both surface and subsurface soils since it is between the 10 to 100 CV% range (Table 2).

Available Copper

Copper is a crucial micronutrient for the growth and development of plants, but it may also be toxic (Ali *et al.,* 2020). In the surface soil (0–20 cm depth), the amount of copper that was readily available ranged from 3.19 to 10.88 mg kg^{-1}, and in the subsurface soil (20–40 cm depth), it ranged from 2.21 to 6.85 mg kg^{-1}. Near the salt-affected agricultural soils of the South Ethiopian Rift Valley's Abaya and Chamo Lakes, there is a readily available and very high concentration of copper. The surface soil (0–20 cm depth) and the subsurface soil (20–40 cm depth) have mean available copper levels of 5.22 mg kg^{-1} and 3.82 mg kg^{-1}, respectively (Table 2). The high concentration of copper in the agricultural salt-affected soils in the study area could be attributed to the abundance of copper-rich volcanic rocks in the region due to its volcanic origin (Hua *et al.*, 2021). Additionally, the alkaline nature of the soils and their high clay content create favorable conditions for the retention of copper in the soil (Kome et al., 2019). Over time, copper is gradually released from these rocks through weathering and leaching and builds up in the soil, leading to high levels of available copper that can cause harm to animals, humans, and plants (Hough, 2010; Izydorczyk *et al.,* 2021). In most soils, the copper content ranges from 2 to 100 mg kg^{-1}, with an average value of about 30 mg kg^{-1}, so this value falls within the normal range (Panagos *et al.,* 2018). According to Bhatla *et al.* (2018), most of this is in unavailable mineral form. It may pollute water bodies as well. Following the standards and interpretation guidelines, Wogi *et al.* (2021) developed a very high available copper level greater than 3 mg kg^{-1} (Figure 3). There are various ways to reduce the quantity of available copper in the soil. One of the ways is to remove the copper-rich rocks in the region. Another option is to add organic matter to the soil, which helps to bind the copper and decrease its availability to plants and animals. It is crucial to monitor the amount of available copper in the soil and take necessary measures to reduce it. The high level of readily available copper can pose a significant risk to the environment and can have a negative impact on agriculture (Alengebawy *et al.*, 2021; Tóth *et al.*, 2016; Van der Ent and Reeves, 2015; Vinod *et al.*, 2021). The available copper coefficient of variation was deemed moderate for both surface and subsurface soils due to its value falling within the range of 10 to 100 CV% (Table 2).

CONCLUSION

Soil properties and distribution are crucial for developing soil health and fertility management plans, as soil fertility decreases due to salinity and sodicity, impacting essential micronutrient solubility. The study aims to analyze salt-affected soils' micronutrient content and map fertility status for successful crop production, land use planning, and reclaiming salt-affected soils. The study found high levels of available iron, manganese, and copper in the soils, while zinc was low. For soil with Fe available, the nugget effect was commonly higher; this suggested that regional heterogeneity in soil qualities existed at short distances while the rest of the micronutrient regional heterogeneity existed at long distances. The available iron coefficient of variation was rated strong surface soil while moderate for subsurface soils. Meanwhile, the available copper, manganese, and zinc coefficients of variation were deemed moderate for both surface and subsurface soils. The study recommends incorporating organic matter into the soil to enhance its structure, water retention, nutrient availability, and reclamation by using different reclaiming materials for salt-affected soils. The study area predominantly has low zinc fertilizer levels, suggesting low soil zinc availability for plants, but they may still require additional zinc fertilizer for optimal yield. On the other hand, very high micronutrient contents must be managed to reduce their toxicity on plant growth and human life.

Acknowledgments
The authors are grateful for the assistance and support of various individuals and institutions during their study. The authors express their appreciation for Mr. Samson Tsegaye's help in the lab and the field and Mr. Geremew Zafu for supporting ArcGIS work. Additionally, they acknowledge the lab personnel and the Ethiopia Design and Water Works soil laboratory in Addis Ababa for their contributions. Lastly, the authors thank Arba Minch University for their logistical support throughout the study or project.

