MAPPING THE SPATIAL VARIABILITY OF SOIL ACIDITY AND EVALUATION OF PHYSICO-CHEMICAL SOIL PROPERTIES:- IN CASE OF DEWOSHE SUB-WATERSHED, GUMMER DISTRICT, GURAGE ZONE , ETHIOPIA

MSc. THESIS

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As *Thesis* Research advisor, I hereby certify that I have read and evaluated this *Thesis* entitled Mapping the Spatial Variability of Soil Acidity and Evaluation of Physico-Chemical Soil Properties:- In case of Dewoshe Sub-Watershed, Gummer District, Gurage Zone, Ethiopia**.** I recommend that it be submitted as fulfilling the *Thesis* requirement.

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STATEMENT OF THE AUTHOR

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BIOGRAPHICAL SKETCH

The author was born on 11 January 1987 E C, in Asgedom Bata Kebele, Wogera Woreda, North Gondar zone. He attended elementary school education from 1996-2003 at Avalay. He then transferred to Abagiorgis Senior Secondary School and studied his secondary education from 2004-2007.

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LIST OF ABBREVIATIONS AND ACRONYMS

Al	Aluminium
ANOVA	Analysis of variance
BD	Bulk Density
C: N	Carbon Nitrogen Ratio
Ca	Calcium
CEC	Cation Exchange Capacity
cm^{-3}	Centi mole per cube
Cmol	Centi mole
CSA	Central Statistical Agency
EDTA	Ethylendiamine Tetraacetic Acid
FAO	Food and Agricultural Organization
GIS	Geographical Information System
GLM	General Linear Model
gm	gram
GPS	Geographical Position System
GWANRO	Gummer Woreda Agricultural and Natural Resource Organization
H	Hydrogen
ha	Hectare
HCl	Hydrochloric acid
hrs	hours
KCl	Potassium Chloride
Kg	Kilogram
LSD	List Significant Difference
masl	meter above sea level
Mg	Magnesium
mm	millimeter
Na	Sodium
NH_4OAc	Ammonium Acetate
OC	Organic Carbon
OM	Organic Matter
P	Available Phosphorous

P	Phosphorus
PBS	Percent Base Saturation
PD	Particle Density
pH	Power of Hydrogen
pH-H_2O	power of Hydrogen in water solution
pH-KCl	power of Hydrogen in Potassium Chloride solution
RCBD	Randomized Complete Block Design
RMSE	Root Mean Square Error
SAS	Statistical Analysis Software
SNNPR	Southern Nations, Nationalities, and Peoples Region
SOM	Soil Organic Matter
TN	Total Nitrogen
USDA	United State Department of Agriculture

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ABSTRACT

Mapping the spatial variability of soil acidity and evaluation of physico-chemical soil properties on the study area is important to design appropriate soil fertility management practices. Mapping the spatial variability is a key operation as it provides knowledge about soil acidity and how it can be used sustainably. The study was conducted at the Dewoshe sub-watershed Gummer district, Guraghe Zone, SNNPR, Ethiopia. Twenty-eight soil samples were collected from two crop types with seven replication at two soil depths (0–20 and 20–40 cm), respectively. The evaluation of physico-chemical soil properties were analyzed using the ANOVA GLM procedure of SAS software, and mapping the spatial variability of soil acidity were analyzed using Arc GIS 10.4. Furthermore, the study has investigated that various physico-chemical soil properties were profoundly influenced due to crop types and soil depths. Soil BD, total porosity, and exchangeable acidity, TN, OM, and C: N, available P, exchangeable Mg, CEC, and exchangeable acidity were significantly affected due to Enset and cereal crops, soil depths, and their interaction between crop types and soil depths. In contrast, sand, silt, and clay fraction and change of pH exhibited no statistically significant variation within the crop and their interaction between crop types and soil depths. But there was a variation of sand and clay on soil depths. Exchangeable (K, Na, and H) were only varied in crop types. The change of pH, exchangeable Al, and Ca were varied within crop types, soil depths, and their interaction between crop types and soil depths and only within crop types and soil depths, respectively. The highest and the lowest values of some physico-chemical soil properties of sand, clay, BD, total porosity, pH-H_2O, pH-KC, OM, TN, available P, and CEC were (38.9, 34.4), (23.07, 19.4), (1.35, 1.07), (59.7, 49), (6.27, 4.84), (5.67, 4.1), (4.58, 0.79), (0.26, 0.07), and (28.6, 15.6) within cop types, and soil depths respectively. Cereal crop fields as compared to the Enset crop fields were suffered from soil degradation and decline in soil fertility on the spatial points of beginning at strong to steep slope mapping parts with the same soil depths. But both in the study area, in general, pointed out that these changes are not in favour of the ecosystem and caused deterioration in the quality of soil resources which in turn led to a decline in agricultural crop productivity. This calls for urgent measures to be taken that encompass a mix of technological and policy options. Further research and development interventions into the dynamics and impact of crop land-use change on ecosystems and their components at various scales (from small sub-watersheds to region and country) are required if conservation and agricultural development goals for this sub-watershed in particular and the country in general, are to be met on a sustainable basis. And again, mapping the spatial variability of soil acidic problems by OK is needed to clearly show the specific locations of the study areas, where attention is required with respect to sustainable management of crop nutrients.

***Keywords*:-** Arc GIS; Crop types; Ordinary kriging; Physico-chemical soil properties; SAS; Soil depths; Spatial variability; Sustainable management;.

INTRODUCTION

1.1. Background

Soil is the foundation natural resource on which the life-supporting system and socio-economic development depend. Soils provide food, fodder, and fuel for meeting basic human and animal needs (Pulakeshi *et al*., 2014). Since soil is a scarce resource with a carrying capacity that can be stretched only to a limited extent with the help of technology (Buzuayehu *et al*., 2002), there is an increasing demand for information on it (Fasina *et al*., 2007; Nicolaescu *et al*., 2009).

Soil acidity is a term used to describe soils with a pH value less than 7 (Robarge, 2008). It is a major constraint to agricultural productivity throughout Africa where high rainfall is common due to the deficiencies of nitrogen by leaching, phosphorus by fixation, and low soil organic matter (Kenyanjua, 2002; Kisinyo, 2011).

Mapping the spatial variability of soil acidity on crop types provides pertinent information on soil acidity across landform and topographic gradient (slope gradient) (Denton *et al*., 2017) especially on crop fields. Although strong efforts and several case studies regarding Geostatistics in soil mapping have been done in developed countries (Reuter *et al*., 2008; Robinson and Metternicht, 2006), little experience in the application of geostatistics exists in developing countries like Ethiopia, particularly Gummer district. In line with, Ripendra *et al*. (2019) spatial distribution of the soil acidity based on kriging shows a high level of variability even though the sampled field is relatively small. Moreover, it may provide reliable and timely information to improve the implementation of effective management strategies for sustainable agricultural crop production in acid-affected areas especially in Ethiopian highland areas like Gummer districts, Dewoshe sub-watershed area.

Physico-chemical soil property indicates a state of soil functions and soil quality degradation status. It is suggested for understanding the sustainability of soil resources (Arshad and Martin, 2002; Singh and Khera, 2009). Successful crop production depends on the sustainable use of soil resources, because of the decline in soil quantity within a short time (Brady and Weil, 2002).

Most of the Sub–Saharan Africa (SSA) soils are naturally less fertile than soils of North America, Europe, and Asia. They are typically low in TN, CEC, SOM, and commonly deficient in P, Mg, and Sulphur (John *et al*., 1995). Therefore, soil fertility constraints to crop production in regions are recognized as the major obstacles to food security (Sanchez *et al*., 2000). Also, soil fertility is declining particularly in densely populated and hilly countries of the Rift Valley areas such as Ethiopia, Kenya, Rwanda, and Malawi (Roy *et al*., 2003; Bationo *et al*., 2006). In Ethiopia, the depletion rate of macronutrients N, P, and K were 122, 13, and 82 kg ha^{-1} $year^{-1}$, respectively which is estimated to be the highest in Sub–Saharan Africa (Amare *et al*., 2005). Ethiopia has potentially rich land resources but agricultural crop productivity has been below optimum yield mainly due to a range of factors including soil erosion, acidity, and nutrient depletion, lack of soil fertility replenishment, nutrient mining, and lack of balanced fertilization (Tesfahunegn *et al*., 2011; Wondwosen and Sheleme, 2011).

Good crop production is a function of its physico-chemical soil properties on which have not only qualitative but also quantitative information to formulate the appropriate crop production management programs (Adeyolanu and Ogunkunle, 2016). According to GWANRO (2018), extensive research is required on soil acidity and physico-chemical soil properties of the study area of the Gummer district, especially the Dewoshe sub-watershed area. Empirical solutions such as applying major plant nutrients or essential materials to the soil were not sufficient without research findings. Knowing about soil acidity and physico-chemical soil properties were the most valuable asset for crop production. Therefore, to improve its application and to rate soils based on their soil acidity and fertility status, evaluation was a prerequisite. In Ethiopia, the information presently available on mapping soil acidity and physico-chemical soil properties were not adequate to meet the requirement of agricultural development programs, and rational fertilizer promotions and recommendations based on actual limiting nutrients for a given crop. Periodic evaluation of important physico-chemical soil properties and their responses to changes in crop management is necessary to improve and maintain the fertility and productivity of soil (Wakene and Heluf, 2003). Mapping the spatial variability of soil acidity by applying a geographic information system (GIS) was also the order of the day to available information for present and future uses. The soil acidity mapping can be used for delineating soil acidity, studying soil acidity change due to soil depth dynamics, and determining the nutrient requirement for the deficient areas. According to Gummer Woreda Agriculture Office, more than 70% of the area is affected by soil acidity resulting in severe yield reduction. However, there is little or no scientific information pertinent to mapping the spatial variability of soil acidity and evaluation of physico-chemical soil properties in the district. Hence, this study was initiated with the following specific objectives:-

- To map the spatial variability of soil acidity in the study area within two soil depths.
- To evaluate the variation of selected phsico-chemical soil properties across crop types and soil depths.

2. LITRATURE REVIEW

2.1. Concepts of Soil Properties and Crop Types

Crop in agricultural science is very dynamic in nature and fertilizer practices change with time due to the release of new cultivars and changing production practices in sustainable crop production systems. The use of nutrients in crop plants provides in-depth scientific information that is applicable through many methods of crop production. It is a valuable tool for improving crop yields at a lower cost and less stress on the environment (Fageria, 2019).