Funding. Under the "Reducing Land Degradation Through and for Sustainable Rural Land Use Research South Ethiopia Rift Valley" Project of the Interuniversity Cooperation program with Arba Minch University of Ethiopia (AMUET2017IUC035A101), VLIR-UOS Belgium provided funding for the study. The fact that the research expenses have been accounted for by the Ph.D. subsidiary funds from the Arba Minch University Research Directorate and the Ethiopian Ministry of Education is also encouraging.

Conflict of interest. The authors have stated that they do not have any conflicts of interest to disclose.

Compliance with ethical standards. Does not apply.

Data availability. The supporting data for the study are all provided in the publication, and if you require any additional data, you may contact the corresponding author for further assistance.

Author contribution statement (CRedit). Azmera Walche: Conceptualization, Data curation, Formal analysis, Visualization, Validation, Investigation, Methodology, Writing an original draft. **Wassie Haile:** Data curation, Visualization, Validation, Investigation, Supervision, review and editing. **Alemayehu Kiflu:** Data curation, Visualization, Validation, Investigation, Supervision, review and editing. **Dereje Tsegaye:** Data curation, Visualization, Validation, Investigation, Supervision, review and editing.

REFERENCES

Abdi, D. and Gebrekristos, S., 2022. Regionalization of Low Flow Analysis in Data Scarce Region: The Case of the Lake Abaya-Chamo Sub-basin, Rift Valley Lakes Basin, Ethiopia. *Journal of Water Management Modeling*. https://doi.org/10.14796/JWMM.C487

Acosta, J. A., Jansen, B., Kalbitz, K., Faz, A. and Martínez-Martínez, S., 2011. Salinity increases mobility of heavy metals in soils. *Chemosphere*, *85*(8), pp. 1318–1324. https://doi.org/10.1016/j.chemosphere.2011.07.046

Addis, H. K., Klik, A. and Strohmeier, S., 2015. Spatial variability of selected soil attributes under agricultural land use system in a mountainous watershed, Ethiopia. *International Journal of Geosciences*, *6*(06), pp. 605-613. https://doi.org/10.4236/ijg.2015.66047

Addise, T., Bedadi, B., Regassa, A., Wogi, L. and Feyissa, S., 2022. Spatial variability of soil organic carbon stock in Gurje Subwatershed, Hadiya Zone, Southern Ethiopia. *Applied and Environmental Soil Science*, *2022*. pp. 1-12. https://doi.org/10.1155/2022/5274482

Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R. and Wang, M.-Q., 2021. Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. *Toxics*, *9*(3), 42. https://doi.org/10.3390/toxics9030042

Ali, A., Bhat, B. A., Rather, G. A., Malla, B. A. and Ganie, S. A., 2020. Proteomic studies of micronutrient deficiency and toxicity. In: Aftab, T., Hakeem, K.R. (eds). *Plant Micronutrients.* Springer, Cham. https://doi.org/10.1007/978-3-030-49856-6_11

Alloway, B. J., 2013. Heavy metals and metalloids as micronutrients for plants and animals. Heavy Metals in Soils: Trace Metals and Metalloids in Soils and Their Bioavailability. *Environmental Pollution*. Springer Dordrecht. 22, pp. 195–209. https://doi.org/10.1007/978-94-007-4470-7

Andrunik, M., Wołowiec, M., Wojnarski, D., Zelek-Pogudz, S. and Bajda, T., 2020. Transformation of Pb, Cd, and Zn minerals using phosphates. *Minerals*, *10*(4), 342. https://doi:10.3390/min10040342

Arétouyap, Z., Njandjock Nouck, P., Nouayou, R., Ghomsi Kemgang, F. E., Piépi Toko, A. D. and Asfahani, J., 2016. Lessening the adverse effect of the semivariogram model selection on an interpolative survey using kriging technique. *SpringerPlus*, *5*(1), pp. 1–11. https://doi:10.1186/s40064-016-2142-4.

Barman, A., Sheoran, P., Yadav, R. K., Abhishek, R., Sharma, R., Prajapat, K., Singh, R. K. and Kumar, S., 2021. Soil spatial variability characterization: Delineating index-based management zones in salt-affected agroecosystem of India. *Journal of Environmental Management*, *296*, 113243. https://doi.org/10.1016/j.jenvman.2021.113243

Baruah, R., 2018. Towards the Bioavailability of Zinc in Agricultural Soils. In: Meena, V. (eds) Role of Rhizospheric Microbes in Soil. Springer, Singapore. https://doi.org/10.1007/978-981-13-0044-8_4.