Most of the Sub–Saharan Africa (SSA) soils are naturally less fertile than soils of North America, Europe, and Asia. They are typically low in available N, CEC, SOM, and commonly deficient in P, Mg, and Sulphur (John *et al*., 1995). Therefore, soil fertility constraints to crop production in regions are recognized as the major obstacles to food security (Sanchez *et al*., 2000). Also, soil fertility is declining particularly in densely populated and hilly countries of the Rift Valley areas such as Ethiopia, Kenya, Rwanda, and Malawi (Roy *et al*., 2003; Bationo *et al*., 2006). In Ethiopia, the depletion rate of macronutrients N, P, and k were 122, 13, and 82 kg ha-^{1} year^{-1}, respectively which is estimated to be the highest in Sub–Saharan Africa (Amare *et al*., 2005). Ethiopia has potentially rich land resources but agricultural productivity has been below optimum yield mainly due to a range of factors including soil erosion, acidity, and nutrient depletion, lack of soil fertility replenishment, nutrient mining, and lack of balanced fertilization (Tesfahunegn *et al*., 2011; Wondwosen and Sheleme, 2011).

Crop yield tends to decrease when the soil gets depleted in its nutrients (Tilahun, 2007). The problems might be more in the case of the Southern Nations, Nationalities, and Peoples' Regional State (SNNPRS) due to high population density and fragmented farmland as well as continued farming. The proper rates of plant nutrients can be determined by knowledge about the nutrient requirement of the crop and supplying power of the soil (Tilahun, 2007). However, Ethiopian farmers used to apply only chemical fertilizers diammonium phosphate (DAP) and urea to increase crop yields for about five decades and this did not consider soil fertility status and crop requirement.

The morphological and physico-chemical soil properties determine their adaptability to cultivation and the level of biological activity that can be supported by the soil (Brady and Weil, 2002).

Soil properties are a thing that indicates a state of soil functions and soil quality degradation status. It is suggested for understanding the sustainability of soil resources (Arshad and Martin, 2002; Singh and Khera, 2009). Successful crop production depends on the sustainable use of soil resources, because of the decline in soil quantity within a short time. For this reason, the action of marginal land has a high priority. Whatever extent, it is being achieved only through a good understanding of the physico-chemical, and biological soil properties and the resilience characteristics of the soils (Brady and Weil, 2002). Soil properties are an indicator of soil quality that could be understood through biological, physico-chemical, and function of soil management practices (Moges *et al*., 2013; Ketema and Yimer, 2014). And soil quality can respond correctly to the capacity of a soil function within a natural or managed ecosystem to sustain plants and animal productivity, maintain or enhance water and air quality and finally support human health (Moges *et al*., 2013).

In case the soil quality is becoming a great significant resource to raise crop productivity. It arranges the food required for the current and future population in developing countries like Ethiopia, as their economy mainly depends on agriculture (Negasa *et al*., 2017). Serious development challenges in many developing countries including Ethiopia are a problem of soil degradation. Soil degradation induced by land and soil mismanagement systems coupled with high dependency on an erratic and unreliable rain-fed farming system has aggravated the problem of food insecurity in Ethiopia (Tesfahunegn and Gebru, 2020).

2.1.1. Concepts of physical soil properties on crop fields

In the soil moisture retention capacity, ease of root penetration, aeration, and retention of plant nutrients are all closely connected with the physical properties of the soil (Brady and Weil, 2002).

Plants are growing on soil properties that make them useful-provides of water, nutrients, and anchorage for annual and perennial crops and other land use types

(Mamun *et al.*, 2011). From physical soil properties bulk density, total porosity, and textures are the main part that influences on crop types.

2.1.1.1. Texture

Texture forms the inherent property of soils and textural classes are not subject to easy modification in the field (Kiflu and Beyene, 2013; Teshome, 2019). Soil texture is a basic property that controls moisture-holding capacity, supply of nutrients, water percolation and aeration, etc (Sehgal, 1996). Accordingly, Haile and Fetene (2012) extreme textures of soil are unfavourable for most plant species. Cereals are known to give the best productivity on moderately fine-textured soils; while fine-textured soils and deep soil have been favourable for tap-rooted plants. The most dominant soil texture groups in Enset and cereal farms are clay and silt clay in nature.

2.1.1.2. Bulk density

Bulk density is used as an indicator of compaction, it can also be used to judge the value of soil porosity (Flint and Flint, 2002), which largely determines air and water movement and a range of associated soil functions to crop. As bulk density increases, porosity generally decreases. A reduction in total pore space can reduce soil's water storage capacity and can restrict gas flow as well. The effects of compaction on soil biota vary; compaction can generate both positive and negative effects on soil and biota, though an upper limit of roughly 1.7 g cm^{-3} was suggested to exist, with negative effects on soil structure (Horn and Fleige, 2009) and microbial communities (Beylich *et al.*, 2010) mainly occurring once bulk density exceeds this value.

Bulk density can be modified by soil OM management and tillage practices (Brady and Weil, 2002). Soil bulk density is among the hydro-physical properties affected by soil management practices, mainly cultivation. Bulk densities are found to be high in cultivated tropical soils due to rapid loss of organic matter due to its turnover and rapid rate of oxidation, and soil compaction due to heavy machinery (Buytaert *et al.*, 2002; Zhang and Zhang, 2005). This demonstrates cultivation of deforested land may rapidly diminish soil quality, as ecologically sensitive components of the previous ecosystem are not able to buffer the effects of agricultural practices. Therefore, these changes are functions of the length of time the soils were subjected to cultivation (Mulugeta, 2004).

2.1.2. Concepts of chemical soil properties on crop farm fields

In agriculture, the farming system is significantly affected by chemical soil properties. The crop plant species also modifies soil chemistry by providing different (quantitatively and qualitatively) crop residues (Kwiatkowski and El˙zbieta, 2020). The values of weathering of mineral components, decomposition of organic materials, and the activity of plants, and animals affect processes leading to soil development and soil fertility is occurred in the chemical reactions of soils (Sumner, 2000). Many soil properties, however, change with variation in land use/management practices and are more susceptible to erosion losses.

The organic cropping systems for most crops are associated with strict adherence to the principle that synthetic mineral fertilizers and crop protection chemicals should not be used (Kwiatkowski *et al*., 2020). The genus and species of the crop plant also have a substantial impact on chemical soil properties. Cereal crops are contributed to less favourable chemical composition of soils and their enzymatic properties than root and Leguminosae crops. This is due to the less beneficial chemical composition of cereal crop residues that enter the soil. In other ways more beneficial chemical composition of root and legume crop residues that enter the soil (Kwiatkowsk *et al*., 2020).

2.1.2.1. Soil reaction (pH)

Soil reaction is the broad term referring to the acidity or alkalinity of the soil. Its measure is indicated by soil pH, which is a fundamental property that can affect soil quality (acidity or alkalinity) and use. And also, it is the main factor affecting soil nutrient availability and chemical substances (Caritat, *et al*., 2011). Soil reaction (pH) in particular, can be considered a key variable due to its influence on many other soil proprieties and processes affecting plant growth. Indeed, microorganism activity as well, as nutrient solubility and availability, is some of the most important processes that depend on pH. For instance, in acidic soils, most micronutrients are more available to plants than in neutral-alkaline soils, generally favouring plant growth (Loncaric *et al*., 2008). Based on pH many crop plants' characteristics such as height, lateral spread, biomass, flower size and number, pollen production, etc., are influenced by soil pH (Jiang *et al*., 2017). Generally, soil nutrient availability was affected by soil pH, while chemical reactions and the physical and biological environment in the soil were modified by SOC (Behera *et al.*, 2018).

Where precipitation is high enough to leach appreciable quantities of cations (Ca2+, Mg2+, K+, and Na+), soil acidity is common in all regions from the surface layers of the soils (Brady and Weil, 2002). In case the lowest value of soil pH is recorded in the farmlands to the continuous removal of basic cations by high yielding crop varieties (Wakene and Heluf, 2003).

2.1.2.2. Organic matter, total nitrogen and C: N ratio

SOM plays an essential role in sustaining crop production and preventing land degradation (Ouedraogo, 2004). Because of its positive influence on several soil processes, on crop productivity, and environmental quality and it is often considered to be the single most important indicator of soil quality and sustainable land management (Vance, 2000; Doran, 2002). Organic matter improves soil structural stability in addition to providing mineral nutrients for plants and microorganisms through the mineralization process or biochemical oxidation of organic substrates. For this reason, soil OM content is the result of equilibrium between the processes supplying new organic inputs and the rate of mineralization of the existing OM (Stockdale *et al.*, 2000).

Nitrogen (N) is considered to be one of the key crop growth limiting factors (Cavigelli *et al.*, 2008). Soil total N composed of inorganic (NH4 +, NO3 - and NO2 -) and organic forms, is subject to change due to various factors. Management (cropping, fertilization, erosion, and leaching) and climatic conditions (temperature and moisture) determine the dynamics and level of N found in soils (Moody *et al.*, 2008). The previous investigations on soil properties along landscapes affected by long-term tillage indicate that soil total N and OC contents are lower in areas of soil removal than in areas of soil accumulation (Shimeles, 2006; Solomon, 2006; Ashenafi *et al.*, 2010).

2.1.2.3. Available phosphorus

Crop productivity is directly affected by P availability in agricultural soils (Williams *et al.*, 2013). However, in some agricultural crop soils, the concentration of total P is naturally high, which can limit plant growth due to the low solubility and rapid conversion of P compounds to unavailable or poorly available P after fertilizer application (Malik *et al*., 2012). A synthetic chemical fertilizer application can ensure sufficient availability of P for plant uptake (Ayaga *et al*., 2006). There has been growing confirmation that long-term excessive application of inorganic P fertilizers decreases P use efficiency that may result in excessive accumulation of P in soil (Liu *et al*., 2013). Hence mostly in Ethiopia, its deficiency is directly related to food security issues, especially in the tropics where severe soil degradation is responsible for series of deterioration in soil quality (Stocking, 2003; Zhang and Zhang, 2005). Different researchers (Yesuf and Duga, 2001; Ahmed, 2002) reported that P plant nutrients to be the most deficient mineral components in the soils of Arsi, causing strong challenges to the farming communities, particularly in the upper highlands. This can be ascribed to the high rainfall in the highlands, erosion hazards, and intensive cultivation.

2.1.2.4. Exchangeable bases

The response to K fertilizer is expected from most crops that have different ranges of nutrient requirements (Barber, 1984). It is commonly believed that Ethiopian soils contain sufficient K and no deficiency problem for crop production. However, several research works of Wakene and Heluf (2004), Shimeles (2006), Sintayehu (2006), and Wondwosen and Sheleme (2011) revealed that K was deficient in various soil types (Umbrisols, Nitisols, Plinthosols) which were subjected to intensive cultivation and/or different landscapes.