Basak, N. et al. (2022). Salt Affected Soils: Global Perspectives. In: Shit, P.K., Adhikary, P.P., Bhunia, G.S., Sengupta, D. (eds) Soil Health and Environmental Sustainability. Environmental Science and Engineering. Springer, Cham. https://doi.org/10.1007/978-3-031-09270-1_6.

Beal, T., Massiot, E., Arsenault, J. E., Smith, M. R. and Hijmans, R. J., 2017. Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. *PloS One*, *12*(4), e0175554. https://doi.org/10.1371/journal.pone.0175554.

Bedadi, B., Beyene, S., Erkossa, T. and Fekadu, E., 2023. Soil Management. In *The Soils of Ethiopia*. Springer Cham. pp. 193–234). https://doi.org/10.1007/978-3-031-17012-6

Bhatla, S. C., A. Lal, M., Kathpalia, R. and Bhatla, S. C., 2018. In book: Plant mineral nutrition. *Plant Physiology, Development and Metabolism* . Springer Nature Singapore Pte Ltd. 2018. pp. 37–81.+ https://doi.org/10.1007/978-981-13-2023-1_1

Bindraban, P. S., Dimkpa, C. O. and Pandey, R., 2020. Exploring phosphorus fertilizers and fertilization strategies for improved human and environmental health. *Biology and Fertility of Soils*, *56*(3), pp. 299–317. https://doi.org/10.1007/s00374-019-01430-2.

Bisht, N. and Chauhan, P. S., 2020. Excessive and disproportionate use of chemicals cause soil contamination and nutritional stress. *Soil Contamination-Threats and Sustainable Solutions*, pp. 1–10. https://doi.org/10.5772/intechopen.94593

Blanca Mena, M. J., Alarcón Postigo, R., Arnau Gras, J., Bono Cabré, R. and Bendayan, R., 2017. Non-normal data: Is ANOVA still a valid option? *Psicothema, 2017, Vol. 29, Num.* 4, pp. 552-557. https://doi.org/10.7334/psicothe-ma2016.383

Borena, F. R. and Hassen, J. M., 2022. Impacts of Soil Salinity on Irrigation Potential: In the Case of Middle Awash, Ethiopian Review. *Open Access Library Journal*, *9*(4), pp. 1–18. https://doi.org/10.4236/oalib.1108123

Brevik, E. C., Calzolari, C., Miller, B. A., Pereira, P., Kabala, C., Baumgarten, A. and Jordán, A., 2016. Soil mapping, classification, and pedologic modeling: History and future directions. *Geoderma*, *264*, pp. 256–274. https://doi:10.1016/J.GEODERMA.2015.05.017

Cambardella, C. A., Moorman, T. B., Novak, J. M., Parkin, T. B., Karlen, D. L., Turco, R. F. and Konopka, A. E., 1994. Field-scale variability of soil properties in central Iowa soils. *Soil Science Society of America Journal*, *58*(5), pp. 1501–1511. https://doi.org/10.2136/SSSAJ1994.03615995005800050033X

Challa, A., Kitila, K. and Workina, M., 2022. Evaluation of Gypsum and Leaching Application on Salinity Reclamation and Crop Yield at Dugada District, East Shoa Zone of Oromia. *International Journal of Environmental Chemistry*, *6*(1), pp. 1-6. https://doi.org/10.11648/j.ijec.20220601.11

Chhabra, R. and Chhabra, R., 2021a. Nature and origin of salts, classification, area and distribution of salt-affected soils. *Salt-Affected Soils and Marginal Waters: Global Perspectives and Sustainable Management*, pp. 1–47. https://doi:10.1007/978-3-030-78435-5_1.

Chhabra, R. and Chhabra, R., 2021b. Nutrient Management in Salt-affected Soils. *Salt-Affected Soils and Marginal Waters: Global Perspectives and Sustainable Management*, pp. 349–429. https://doi.org/10.1007/978-3-030-78435-5-8.

Choukr-Allah, R., Mouridi, Z. El, Benbessis, Y. and Shahid, S. A., 2023. Salt-Affected Soils and Their Management in the Middle East and North Africa (MENA) Region: A Holistic Approach. In: Choukr-Allah, R., Ragab, R. (eds) Biosaline Agriculture as a Climate Change Adaptation for Food Security. Springer, Cham. https://doi.org/10.1007/978-3-031-24279-3_2.

Chrysargyris, A., Höfte, M., Tzortzakis, N., Petropoulos, S. A. and Di Gioia, F., 2022. Micronutrients: The borderline between their beneficial role and toxicity in plants. *Frontiers in Plant Science*, *13*, 840624. https://doi.org/10.3389/fpls.2022.840624

Corwin, D. L. and Yemoto, K., 2020. Salinity: Electrical conductivity and total dissolved solids. *Soil Science Society of America Journal*, *84*(5), pp. 1442–1461. https://doi.org/10.1002/saj2.20154

da Silva, J. G., 2019. Food systems and nutrition in the context of climate change. In book: *Water and Sanitation-Related Diseases and the Changing Environment: Challenges, Interventions, and Preventive Measures*, pp. 111–126. https://doi.org/10.1002/9781119415961.ch9

Dhaliwal, S. S., Sharma, V., Shukla, A. K., Verma, V., Kaur, M., Alsuhaibani, A. M., Gaber, A., Singh, P., Laing, A. M. and Hossain, A., 2023. Minerals and chelated-based manganese fertilization influences the productivity, uptake, and mobilization of manganese in wheat (Triticum aestivum L.) in sandy loam soils. *Frontiers in Plant Science*, *14*, 1163528. https://doi.org/10.3389/fpls.2023.1163528

Dimkpa, C., Adzawla, W., Pandey, R., Atakora, W. K., Kouame, A. K., Jemo, M. and Bindraban, P. S., 2023. Fertilizers for food and nutrition security in sub-Saharan Africa: an overview of soil health implications. *Frontiers in Soil Science*, *3*, 1123931. https://doi.org/10.3389/fsoil.2023.1123931

El-Ramady, H., Faizy, S., Amer, M. M., Elsakhawy, T. A., Omara, A. E.-D., Eid, Y. and Brevik, E., 2022. Management of Salt-Affected Soils: A Photographic Mini-Review. *Environment, Biodiversity and Soil Security*, *6*(2022), pp. 61–79. https://doi.org/10.21608/JENVBS.2022.131286.1172

Ferreira, V., Panagopoulos, T., Andrade, R., Guerrero, C. and Loures, L., 2015. Spatial variability of soil properties and soil erodibility in the Alqueva reservoir watershed. *Solid Earth*, *6*(2), pp. 383–392. https://doi.org/10.5194/sed-7-301-2015

Gülser, C., Ekberli, I., and Candemir, F., 2016. Spatial variability of soil physical properties in a cultivated field. *Eurasian Journal of Soil Science*, *5*(3), pp. 192–200. https://dx.doi.org/10.18393/ejss.2016.3.192-200.

Habtamu, A. and Wassie, H., 2022. Review on Causes and Management Strategies of Salt Affected Soils in Lowlands of Ethiopia. *Archives of*

Crop Science, *5*(2), pp. 1–7. https://doi.org/10.36959/718/615.

Hailu, B. and Mehari, H., 2021. Impacts of soil salinity/sodicity on soil-water relations and plant growth in dry land areas: a review. Journal of Natural Sciences Research 12(3): pp.1-10. https://doi.org/10.7176/jnsr%2F12-3-01

Hewitt, A. E., Balks, M. R., Lowe, D. J., Hewitt, A. E., Balks, M. R. and Lowe, D. J., 2021. Gley Soils. *The Soils of Aotearoa New Zealand*, pp. 73–85. https://doi.org/10.1007/978-3-030-64763-6.

Hough, R. L. (2010). Copper and lead. In Peter S. Hooda, ed. *Trace Elements in Soils*. Copyright © 2010 Blackwell Publishing Ltd. pp. 441–460. https://doi.org/10.1002/9781444319477.ch18

Hua, Z. F., Chen, J., Erwin, D. H., Syverson, D. D., Ni, P., Rampino, M., Chi, Z., Cai, Y. and Xiang, L., 2021. Felsic volcanism as a factor driving the end-Permian mass extinction. *Science Advances*, *7*(47), eabh1390. https://doi.org/10.1126/sciadv.abh1390.