Exchangeable sodium (Na) is found in very small amounts in humid regions, but it can be a major component of soils in arid and semiarid regions. The concentration of Na in the soil varied from 0.1 to 1% (Landon, 1991).

Exchangeable calcium (Ca) and magnesium (Mg) is the dominant exchangeable cation in many soils, except alkaline soil that contains excess Na and acidic soils that contain higher amounts of hydrogen and aluminium. Exchangeable Ca and Mg usually account for more than 60% of the exchangeable cations of soil at pH 5.5 or higher. The concentration of Ca in the soil varies from 1% or less (in non-calcareous soils) to 10% or more (in calcareous soils), whereas the content of Mg is about 2.2%

in lithospheres (Bohn *et al.*, 2001). Due to this the continuous cultivation and inorganic fertilizers application result in declining soil pH and caused loss of basic cations especially soils inherently poor in Ca and Mg sources.

2.1.2.5. Cation exchange capacity (CEC)

Cation exchange capacity is strongly influenced nutrient availability, thus widely used in soil fertility evaluation and soil classification projects (FAO, 2006b). It is depending on clay soil and OM present in the soil. Both clay and colloidal OM are negatively charged and hence can act as anions to adsorb and hold positively charged ions (Seilsepour, 2008). Higher CEC values are usually associated with humus compared to those exhibited by the inorganic clays. According to Hazelton and Murphy (2007) classification, soils consisting of CEC values greater than 40 cmolc kg^{-1} are rated as very high, while the CEC values are between 25 to 40, 12 to 25, and 6 to 12 cmolc kg^{-1} are rated as high, moderate and low, respectively.

2.1.2.5. Exchangeable acidity on crop

Exchangeable H together with exchangeable Al is known as soil exchangeable acidity. Soil acidity occurs when acidic H^{+} ion occurs in the soil solution to a greater extent and when an acid soluble Al^{+3} reacts with water (hydrolysis) and results in the release of H^{+} and hydroxyl Al ions into the soil solution (Brady and Weil, 2002). The high Al concentrations as Al^{3+} represent an important growth and yield limiting factor for crops in acid soils ($pH \leq 5.5$). The most recognized effect of Al toxicity in plants is observed in roots. However, damages in the upper parts (including stem, leaves, and fruits) may also be present (Merino *et al.*, 2010).

Soil acidity is a critical issue requiring immediate action in most highlands of Ethiopia because of its influence on crop production and productivity (Tessema *et al.*, 2012; Melese and Ylihalla, 2016). It is mostly associated with poor chemical and biological properties. And also, it corresponds to the deficiency of available P, Ca, Mg, K, and combined with toxicity Al, H, and other microelements to the plant roots in the soil solution (Kisinyo *et al.*, 2014).

Soil acidity is a complex of several factors involving plant nutrient deficiencies and toxicities, low activities of beneficial microorganisms, and reduced plant root growth which limits the absorption of nutrients and water (Fageria and Baligar, 2003) especial in crop fields.

Low pH or soil acidity converts some available soil nutrients into unavailable form and also acidic soils are poor in their basic cations such as Ca, K, Mg, and some micronutrients which are essential to crop growth and development (Wang *et al*., 2006). Soil acidity knows as a serious threat to crop production in most highlands of Ethiopia (include Gummer district high land area) in general and in the western part of the country in particular (Taye, 2007). In the tropics, the soil acidity is aggravated by leaching or continuous removal of basic cations through crop harvest. About 40.9% of the Ethiopian total land is affected by soil acidity. And it is about 27.7 % are dominated by moderate to weak acid soils (pH- KCl of 4.5 -5.5) and around 13.2 % are strong acid soils (pH in KCl of <4.5) and nearly one-third have aluminium toxicity problems (Mesfin, 2007).

Due to soil acidity among the major land degradation problem and one of the main factors that limit, prevent profitable and sustained agricultural productivity in many parts of the world (Sumner and Noble, 2003). Also, soil acidity in Ethiopia is expanding both in scope and magnitude severely limiting crop production (Wassie and Shiferaw, 2011; Tamene *et al*., 2017). It is a challenge to agricultural productivity posing deficiencies of nitrogen (N) by leaching, phosphorus (P) by fixation, and low soil organic matter (OM) (Kisinyo, 2011; Opala *et al*., 2015).

2.2. Mapping Spatial Variability of Soil Acidity

Soil acidity is a term used to describe soils with a pH value less than 7 (Robarge, 2008). It affects the growth of crops because acidic soil contains toxic levels of aluminium and manganese. Acidity is also, characterized by the deficiency of essential plant nutrients such as P, N, K, Ca, and Mg (Wang et al., 2006). Soil acidity is among the major land degradation problems and limits sustained agricultural productivity in many parts of the world (Sumner and Noble, 2003). It is a major constraint to cropping systems, especially in temperate and tropical regions of the world where high precipitation has put a dominant influence on the pedogenic development of the soils (Brady and Weil, 2002; Van Streaten, 2007; Kochian *et al*., 2015).

Soil acidity is a common problem in high rainfall areas. This is mainly due to leaching and plant uptake of soil nutrients where it can be spatially evaluated to map and draw up strategies for the management of soil acidity in the highland areas (Lydia *et al.*, 2014). However, soil pH values and lime requirements can vary within a field (Schirrmann *et al.*, 2011). Therefore, prudent conservation methods or management decisions entail should be applied according to the spatial distribution of soil pH in an area according to measured and predicted values that are recorded on the map. Given that, this approach to be successful and recommended accurate soil pH maps should be used as one of the major inputs. In line with Lydia *et al.* (2014), the geostatistical system applies effective ways for quantitative mapping the spatial distribution of soil acidity.

Describing the spatial variability across a field was difficult until new technologies such as Global Positioning Systems (GPS) and Geographic Information Systems (GIS) were introduced (Alemu *et al.*, 2016). GIS is a powerful set of tools for collecting, storing, retrieving, transforming, and displaying spatial data (Burrough *et al.*, 1998). GIS can be used in producing a soil acidity map of an area that helps to understand the status of soil fertility spatially and temporally, which will help in formulating site-specific balanced fertilizer recommendations (Lelago *et al.*, 2016). These technologies allow mapping fields accurately and computing complex spatial relationships between soil fertility factors. Numerous studies have been conducted based on geostatistical analysis to characterize the spatial variability of different properties (Cao *et al.*, 2011; Weindorf *et al.*, 2010; Liu *et al.*, 2013; Huang *et al.*, 2007). Thus, information on spatial variability of soil nutrients is important for the sustainable management of soil acidity. Among many geostatistical methods, ordinary kriging is widely used to map spatial variation of soil pH or soil acidity. According to Samira *et al.* (2014), the ordinary kriging (using either Gaussian or Spherical models) is more accurate for predicting the spatial patterns of the soil properties pH and other soil properties than the two other methods IDW and splines, because it provides a higher level of prediction accuracy (Song *et al.*, 2013).

Mapping the spatial variability of soil acidity by applying a geographic information system (GIS) is also the order of the day to avail information for present and future uses. The soil acidity mapping can be used for delineating soil acidity or soil pH level, studying soil acidity changing due to soil depth dynamics, and determining nutrient or management requirements for the deficient areas according to the value directly related to the crop fields.

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1. Location

The study area is located in Gummer District, Gurage Zone of the Southern Nations, Nationalities, and Peoples' Region of Ethiopia. It is geographically located at 38° 01´ 27.84´´- 38° 02´28.32´´ longitude and 8° 01´ 27.84´´ - 8° 01´ 53.76´´ latitude. The capital city of the district is Arekit town located at about 215 km from Addis Ababa, 220 km from Hawassa, and 65 km from Wolkite (the capital city of Guraghe zone). The town is named after Lake Arek'it is (CSA, 2007). The study area Dewoshe sub-watershed is located 8 km away from the Arekit town and covers 539.1 ha. The neighboring Kebeles for the Dewoshe sub-watershed area is Wusho in the south, Deber Kebele in the West, Fetazer Kebele in the North, and Dewoshe Kebele in the East direction.

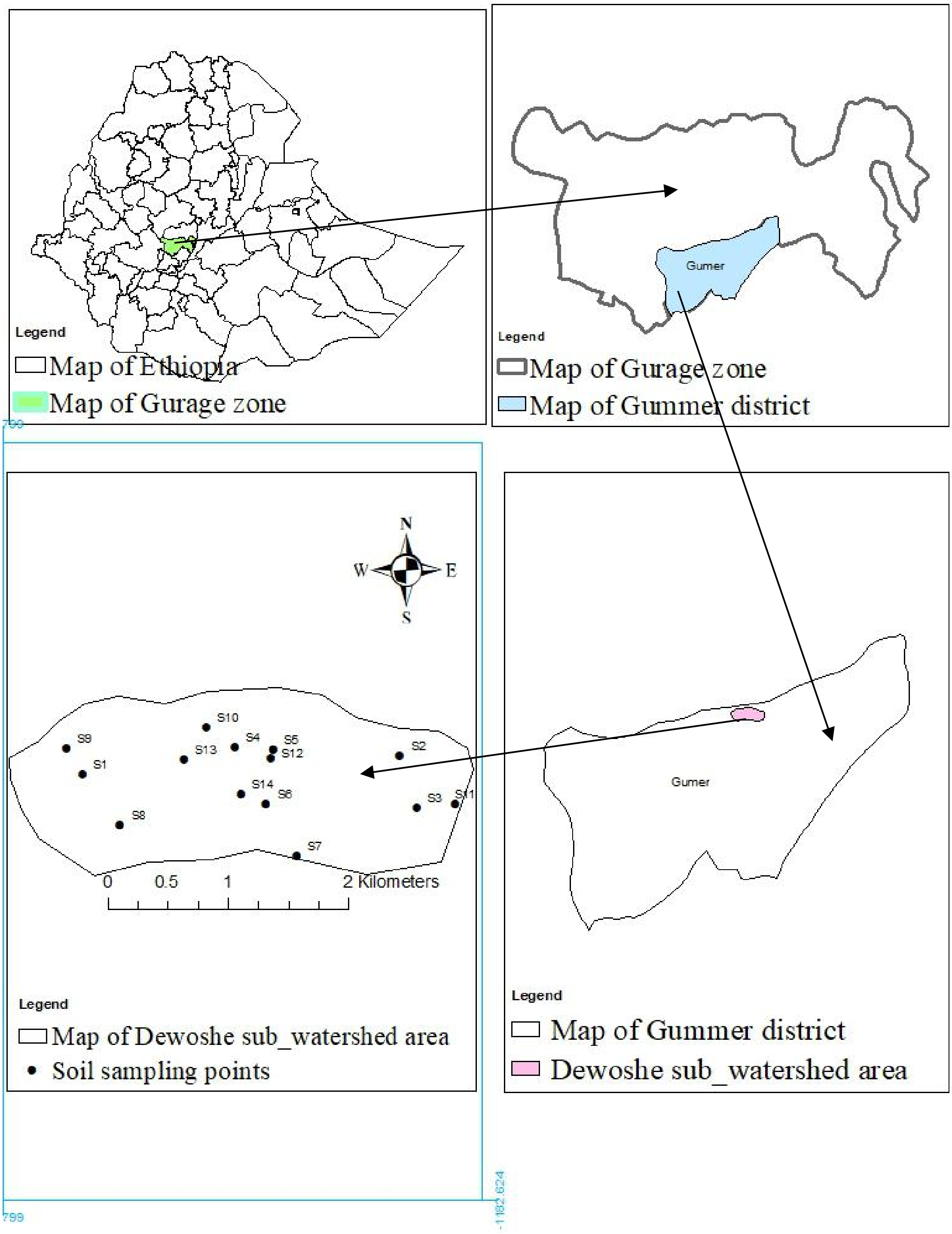

Figure 1. Geographical location of the study area

3.1.2. Topography and Climate

The elevation of the Dewoshe sub-watershed ranges between 2907 and 3045 masl. The climatic condition of the area is characterized by Dega with average annual rainfall 1265.7 mm (Figure 2). The bi-modal (spring and summer) rainy season is applied on the study area. The spring season is beginning from the end of February to mid-June. The effective rainy season is from June to the end of September. Temperature varies between the mean annual minimum of 7.5 °C to mean annual maximum of 26.8 °C (Figure 2).

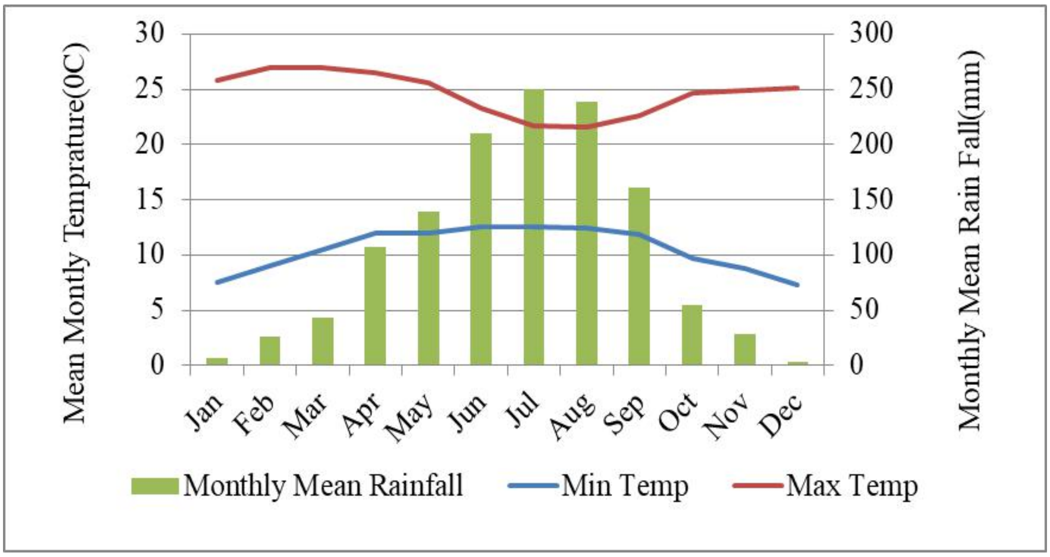

Figure 2. Mean monthly rainfall (mm), and minimum and maximum temperature (°C) of the study area SNNPR National Metrology Agency (2011-2020).

3.1.3. Farming activity

The economic activity of the sub-watershed is primarily a mixed farming system that involves crop production, animal husbandry, and trading. The major development challenges of the area include the presence of high population pressure, poor productivity due to soil degradation, dependence on rain-fed agriculture, and poor socio-economic services. Crop production is the main economic activity of the study area, which includes perennial crops such as Enset or Ensete ventricosum and cereal crops such as; barley (Hordeum vulagare L.) and wheat (Triticum aestivum L.) are found in very small amounts in the summer rainy season. Potato (Salantum tuberosum) is grown during the spring season. Additionally, trade activities neighbouring open market at Bole and nearby towns are common. Additionally, small-scale livestock rearing is practiced along with crop production and trade activities. Cattle and sheep are the common livestock types reared in the sub-watershed. The farming activity is performed using animal labour (GWANRO, 2018).

3.2. Sampling Site and Soil Sampling

3.2.1. Sampling site

First, the reconnaissance soil survey was carried out to locate sampling areas of the Dewoshe sub-watershed. The Dewoshe sub-watershed sampling area was selected on crop type. The two commonly grown croplands, cereal and Enset were identified by slope gradients category in each sampling area by using the Jalu method. The slope gradient categories (nearly level (0.5-1%), very gently sloping (1-2%), gently sloping(2-5%), sloping (5-10%), strongly sloping (10-15%), moderately steep (15-30%) and steep sloping (30-60%) were identified based on FAO (2006a) slope gradient classification system to know the accuracy of the sampling study area.

$$\text{Slope (\%)} = \frac{VI}{HI} \times 100$$

Where; VI=vertical increase and HI=horizontal increase by using 10 meters.

The sampling points in the cropping farmland activities had taken more than decades. The Dewoshe sub-watershed has a bimodal cropping system. In the spring season, potato is commonly planted while during summer cereal crops such as barley and wheat are common. Cereal cropping has been practiced either after harvesting potato crops or from the previous barely or wheat croplands. Totally there was 51% of barley, 42% Enset, and 7% of wheat crop.

3.2.2. Soil sampling

Representative composite samples were collected from each of four treatments (cereal and Enset crop taken within two depths: - 0-20 and 20-40 cm). From the two common crop types within two depths in FAO (2006a) seven slope categories were taken 15-20 sub-samples by a zigzag method. The distances between composite samples were around 200-800 meters according to GPS. After thorough mixing, by the quartering method of about kg, a composite soil sample was taken for laboratory analysis.

Generally, there are twenty-eight (28) composite soil samples were taken in four treatments (two crop types within two depths) and seven slopes were as blocking or replication of treatments. And also, independently each composite sampling point within slopes was used for categorized mapping spatial variability of soil acidity in the study area. Soil samples were not taken from restricted areas such as animal dung accumulation places, poorly drained, recently fertilized and any other places that cannot give representative soil samples. During soil sampling, data of spatial information like latitude and longitude on slope gradient, crop types, and sampling depth were recorded properly. The points of each soil sampling were recorded using a portable Garmin GPS in the center of the total sub-sampled area. The soil samples were coded, properly bagged, and labeled with appropriate information about the sample, and transported immediately to Wolkite zone soil testing centers for preparation and laboratory analysis.

3.3. Soil Sample Preparation and Analyses

Before the analysis, the soil samples collected from each crop at the different slope classes and depths were air-dried, ground, and sieved to pass through a 2 mm size sieve in preparation for laboratory analysis of most soil physical and chemical properties and soil acidity. The soil samples were further sieved to pass through a 0.5 mm size sieve for the analysis of total nitrogen and organic matter.

3.3.1. Soil physical properties analyses

Soil particle size distribution was analyzed by determining the percentage of sand, silt, and clay in each soil sample by following the Bouyoucos hydrometer method (Bouyoucos, 1962), after destroying organic matter using hydrogen peroxide (H_2O_2) and dispersing the soils with sodium hexametaphosphate ($NaPO_3$). Once the particle size distribution was determined in percent, the textural class of the soil was assigned using USDA textural triangle classification system (USDA, 1987).

Soil bulk density was determined by using the undisturbed core sampler method after drying the soil samples in an oven at 105°c to constant weights (Black, 1965). Each sample was taken by core sampler methods and inserted in oven-dried. Then after 24 hrs, bulks density was calculated by dividing the mass of the oven-dry soil by the respective volume as it existed naturally under field conditions. The generally used average value of 2.65 g cm^{-3} for mineral soils was used for the particle density of the soil. Total porosity was estimated from the values of bulk density (BD) and particle density (PD) as: BD = $\frac{W}{V}$

Where, BD= Bulk density, W= weight of oven-dry soil (gm), and V= Volume of soil sample (cm^{-3}).

$$\text{Total Porosity (f (\%))} = 1 - \frac{BD}{PD} \times 100$$

3.3.2. Soil chemical properties analyses

The samples were taken in plastic bags and air-dried, crushed, and passed through a 2 mm sieve for the determination of many of the soil quality indicators. However, the soil samples for TN and OC were analyzed ground to pass a 0.5 mm size sieve. The twenty-eight (28) disturbed composite soil samples were analyzed. The pH of the soil was measured potentiometrically with a digital pH meter in the supernatant suspension in water and 1M KCl solution at the ratio of 1:2.5 for both soil: water, and soil : KCl solutions (Black, 1965). The soil organic carbon was determined by the wet oxidation method (Walkley and Black, 1934) in which the sample was first digested with potassium dichromate in sulphuric acid solution, and titrated with 0.5 N ferrous sulphate solutions and percent organic matter was computed by multiplying the percent soil organic carbon by a conversion factor of 1.724. Available P was determined by the Bray II extraction method as described by (Bray and Kurtz, 1945). The total N content of the soil was determined by wet-digestion, distillation, and titration procedures of the Kjeldahl method as described by (Black, 1965). The CEC was determined by extraction with ammonium acetate (Chapman, 1965). Exchangeable bases (Ca, Mg, Na and K) were extracted with 1M NH4OAc at pH 7 (Sahlemedhin and Taye, 2000). Exchangeable Ca and Mg were measured by the extraction with EDTA titration method (Cheng and Bray, 1951). Exchangeable K and Na were determined by the same extracts with flame photometer as described by Rowell (1994). PBS was calculated by the (sum of basic cations divided by CEC)*100.

Exchangeable acidity was determined by saturating the soil samples with 1M KCl solution and titrating with hydrochloric acid (0.02 M HCl) as described by Rowell (1994). From the same extract, exchangeable Al was determined on 14 soil samples, which have pH less than or equal to 5.5. Again, it was determined by titration with a standard solution of 0.02 M HCl. Finally, exchangeable H was obtained by subtracting exchangeable Al from exchangeable acidity.