Huan, Z., Wu, J., Gao, L., Yu, J., Yuan, X., Zhu, W., Wang, X. and Cui, Z., 2018. Aerobic deterioration of corn stalk silage and its effect on methane production and microbial community dynamics in anaerobic digestion. *Bioresource Technology*, *250*, pp. 828–837. https://doi.org/10.1016/j.biortech.2017.09.149

Izydorczyk, G., Mikula, K., Skrzypczak, D., Moustakas, K., Witek-Krowiak, A. and Chojnacka, K., 2021. Potential environmental pollution from copper metallurgy and methods of management. *Environmental Research*, *197*, 111050. https://doi.org/10.1016/j.envres.2021.111050.

Jennings, K., 2007. *Effect of varying degrees of water saturation on redox conditions in a yellow brown apedal B soil horizon*. University of the Free State. Corpus ID: 99614599. https://www.semanticscholar.org/paper/Effect-of-varying-degrees-of-water-saturation-on-in-Jennings

Kayranli, B., 2021. *Zinc Removal with Lignocellulosic Adsorbents; Interaction Mechanisms, from Biosorbent to Soil Conditioner*. https://doi.org/10.21203/rs.3.rs-400539/v1

Kebede, F., 2023. Status, Drivers, and Suggested Management Scenarios of Salt-Affected Soils in Africa. In: Choukr-Allah, R., Ragab, R. (eds) Biosaline Agriculture as a Climate Change Adaptation for Food Security. Springer, Cham. https://doi.org/10.1007/978-3-031-24279-3_13.

Kögel-Knabner, I., Amelung, W., Cao, Z., Fiedler, S., Frenzel, P., Jahn, R., Kalbitz, K., Kölbl, A. and Schloter, M., 2010. Biogeochemistry of paddy soils. *Geoderma*, *157*(1–2), pp. 1–14. https://doi.org/10.1016/j.geoderma.2010.03.009

Kome, G. K., Enang, R. K., Tabi, F. O. and Yerima, B. P. K., 2019. Influence of clay minerals on some soil fertility attributes: a review. *Open Journal of Soil Science*, *9*(9), pp. 155–188. https://doi.org/10.4236/ojss.2019.99010

Kwakye, S. and Kadyampakeni, D. M., 2022. Micronutrients Improve Growth and Development of HLB-Affected Citrus Trees in Florida. *Plants*, *12*(1), 73. https://doi.org/10.3390/plants12010073

Laurent, C., Bravin, M. N., Crouzet, O., Pelosi, C., Tillard, E., Lecomte, P. and Lamy, I., 2020. Increased soil pH and dissolved organic matter after a decade of organic fertilizer application mitigates copper and zinc availability despite contamination. *Science of the Total Environment*, *709*, 135927. https://doi.org/10.1016/j.scitotenv.2019.135927

Lindsay, W. L. and Norvell, Wa., 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal*, *42*(3), pp. 421–428. https://doi.org/10.2136/sssaj1978.03615995004200030009x

López-Granados, F., Jurado-Expósito, M., Atenciano, S., García-Ferrer, A., Sánchez de la Orden, M. and García-Torres, L., 2002. Spatial variability of agricultural soil parameters in southern Spain. *Plant and Soil*, *246*, pp. 97–105. https://doi.org/10.1023/A:1021568415380

Maguffin, S. C., Abu-Ali, L., Tappero, R. V, Pena, J., Rohila, J. S., McClung, A. M. and Reid, M. C., 2020. Influence of manganese abundances on iron and arsenic solubility in rice paddy soils. *Geochimica et Cosmochimica Acta*, *276*, pp. 50–69. https://doi.org/10.1016/j.gca.2020.02.012

Mantovi, P., Bonazzi, G., Maestri, E., and Marmiroli, N., 2003. Accumulation of copper and zinc from liquid manure in agricultural soils and crop plants. *Plant and Soil*, *250*, pp. 249–257. https://doi.org/10.1023/A:1022848131043

Martínez-Cortijo, J. and Ruiz-Canales, A., 2018. Effect of heavy metals on rice irrigated fields with waste water in high pH Mediterranean soils: The particular case of the Valencia area in Spain. *Agricultural Water Management*, *210*, pp. 108–123. https://doi.org/10.1016/j.agwat.2018.07.037