3.4. Mapping soil acidity

Mapping is used to allow farmers to assess existing farm soils, thus allowing them to make easier and more efficient management decisions and maintain the sustainability of crop productivity (Panday D., 2018). The soil acidity maps were performed using ordinary Kriging. According to Jatav *et al*., (2013), mapping the spatial variability of soil acidity by applying GIS is also the order of the day to obtain information for the current time and predict future uses. Mapping the spatial variability of soil acidity is showed the specific locations of the areas, where attention is required concerning the management of crop nutrients.

3.4.1. Semi-variograms and modelling

Semi-variogram is computed as half the average squared difference between the components of data pairs (Webster and Oliver, 2007). The function is expressed as:-

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(xi) - Z(xi + h)]^2$$

where γ (h) is the semivariance for the distance interval class h, N(h) is the number of sample pairs separated by lag distance (sampling separation distance between slope gradients), Z(xi) is a measured variable at spatial location i, Z(xi + h) is a measured variable at spatial location i + h.

3.4.2. Soil acidity map

If more data are available for the same locations, such as from multiple soil variables were measured at the same position, then the data were used to help with mapping the spatial variation between the variables. However, these co-variables must exhibit strong relationships that were defined. Thus should be presented spatial auto correlation and the spatial variability of the one variable was correlated with the other variable and can be used for its prediction and vice versa (Bivand, 2013). Co-kriging including the ordinary kriging method is one of the most commonly used interpolation methods for predicting the spatial variability of soil properties (Panagiotis *et al*., 2017) including spatial variability of soil acidity. Therefore, mapping soil acidity within spatial variability points of surface and subsurface soil in the study area was done by ordinary kriging interpolation method. Ordinary kriging was used to predict unknown values of soil acidity concentration for non–sampled areas based on the nearby surveyed data. The soil acidity was interpolated in the spatial variability (slope gradients) points using the Geostatistical model and their spatial prediction was evaluated on the study area. Soil acidity was mapped in the study area by ordinary kriging using by ArcGIS 10.4. The formulas of ordinary kriging is;-

$$\hat{Z}\,(s_o) = \sum_{i=i}^{N} \lambda i \, Z(So)$$

Where, $Z^{\wedge}(s_o)$ is the predicted/interpolated value for point S_o, $Z(s_i)$ is the known value, and λi is the corresponding weight for the Z(si) values that satisfies the condition:

3.4.2. Error assessment methods

For surface, and subsurface soil acidity the Gaussian and spherical models, the best-fitted model to these experimental variograms were chosen using the lowest RMSE. The RMSE, and ME were calculated for each model to delineate the best-fitted soil acidity. A value of RMSE close to zero was illustrated the accuracy of the prediction of the model. The following formulas were followed to calculate the RMSE and ME values: The RMSE, which was given an estimate of the standard deviation of the residuals (prediction errors) (Panagiotis *et al*., 2017).

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (Oi - Si)^2}{N}}$$

$$\text{ME} = \frac{\sum_{i=1}^{N} Oi - Si}{N}$$

Where, O_i, is observed value, S_i is the predicted value, N, is the number of samples in the study area. A good model was a value close to zero for ME and RMSE. The compute semi-variogram, and spatial variability relationship between each of surface and subsurface soil acidity was fitted with the best semi-variogram models.

3.4.3. Model parameters

Isotropic semi-variogram for the soil parameters was computed to determine any spatially dependent variance within the field. An experimental semi-variogram was fitted separately and the best model was selected based on the fit. Using the model semi-variogram, basic spatial parameters such as nugget (Co), range (A), and sill (C + Co) were calculated. Nugget is the variance at zero distance, the sill is the lag distance between measurements at which one value for a variable does not influence neighbouring values and range is the distance at which values of one variable become spatially independent of another (López *et al*., 2002). Different classes of spatial dependence for the variables were evaluated by the ratio between the nugget and the sill. For the ratio lower than 25%, the variable was considered strongly spatially dependent, or strongly distributed in patches. For the ratio between 26 and 75%, the soil variable was considered the moderately spatially dependent, the ratio greater than 75%, the soil variable was considered weakly spatially dependent and for the ratio of 100%, or if the slope of the semi-variogram was close to zero, the soil variable was considered non-spatially correlated (pure nugget) (Cambardella *et al*., 1994).

3.5. Statistical Analysis and Mapping

Simple linear correlation analysis was carried out by calculating correlation coefficients (r) among and within physicochemical soil properties in one-way ANOVA. Two-way ANOVA in RCBD factorial method was applied using the GLM procedure of the SAS version 9.3. Significantly differing means were separated using by the LSD method at $p<0.05$.

4. RESULT AND DISCUSSION

4.1. Soil Physical Properties

4.1.1. Soil particle size distribution

Soil particle size distribution differences were observed among soil depths, particularly due to the changes in clay and sand fractions, while no differences were owing to interaction effects of crop types and soil depths (Appendix Table 1). Sand and clay fraction soils varied significantly across soil depths ($p<0.05$) and ($p<0.01$), respectively. Sand fraction soils were highly observed in surface soil 38.93, but low in subsurface soil 34.5, while clay fraction soils were increased in surface soil to subsurface soil (19.36 to 23.07) (Table 1) respectively. It might be due to percolation moment of soil from surface to down ward of the subsurface of soil. The study has shown that the silt soils did not vary statistically significantly ($P < 0.05$) with crop types, soil depth, and the interaction between crop types and soil depths (Table 1).

Table 1. The main effect values of soil particle size distribution under two crop types and two soil depths in the Dewoshe sub-watershed area.

	Particle size distribution			
Crop types	Sand	Silt	Clay	TC
Cereal crops	37^{a}	42^{a}	21^{a}	L
Enset crop	36.5^{a}	41.78^{a}	21.43^{a}	L
LSD (0.05)	NS	NS	NS	-
	Soil depths			
0-20 cm	38.93^{a}	41.7^{a}	19.36^{b}	L
20-40 cm	34.57^{b}	42.07^{a}	23.07^{a}	L
LSD (0.05)	2.748	NS	1.375	-
SE ±	1.308	0.989	0.655	-
CV (%)	9.42	6.25	8.2	-

Where;- TC=Textural Class, L=loam, NS=Not-Significant, LSD=List significant different, SE=Standard Error and CV (%) = Coefficient of variation. Means within a column followed by same letters in superscripts are not significantly different from each other at P<0.05.

The textural class of the study areas within crop types and soil depth was loam (Table 1), since it is inherent soil physical property that might not change over a short time (Kiflu and Beyene, 2013), and texture does not easily affect by crop types and soil fertility management (Teshome, 2019).

According to Khattak and Hussain (2007), the textural analysis of the Dewoshe sub-watershed soils had higher contents of sand and silt. It means that sand and silt had higher in the parent material of soils was derived from the area. On soil fractions, clay contents might have been removed from the upper soils due to soil erosion.

4.1.2. Soil bulk density and total porosity

The result in the analysis of variance indicated significant differences for soil bulk density and total porosity due to crop types ($p<0.01$), soil depths ($p<0.01$), and their interaction between crop types and soil depths ($p<0.05$) (Appendix Table 1). These variations for both bulk density and total porosity were positively related to OM (Table 5). The highest, and the lowest bulk density of the study area were 1.35g/cm^3 from the subsurface soil (20-40 cm) depth in cereal crops, and 1.07g/cm^3 from the surface soil (0-20 cm) depth in Enset crop (Table 2) respectively. But the value of total porosity is irreversibly related to soil bulk density. The highest total porosity is within low soil bulk density. The observed lowest bulk density in the Enset crop at the surface soil (0-20 cm) depth might be attributed to its highest SOM content (Table 3; Appendix Table 2). This is in case of any factor that influences pore space affects bulk density. On the other way, low total porosity was the reflection of the low OM content (Table 2; 3). The intense tillage activities may temporarily loosen tilled soil depth, in the long term with increased bulk density and decreased total pore space of soils. The values consistently increased from surface to subsurface soils across crop types. This is mainly due to the differences observed in OM content along depths and differences in bulk density were paralleled with changes in SOM content. The weight of overlying mass upon the subsurface soil layer is an additional reason to increase the bulk density of underlying soils. This is in agreement with the result of Solomon *et al.* (2002); Wu and Tiessen (2002).

Table 2. Interaction values of bulk density and total porosity under two crop types and two soil depths in the Dewoshe sub-watershed area.

Crop types	Bd	F
	Surface (0-20 cm) soil	
Cereal crops	1.28^b	51.6^b
Enset crop	1.07^c	59.7^a
	Subsurface (20-40 cm) soil	
Cereal crops	1.35^a	49^c
Enset crop	1.25^b	52.7^b
LSD (0.05)	0.046	1.69
SE ±	0.015	0.57
CV (%)	3.28	2.84

Where; - Bd=Bulk density; F=Total porosity; Means within a column followed by same letters in superscripts are not significantly different from each other at $P<0.05$.

4.2. Soil Chemical Properties

4.2.1. Soil pH

The ΔpH had positive values, ranging between 0.6 and 0.83 throughout the soil depths and crop types. Along with the cereal crop types with a relatively medium ΔpH value (0.83) found in the subsurface soil in the study area. Considering the surface soil, the lowest ΔpH value (0.6) was recorded under the Enset crop areas. The ΔpH value increased with depths in the two crop types. It is only statically significant in soil depths, ($p<0.05$), but not statistically significant in both crop types and the interaction between crop types and soil depths (Table 4; Appendix Table 2).

All samples of soils have both pH-H_2O and pH-KCl values less than 7, and was found to be acidic in reaction (Table 3). Some of the soils are strongly acidic as the study area. And it might be received high annual rainfall (>1000 mm) which is responsible for the leaching of the base forming cations. Statistically, soil acidity measures, pH-H_2O, and pH-KCl were found to be all significantly affected by crop types ($P < 0.01$), and the interaction between crop types and soil depths ($P < 0.01$). The pH-H_2O and pH-KCl were not statistically significant, and statistically significant to the influence of soil depths respectively in the study area ($p<0.05$) (Appendix Table 2). According to Foth and Ellis (1997) rate classification considering the pH-H_2O, cereal crops in the surface area has very strongly acidic (4.84) and subsurface soil has strongly acidic (5.3). In the farm of Enset cropland, subsurface soil has moderately acidic (5.64) and surface soil has slightly acidic (6.27) (Appendix Table 4).

According to Islam (1980), most crop species achieved near the maximum growth have been in the pH-H_2O range of 5.5 to 6.5. The cereal crops especially in the surface soil were below the optimum level of pH. It might be due to the continuous attributed of crop residues removal, leaching of basic cations enhanced by intensive cultivation, and drains to streams in runoff generated from accelerated erosion. On the contrary, relative higher soil pH in Enset crop within the surface soil attributed due to the application of manure, wood ashes, and other easily decomposable garbage around the homestead garden. This finding is in agreement with Heluf and Wakene (2006), who reported that land use and management practices have remarkably influenced the soil's chemical properties.

Soil pH-KCl was 4.1 and 4.49 in cereal crops surface and subsurface soil respectively is extremely acidic. Enset crop subsurface and surface soils 4.84 and 5.67 were very acidic and acidic to neutral based on the rate classification of Tekalign (1991) (Appendix Table 4) respectively. The reason for decreasing pH-KCl in cereal crops and increasing in Enset crop is the same as the reason for pH-H_2O in the above discussion. The decrease in soil pH when measured in KCl solution indicates that an appreciable quantity of exchangeable hydrogen has been released into the soil solution through an exchange reaction with K in the KCl solution. This finding is in agreement with Anon (1993) report, that soil acidity is increased due to measurement of pH in KCl solution showing the presence of high potential acidity (Table 3).

4.2.2. Soil organic matter (SOM)

SOM has an important influence on soil physico-chemical soil properties, soil fertility status, plant nutrition, and biological activity in the soil (Brady and Weil, 2002). In this study, OM was statistically significant within crop type ($p<0.05$), soil depths

($p<0.05$), and the interaction between crop types, and soil depths ($p<0.05$) (Table 3; Appendix Table 2). From this observation, the OM was highly decreased from surface to subsurface soil in both crop types (Table 3).

The SOM contents decreased from 1.15% in surface to 0.79% in subsurface soil under cereal crops, and from surface 3.19% to 1.48% subsurface soil, under Enset crop types. The Enset crop values for the level of SOM in surface soil depths (3.19%) were much higher than for the corresponding subsurface Enset crop (1.48%), and cereal crops (Table 3). This is attributed partly to the adding of wood ash, continuous accumulation of household refuses by servers, and might be low participation of roots on the upper part of the soil in the Enset crop. The finding of this study area is in agreement with the results of similar recent studies reported by Weldeamlak and Stroosnijder (2003); Genxu *et al.* (2004). Relatively the cereal crops might be implies that high velocity of surface erosion, low infiltration rate and the gradual decline of OC process are continuing increased in the study area. This is similarly to Jemaludin (2020) reports on the effect of Enset management practices on soil fertility.

According to Tekalign (1991), OM rating, 1.15% and1.48% is low organic matter contents within surface cereal and subsurface Enset crop respectively. However, subsurface soil under cereal crops (0.79%) and surface soil under Enset crop (3.19%) are very low and medium respectively. In this study, subsurface soil under cereal and Enset crop shown that, SOM is decreased with increasing of soil depth (Table 3).

4.2.3. Total nitrogen and carbon to nitrogen ratio

The TN of the soil was statistically significant within crop type ($p<0.01$), soil depths ($p<0.01$), and the interaction between crop types and soil depths ($p<0.05$) (Table 3; Appendix Table 2). It was directly associated with OM content along with the soil depth within crop types (Table 3). The highest (0.26%) value of TN was recorded in the surface Enset crop (Table 3). Considering the ratings given in Tekalign (1991), the current TN status of soils of the study area can be rated as the low, medium, and high range. The low level of TN, in both surface and subsurface soil of cereal crops might be attributed to its low level of OM content. Moreover, the strong and positive correlation ($r = 0.93^{**}$) between TN and OM indicates that soil OM is the main source of nitrogen in the soil (Table 5). Therefore, the deficient status of soil TN content tends to be a limiting factor for crop production. In agreement with the findings of the present observation, Shimeles *et al*. (2013) stated that a statistically significant correlation between OC and TN indicates that most of the N is organic in nature.

The study has shown that the carbon to nitrogen (C: N) was vary statistically significantly within crop type and soil depth ($P < 0.05$), and the interaction between crop types and soil depth ($p<0.01$) (Table 3; Appendix Table 2).

Generally, according to Enset crop, TN is very low. It might be due to crop landscape position, which might be exposed easily by erosion. The finding agreed with the explanation of Funte *et al*. (2010) who noted that leaching losses of plant nutrients, particularly nitrogen, may be reduced by Enset as compared to cereal crops. This should be possible because of the continuous soil occupation by the roots. At the beginning of the rainy season and after maturation, cereal crops have little root proliferation and little effect on nutrient leaching. For established Enset, roots already proliferate the soil profile at the beginning of the rainy season. The large mass of the plant should serve as a storage reserve, reducing the availability of the nutrients in the soil by leaching (Jemaludin, 2020).

4.2.4. Available phosphorus

The statistical analysis has indicated that available P content was observed significant differences affected by crop types ($P<0.01$), soil depths ($p<0.05$), and the interaction between crop types and soil depths ($P<0.05$) (Appendix Table 2). The average available P content of the surface depth of soils of the study area varied from 9.69 mg/kg in Enset crop surface soils to 0.37 mg/kg in soils under cereal crops subsurface soils with great variations between both factors of soil samples (Table 3). According to Barber (1984) rating of available P subsurface (0.37 mg/kg), surface (0.59 mg/kg) cereal crop and subsurface (3.38 mg/kg) Enset crop soils was found in very low range. But, the surface (9.69 mg/kg) Enset crop soils was found in the low range. Because of available P was strong and positive correlation with that of OM, TN, pH-H_2O, pH-KCl, Ca, Mg, K, CEC and Na at the (r=0.92**, 0.96**, 0.82**, 0.85**, 0.83**, 0.87**, 0.73**,0.79** and 0.65*) (Table 5) respectively.

Generally, the available P status is very low and low range both in the interaction between crop types and soil depths in the study area (Table 3; Appendix Table 4). According to Barber (1984) rating, indicating that soil P infertility is among the influences that are highly limiting the productivity of the soils. In this observation, it could even be said that available P was highly deficient and it is probably the first limiting nutrient in the study area. In line with the findings of the study, many researchers (Warren, 1992; Buehler *et al.*, 2002) have also 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.

4.2.5. Exchangeable basic cations and percent base saturation

From the study sub-watershed area observations, exchangeable Ca (Table 4) and Mg (Table 3) were varied statistically significant within crop types and soil depths. But exchangeable Ca was not varied statistically significant within the interaction between crop types and soil depths. It was significantly varied within crop types ($p<0.01$), and soil depths ($p<0.05$) (Appendix Table 5). Exchangeable Mg was significantly varied within crop types ($p<0.01$), soil depths ($p<0.01$), and the interaction between crop types and soil depths ($P<0.05$) (Appendix Table 5). Based on the rating suggested by FAO (2006a) the finding observation exchangeable Ca from Enset crop field (5.29), surface (4.76), and subsurface (4.33) soil depths had medium, while cereal crops field has low which might be due to crop removal and erosion phenomena in the fields (Table 4).

Similarly, within a line of exchangeable Ca, the Enset crop field had medium exchangeable Mg within interaction effect of Enset crop and soil depths, and low in cereal crops field within soil depths. It might be due to the same reason to exchangeable Ca. Generally, there are not enough exchangeable Ca and Mg values in the study area. It might be the cause of unwise use and less proper crop field management practices were found in the local farmers in both crop types of the fields.

Exchangeable Ca and Mg had also a statistically significant negative association with total Bulk density ($p \leq 0.01$), exchangeable acidity, and Aluminium ($p \leq 0.05$), exchangeable Hydrogen ($p \leq 0.01$), and a statistically significant positive correlation with total porosity ($p \leq 0.01$), pH-H_2O, pH-KCl, available P, OM and TN ($p \leq 0.01$). But, the exchangeable Ca was not a strongly positive correlation with OM, it is significantly at the ($p<0.05$) with OM (Table 5).

The exchangeable K, and Na observations were varied statistically significant within crop types ($p<0.05$). But not varied statistically within soil depths and the interaction between crop types and soil depths (Table 4; Appendix Table 3). However, the relatively higher values of both exchangeable K (0.39), and Na (0.104) concentrations were recorded in the Enset crop type. Whereas, the lowest values of exchangeable K (0.135), and Na (0.055) were observed in the cereal crops type of the fields (Table 4). Based on the rating suggested by FAO (2006a), the soil exchangeable K observed in cereal crops, Enset crop, for both surface and subsurface soil depth was categorized as very low, medium, and low range respectively. Whereas, the soil exchangeable Na observed in the Enset crop field was categorized as low and the other cereal crops field, surface, and subsurface soil depths were found in very low range. Averagely, the exchangeable K were observed in the study area was low in range. It might be the case of the intensity of weathering, intensive cultivations, and uses of acid-forming inorganic fertilizers have occurred in the study area. Not only exchangeable K, but also, an exchangeable Na content of the soils under both crop types and soil depths were generally low as compared to the critical level that annual rainfall at the study area which causes leaching of the basic cations, and finally cause soil acidity. Because, the threshold level of exchangeable Na varies depending on the CEC, clay content, clay mineralogy and the type of crop to be grown.

All exchangeable cations were strongly related and statistically significant to the total porosity, pH-H_2O, pH-KCl, available P, OM, TN and CEC ($p<0.01$). From the other like, bulk density and exchangeable acidity were negatively related and statistically significant to exchangeable cations (Ca, Mg, K and Na), (Table 5). The exchangeable cations were almost low in the study area. This might be due to the related reason that low OM contents applied to the soil and complete removal of biomass from the cultivated field. This is in agreement with the reports of Yihenew (2002).

The PBS observation, was not statistically significant within crop types, soil depths, and the interaction between crop types and soil depths ($P<0.05$) (Appendix Table 3).

According to, Hazelton and Murphy (2007) rating classification PBS was found in the low range of the study area.

4.2.6. Cation exchange capacity

There was variation in CEC of the soils under the two crop types both in surface, and subsurface soils especially, in Enset crop type (Table 3). The statistical analysis of CEC was significantly varied within crop types ($P<0.01$), soil depths ($p<0.05$) and the interaction between crop types and soil depths ($P<0.05$) (Appendix Table 3).