Mengistu, H. A., Demlie, M. B. and Abiye, T. A., 2019. Groundwater resource potential and status of groundwater resource development in Ethiopia. *Hydrogeology Journal*. 27, pp. 1051–1065. https://doi.org/10.1007/s10040-019-01928-x

Mustafa, A., Athar, F., Khan, I., Chattha, M. U., Nawaz, M., Shah, A. N., Mahmood, A., Batool, M., Aslam, M. T. and Jaremko, M., 2022. Improving crop productivity and nitrogen use efficiency using sulfur and zinc-coated urea: A review. *Frontiers in Plant Science*, *13*, 942384. https://doi.org/10.3389/fpls.2022.942384

Neal, O. S. and Zheng, W., 2015. Manganese toxicity upon overexposure: a decade in review. *Current Environmental Health Reports*, *2*, pp. 315–328. https://doi.org/10.1007/s40572-015-0056-x

Nivethadevi, P., Swaminathan, C. and Kannan, P., 2021. Chapter-4 Soil Organic Matter Decomposition-Roles, Factors and Mechanisms. *In Sukul SP*, *ed.: Latest Trends in Soil Sciences volume 1Publisher: Integrated Publications, New Delhi*, *133*, 61. https://doi.org/10.22271/int.book.33

Ohanenye, I. C., Emenike, C. U., Mensi, A., Medina-Godoy, S., Jin, J., Ahmed, T., Sun, X. and Udenigwe, C. C., 2021. Food fortification technologies: Influence on iron, zinc and vitamin A bioavailability and potential implications on micronutrient deficiency in sub-Saharan Africa. *Scientific African*, *11*, e00667. https://doi.org/10.1016/j.sciaf.2020.e00667.

Panagos, P., Ballabio, C., Lugato, E., Jones, A., Borrelli, P., Scarpa, S., Orgiazzi, A. and Montanarella, L., 2018. Potential sources of anthropogenic copper inputs to European agricultural soils. *Sustainability*, *10*(7), 2380. https://doi.org/10.3390/su10072380

Pasala, R., Kulasekaran, R., Pandey, B. B., Manikanta, C., Gopika, K., Daniel, P. S. J., Elthury, S. and Yadav, P., 2022. Recent advances in micronutrient foliar spray for enhancing crop productivity and managing abiotic stress tolerance. *Plant Nutrition and Food Security in the Era of Climate Change*, pp. 377–398. https://doi.org/10.1016/B978-0-12-822916-3.00008-1

Prăvălie, R., 2021. Exploring the multiple land degradation pathways across the planet. *Earth-Science Reviews*, *220*, 103689. https://doi.org/10.1016/j.earscirev.2021.103689

Pulido-Bosch, A., Rigol-Sanchez, J. P., Vallejos, A., Andreu, J. M., Ceron, J. C., Molina-Sanchez, L. and Sola, F., 2018. Impacts of agricultural irrigation on groundwater salinity. *Environmental Earth Sciences*, *77*, pp. 1–14 https://doi.org/10.1007/s12665-018-7386-6

Rajičić, V., Popović, V., Perišić, V., Biberdžić, M., Jovović, Z., Gudžić, N., Mihailović, V., Čolić, V., Đurić, N. and Terzić, D., 2020. Impact of nitrogen and phosphorus on grain yield in winter triticale grown on degraded vertisol. *Agronomy*, *10*(6), 757. https://doi.org/10.3390/agronomy10060757

Regassa, A., Kibret, K., Selassie, Y. G., Kiflu, A. and Tena, W., 2023. Soil Properties. In Beyene S., Regassa A., Mishra BB. and Haile M, eds. *The Soils of Ethiopia*. pp. 111–156. Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-031-17012-6

Rehman, A. U., Masood, S., Khan, N. U., Abbasi, M. E., Hussain, Z. and Ali, , 2021. Molecular basis of Iron Biofortification in crop plants; A step towards sustainability. *Plant Breeding*, *140*(1), pp. 12–22. https://doi.org/10.1111/pbr.12886