The depletion of CEC from the cereal crops was 17.7 and 15.6 both in surface and subsurface soil respectively; as compared to the CEC of surface and subsurface Enset crop (Table 3). The CEC was decreased almost consistently from the surface to the subsurface soil in the cereal and Enset crop types. The decrease in CEC with subsurface is attributed to a decrease in organic matter content. Therefore, the depletion of organic matter as a result of intensive cultivation has reduced the CEC under the cereal crops. And also, the depletion of OM within subsurface under Enset crop might be due to application of household refuses and manure contribute removed by erosion phenomena in surface and it might be a low accumulation of manures in a rooting system of Enset crop. On the other hand, the decrease in CEC with pH can be attributed to a decrease in CEC values as pH-dependent charge as pH declines. This result was in accordance with the result of Johnson (2002). According to, Hazelton and Murphy (2007) rating classification of CEC, 15.6, 17.7, and 21.7 values of subsurface and surface cereal crops and subsurface Enset crop was found in medium-range respectively (Table 3). The other 28.6 value of Enset crop from the surface soil was high in range. It might be due to the application of household refuses and manure contributing to an increase in surface Enset crop. This finding was also in good agreement with Jemaludin (2020).

Table 3. Interaction values of selected soil chemical properties under two crop types and two soil depths in the Dewoshe sub-watershed area.

		Soil Parameters									
Crop types	pH-H_2O	pH-KCl	%OC	%OM	TN	C:N	P (mg/kg)	Mg	CEC Soil (Cmolc/k)	Ac	Al
		Surface (0-20 cm) soil									
Cereal crops	4.84^{d}	4.1^{d}	0.66^{b}	1.153^{b}	0.096^{bc}	6.55^{b}	0.59^{c}	0.58^{c}	17.7^{c}	3.37^{a}	0.23^{a}
Enset crop	6.27^{a}	5.67^{a}	2.66^{a}	4.58^{a}	0.26^{a}	10.4^{a}	9.69^{a}	1.76^{a}	28.6^{a}	1.24^{c}	undetected
		Subsurface (20-40 cm) soil									
Cereal crops	5.3^{c}	4.49^{c}	0.46^{b}	0.79^{b}	0.07^{c}	6.2^{b}	0.37^{c}	0.39^{c}	15.6^{c}	3.35^{a}	0.15^{a}
Enset crop	5.64^{b}	4.84^{b}	0.856^{b}	1.48^{b}	0.135^{b}	6.24^{b}	3.38^{b}	1.13^{b}	21.7^{b}	2.39^{b}	0.18^{a}
LSD (0.05)	0.221	0.298		0.55	0.036	2.39	1.73	0.194	3.022	0.746	0.12
SE ±	0.074	0.1	0.145	0.25	0.012	0.81	0.582	0.065	1.017	0.251	0.04
CV (%)	3.57	5.55	33.03	33.03	22.6	29.03	43.9	17.9	12.9	25.68	76.48

Where;- Ac= Exchangeable Acid, Al= Exchangeable Aluminium, LSD=List Significant Difference, SE±=Standard Error and CV (%) =Coefficient of variation in percent. *Means within a column followed by same letters in superscripts are not significantly different from each other at P= 0.05.

Table 4. The main effects of some chemical soil properties.

		Soil Parameters					
Crop types	ΔpH	C:N	Ca	K	Na	PBS	H
Cereal crops	0.78^{a}	6.55^{a}	3.8^{b}	0.135^{b}	0.055^{b}	28.1^{a}	3.17^{a}
Enset crop	0.7^{a}	6.9^{a}	5.29^{a}	0.39^{a}	0.104^{a}	29.5^{a}	1.73^{b}
LSD (0.05)	NS	NS	0.18	0.067	0.019	NS	0.539
		Soil depths					
0-20 cm	0.66^{b}	6.2^{a}	4.76^{a}	0.29^{a}	0.089^{a}	28^{a}	2.19^{a}
20-40 cm	0.81^{a}	6.24^{a}	4.33^{b}	0.231^{a}	0.07^{a}	29.53^{a}	2.71^{a}
LSD (0.05)	0.13	NS	0.18	NS	NS	NS	NS
SE ±	0.06	0.523	0.09	0.032	0.009	1.53	0.2569
CV (%)	21.8	21.4	5.06	32.15	30.55	14.1	27.8

Where; ΔpH= change of power of Hydrogen, H= Exchangeable Hydrogen, NS=Not-Significant, LSD=List Significant Difference, SE±=Standard Error and CV (%) =Coefficient of variation in percent. *Means within a column followed by same letters in superscripts are not significantly different from each other at P= 0.05.

4.2.7. Exchangeable acidity

Exchangeable acidity can be expressed as the sum of exchangeable H and Al ions, and it varied statistically significant along with the crop types ($p<0.01$), soil depths ($p<0.05$), and the interaction between crop types and soil depths ($p<0.05$) (Table 3; Appendix Table 3). The highest and the lowest exchangeable acidity values were recorded on cereal crops and Enset crop surface soil respectively. The reason for the existence of a higher concentration of exchangeable acidity on the cereal crops surface soil could be due to the release of certain organic acids from the functional groups of OM owing to the higher OM content of the cereal crop fields than the surface soil Enset crop fields. The observation result was in agreement with the investigation reported by Ahmed (2002). And also, it might have occurred in the high rainfall problems. This is agreed with the findings of Slattery and Hollier (2002).

Exchangeable Al was statically significant within crop types ($p< 0.05$) and the interaction effects between crop types and soil depths ($p<0.01$). But it was not statistically significant within soil depths (Table 3; Appendix Table 3). Exchangeable H was only statistically significant on crop types ($p< 0.01$) (Table 4; Appendix Table 3).

Table 5. Pearson’s correlation matrix for various physico-chemical soil parameters in the Dewoshe sub-watershed area.

	BD	F	Sand	Silt	Clay	pH1	pH2	ΔpH	Ac	Al	H	P	OM	TN	C:N	Ca	Mg	K	Na	CEC
BD	1																			
F	-0.9**	1																		
Sand	-0.17	0.18	1																	
Silt	0.25	-0.25	-0.7**	1																
Clay	0.03	-0.04	-0.72**	0.08	1															
PH1	-0.83**	0.83**	-0.03	0.15	-0.15	1														
PH2	0.84**	0.85**	0.07	-0.21	0.07	0.97**	1													
ΔpH	0.29	-0.29	-0.40*	0.29	0.28	-0.18	-0.40*	1												
Ac	0.74**	-0.74**	-0.18	0.35	-0.02	-0.74**	-0.8**	0.42*	1											
Al	0.64*	-0.64*	0.16	-0.07	-0.11	-0.81**	-0.76**	0.03	0.52*	1										
H	0.70**	-0.69**	-0.21	0.38	-0.01	-0.67**	-0.73**	0.44*	0.99**	0.42*	1									
P	-0.81**	0.81**	0.25	-0.18	-0.22	0.82**	0.85**	-0.37	-0.71**	-0.52*	-0.68**	1								
OM	-0.92**	0.92**	0.26	-0.25	-0.17	0.83**	0.86**	-0.37	-0.69**	-0.59**	-0.66**	0.9**	1							
TN	-0.87**	0.87**	0.27	-0.2	-0.21	0.81**	0.84**	-0.38*	-0.73**	-0.54*	-0.70**	0.96**	0.93**	1						
C:N	-0.61**	0.62**	-0.12	-0.14	0.23	0.53**	0.52**	-0.09	-0.36	-0.55**	-0.32	0.27	0.57**	0.29	1					
Ca	-0.84**	0.83**	0.014	-0.21	0.13	0.81**	0.81**	-0.25	-0.80**	-0.61*	-0.77**	0.83**	0.62*	0.82**	0.001	1				
Mg	-0.89**	0.89**	0.16	-0.25	-0.06	0.86**	0.88**	-0.36	-0.80**	-0.59*	-0.77**	0.87**	0.75**	0.89**	0.03	0.90**	1			
K	-0.84**	0.84**	0.104	-0.34	0.11	0.84**	0.82**	-0.17	-0.69**	-0.56*	-0.56**	0.73**	0.78**	0.85**	0.06	0.86**	0.88**	1		
Na	-0.81**	0.81**	0.12	-0.35	0.13	0.71**	0.71**	-0.23	-0.66**	-0.47*	-0.64*	0.65	0.66**	0.66**	0.3	0.79**	0.78**	0.76**	1	
CEC	-0.89**	0.89**	0.04	-0.14	0.03	0.84**	0.85**	-0.28	-.78**	-0.69**	-0.74**	0.79**	0.72**	0.83**	0.1	0.89**	0.89**	0.82**	0.8**	1

Where;- pH1 and pH2= power of Hydrogen within H_2O and KCl solution respectively.= power of Hydrogen within KCl solution, and the others are list on the above tables and acronyms.

4.3. Mapping the Spatial Variability of Soil Acidity

4.3.1. Spatial autocorrelation and model validation for surface and subsurface soil pH of the water

The fitted experimental semi-variogram for surface and subsurface soil pH of the water was shown in Appendix Figures 3, and 4 respectively. The associated semi-variograhpic parameters are shown in Table 6. It was observed that the general spatial structure of surface soil pH of water along with the fitted Gaussian semi-variogram was strong as indicated by the nugget to sill ratio of 0.18 with a spatial dependence of up to 1445 m. The general spatial structure of subsurface soil pH along with the fitted Spherical semi-variogram was medium as indicated by the nugget to sill ratio of 0.31 with a spatial dependence of up to 2021 m.

The Gaussian and Spherical nature of the fitted semi-variogram was suggested medium and less constant pattern of variation for soil pH at the study area, respectively. Gaussian was further shown that soil pH more varied continuously across the study area. A Spherical model was shown that subsurface soil pH less varied continuously across the study area. Both areas were illustrated by the smaller nugget effect and larger range of its semi-variogram, and the ME and RMSE of soil pH were near to zero indicating the sampling points were accurate for surface soil pH in the study area. These results show that the model was evaluating the spatial variability of predictions for soil pH from the true values fairly well. This result is supported by the previous finding of Lydia (2014).

4.3.2. Ordinary kriging interpolated surface and subsurface for soil pH

The spatial variability map of surface soil pH of the water was generated based on the distribution measured data, prediction map, and prediction standard error map is shown in Figures 3, 4, and 5 respectively. And also, the spatial variability map of subsurface soil pH of the water was generated based on the distribution measured data, prediction map, and prediction standard error map is shown in Figures 6, 7, and 8 respectively. According to Tekalign (1991), the surface soil pH of water distribution measured, and prediction data are very strongly (4.9) to slightly (6.3) acidic (Figure 3), strongly (5.1) to slightly (6.15) acidic (Figure 4), and 0.7-0.9 (Figure 5), respectively.