Rengel, Z., 2023. Plant responses to soil-borne ion toxicities. In *Marschner's Mineral Nutrition of Plants* pp. 665–722. Elsevier. https://doi.org/10.1016/B978-0-12-819773-

8.00001-0

Rout, G. R. and Sahoo, S., 2015. Role of iron in plant growth and metabolism. *Reviews in Agricultural Science*, *3*, pp. 1–24. https://doi.org/10.7831/ras.3.1

Saleh, A. M., 2018. Spatial variability mapping of some soil properties in Jadwal Al_Amir Project/Babylon/Iraq. *Journal of the Indian Society of Remote Sensing*, *46*(9), pp. 1481–1495. https://doi.org/10.1007/s12524-018-0795-x

Sani, S., Abdulkadir, A., hmad Pantami, S. A., Sani, M., Amin, A. M. and Abdullahi, M. Y., 2023. Spatial Variability and Mapping of Selected Soil Physical Properties under Continuous Cultivation. *Turkish Journal of Agriculture-Food Science and Technology*, *11*(4), pp. 719–729. https://doi.org/10.24925/turjaf.v11i4.719-729.5733

Shahrajabian, M. H., Sun, W. and Cheng, Q., 2022. Foliar application of nutrients on medicinal and aromatic plants, the sustainable approaches for higher and better production. *Beni-Suef University Journal of Basic and Applied Sciences*, *11*(1), pp. 1–10. https://doi.org/10.1186/s43088-022-00210-6

Shanshan, L., Chen, S., Wang, M., Lei, X., Zheng, H., Sun, X., Wang, L. and Han, Y., 2021. Redistribution of iron oxides in aggregates induced by pe+ pH variation alters Cd availability in paddy soils. *Science of the Total Environment*, *752*, 142164. https://doi.org/10.1016/j.scitotenv.2020.142164

Sharma, D. K. and Singh, A., 2017. Current trends and emerging challenges in sustainable management of salt-affected soils: a critical appraisal. *Bioremediation of Salt Affected Soils: An Indian Perspective*, pp. 1–40. https://doi.org/10.1007/978-3-319-48257-6_1

Shukla, A. K., Behera, S. K., Pakhre, A. and Chaudhari, S. K., 2018. Micronutrients in soils, plants, animals and humans. *Indian Journal of Fertilisers*, *14*(3), pp. 30–54. https://www.researchgate.net/publication/324497356

Steffan, J. J., Brevik, E. C., Burgess, L. C. and Cerdà, A., 2018. The effect of soil on human health: an overview. *European Journal of Soil Science*, *69*(1), pp. 159–171. https://doi.org/10.1111/ejss.12451

Steger, F., Rachbauer, L., Windhagauer, M., Montgomery, L. F. R. and Bochmann, G., 2017. Optimisation of continuous gas fermentation by immobilisation of acetate-producing Acetobacterium woodii. *Anaerobe*, *46*, pp. 96–103. https://doi.org/10.1016/j.anaerobe.2017.06.010

Stritih, A., 2021. *Risk-based assessments of ecosystem services: Addressing uncertainty in mountain forest management*. ETH Zurich. Thesis for: Doctor of Sciences. Diss. ETH NO. 27728 ETH Zürich, Planning of Landscape and Urban Systems. https://doi.org/10.3929/ethz-b-000493088

Suganya, A., Saravanan, A. and Manivannan, N., 2020. Role of zinc nutrition for increasing zinc availability, uptake, yield, and quality of maize (Zea mays L.) grains: An overview. *Commun. Soil Science. Plant Analysis*, *51*(15), 2001–2021. https://doi.org/10.1080/00103624.2020.1820030

Swafo, S. M. and Dlamini, P. E., 2023. Utilisation of Intrinsic and Extrinsic Soil Information to Derive Soil Nutrient Management Zones for Banana Production in a Smallholder Farm. *Land*, *12*(9), 1651. https://doi.org/10.3390/land12091651

Tessema, N., Yadeta, D., Kebede, A. and Ayele, G. T., 2023. Soil and Irrigation Water Salinity, and Its Consequences for Agriculture in Ethiopia: A Systematic Review. *Agriculture (Switzerland)*, *13*(1). https://doi.org/10.3390/agriculture13010109

Thampatti, K. C. M., 2022. Problem Soils: Constraints and Management (1st ed.). CRC Press. https://doi.org/10.1201/9781003347354

Tiruneh, T. A. (2005). *Water quality monitoring in Lake Abaya and Lake Chamo region : a research based on water resources of the Abaya-Chamo Basin - South Ethiopia* [Fachbereich 8, Chemie - Biologie]. https://nbn-resolving.org/urn:nbn:de:hbz:467-1040

Tóth, G., Hermann, T., Da Silva, M. R. and Montanarella, L., 2016. Heavy metals in agricultural soils of the European Union with implications for food safety. *Environment International*, *88*, pp. 299–309. https://doi.org/10.1016/j.envint.2015.12.017

Tripathi, D. K., Singh, S., Singh, S., Mishra, S., Chauhan, D. K., and Dubey, N. K., 2015. Micronutrients and their diverse role in agricultural crops: advances and future prospective. *Acta Physiologiae Plantarum*, *37*, pp. 1–14. https://doi.org/10.1007/s11738-015-1870-3

Van der Ent, A. and Reeves, R. D., 2015. Foliar metal accumulation in plants from copper-rich ultramafic outcrops: case studies from Malaysia and Brazil. *Plant and Soil*, *389*, pp. 401–418. https://doi.org/10.1007/s11104-015-2385-9

Vinod, K., Pandita, S., Sidhu, G. P. S., Sharma, A., Khanna, K., Kaur, P., Bali, A. S. and Setia, R., 2021. Copper bioavailability, uptake, toxicity and tolerance in plants: A comprehensive review. *Chemosphere*, *262*, 127810. https://doi.org/10.1016/j.chemosphere.2020.127810

Walche, A., Haile, W., Kiflu, A. and Tsegaye, D., 2023. Assessment and Characterization of Agricultural Salt-Affected Soils around Abaya and Chamo Lakes, South Ethiopia Rift Valley. *Applied and Environmental Soil Science*, *2023*, pp. 1–18. https://doi.org/10.1155/2023/3946508

Wang, K., 2022. *Reduction of Se (IV), Se (VI) and Re (VII) by Fe reactive phases present in CEMs and COx*. Université Grenoble Alpes .Thesis [2020-....]. https://www.researchgate.net/publication/364383235

White, P. J. and Broadley, M. R., 2009. Biofortification of crops with seven mineral elements often lacking in human diets–iron, zinc, copper, calcium, magnesium, selenium and iodine. *New Phytologist*, *182*(1), pp. 49–84. https://doi.org/10.1111/j.1469-8137.2008.02738.x

Willy, D. K., Muyanga, M., Mbuvi, J. and Jayne, T., 2019. The effect of land use change on soil fertility parameters in densely populated areas of Kenya. *Geoderma*, *343*, pp. 254–262. https://doi.org/10.1016/j.geoderma.2019.02.033

Wogi, L., Dechassa, N., Haileselassie, B., Mekuria, F., Abebe, A. and Tamene, L., 2021. A guide to standardized methods of analysis for soil , water , plant , and fertilizer resources for data documentation and knowledge sharing in Ethiopia. *International Center for Tropical Agriculture (CIAT)*, *519*, pp. 41. https://alliancebioversityciat.org/publications-data/guide-standardized-methods-analysis-soil-water-plant-and-fertilizer-resources.

Worku, A., Bedadi, B. and Mohammed, M., 2015. *Assessment and Mapping of Fertility Status of Salt Affected soils Amibara Area, Central Rift Valley of Ethiopia*. MSc Thesis, School of Graduate Studies, Haramaya University, Haramaya, Ethiopia. https://www.researchgate.net/publication/330511238

Yao, X., Yu, K., Deng, Y., Liu, J. and Lai, Z., 2020. Spatial variability of soil organic carbon and total nitrogen in the hilly red soil region of Southern China. *Journal of Forestry Research*, *31*(6), pp. 2385–2394. https://doi.org/10.1007/s11676-019-01014-8

Younas, N., Fatima, I., Ahmad, I. A. and Ayyaz, M. K., 2023. Alleviation of zinc deficiency in plants and humans through an effective technique; biofortification: A detailed review. *Acta Ecologica Sinica*, *43*(3), pp. 419–425. https://doi.org/10.1016/j.chnaes.2022.07.008