In the study area based on the distribution measured, and prediction surface soil pH of water very strongly to strongly acidic parts are on the steep, moderately steep, and strongly sloping (spatial variability) points mostly occurred within cereal crop type. On the other sloping, gently sloping, very gently sloping and nearly level sloping (spatial variability) points are moderate to slightly acidic were occurred in Enset crop type. The finding was similar to the previous study Mulugeta (2015).

The subsurface soil pH of water distribution measured, and prediction data are very strongly (4.9) to moderately (6.1) acidic (Figure 6), very strongly (4.98) to moderately (6.1) acidic (Figure 7) and, 0.29-0.46 (Figure 8), respectively. The subsurface soil pH of water distribution measured and prediction data were the same range of soil acidity on both figures 6, and 7. This indicated that mapping the spatial variability of soil acidity is best based on the nearby surveyed data by ordinary kriging to predict unknown values of soil pH concentration for non–sampled study areas. Similar research results were reported by Lelago (2016). The acidic part of subsurface soil on the spatial points was almost the same for cereal and Enset crop types.

The prediction standard error was high in surface related to subsurface soil pH of water. It might be due to sampling error on the surface points and the best accuracy of subsurface soil sampling methods applied on it.

Generally, mapping the spatial variability of soil acidity on soil depths in the cropland was clearly observed that the distribution measured, prediction, and prediction standard error of surface, and subsurface soil pH variance was linked to the density of data in sampling points.

Table 6. Fitted variogram parameters and prediction errors for ordinary Kriging (OK) model for prediction of surface soil pH of the water.

			Ss.pH						
Act.ty	Mot	Mean	RMSE	R	C_o	$C_o + C$	Ps	C0/ (C0 + C) %	Spd
Prsph	Gu	0.0121	0.265	1445	0.047	0.255	0.208	18.4	Strong
SEsph	Gu	-0.0119	0.0329	1577	0.000007	0.00288	0.0027	0.25	Strong
			Subs.pH						
Prsbph	Spr	0.00847	0.2644	2021	0.00429	0.13829	0.134	31	Medium
SEsbph	Spr	-0.01739	-0.2636	980	0.000004	0.003931	0.0039	0.1	Strong

Where;- Ss.pH= Surface soil pH, Act.ty= Activity types, Prsph= Predict surface soil pH of water, SEsph= Standard error surface pH, Subs.pH= Subsurface soil pH of water, Prsbph= Predict subsurface pH, SEsbph= Standard error subsurface pH, Gu= Guassian model, Spr= Spherical model, Mot= Model type, R= Range in meter, Co= Nugget effect, $C_o + C$= Sill effect, Ps= Partial sill, Co/ $C_o + C$= Nugget/sill ratio and Spd= Spatial dependency.

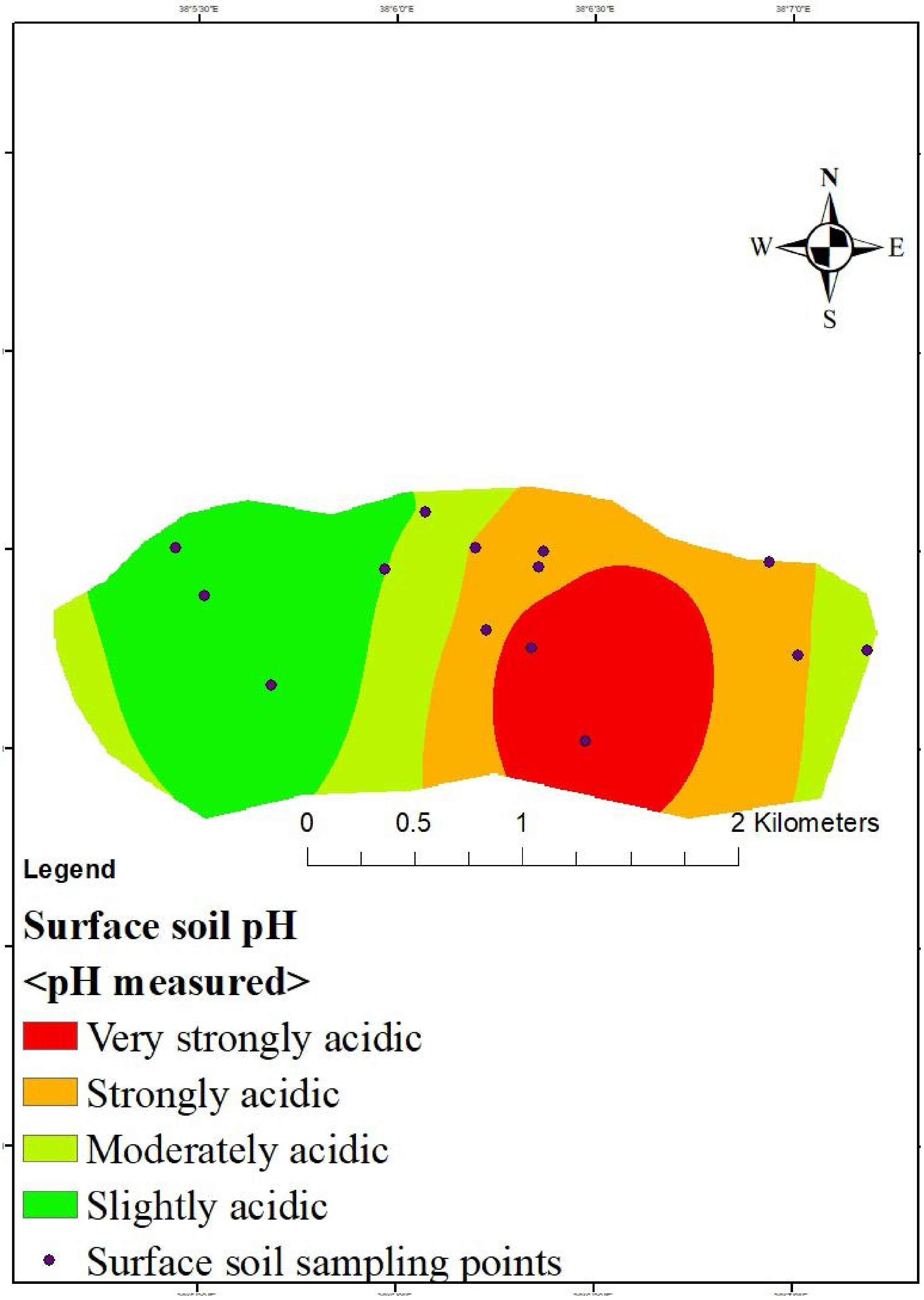

Figure 3. Spatial distribution of measured surface (0-20 cm) soil pH of the water.

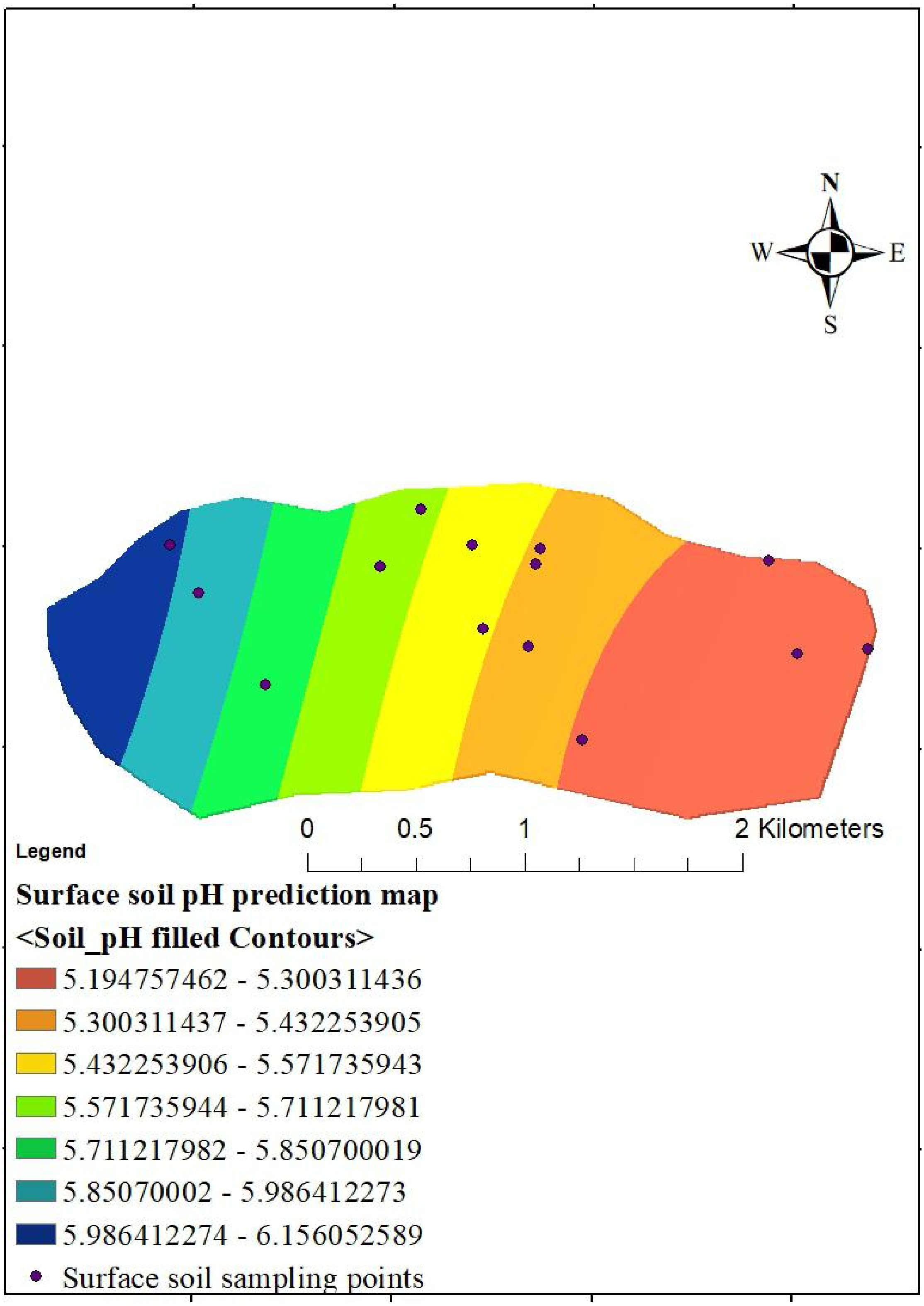

Figure 4. Spatial prediction of surface (0-20 cm) soil pH of the water.

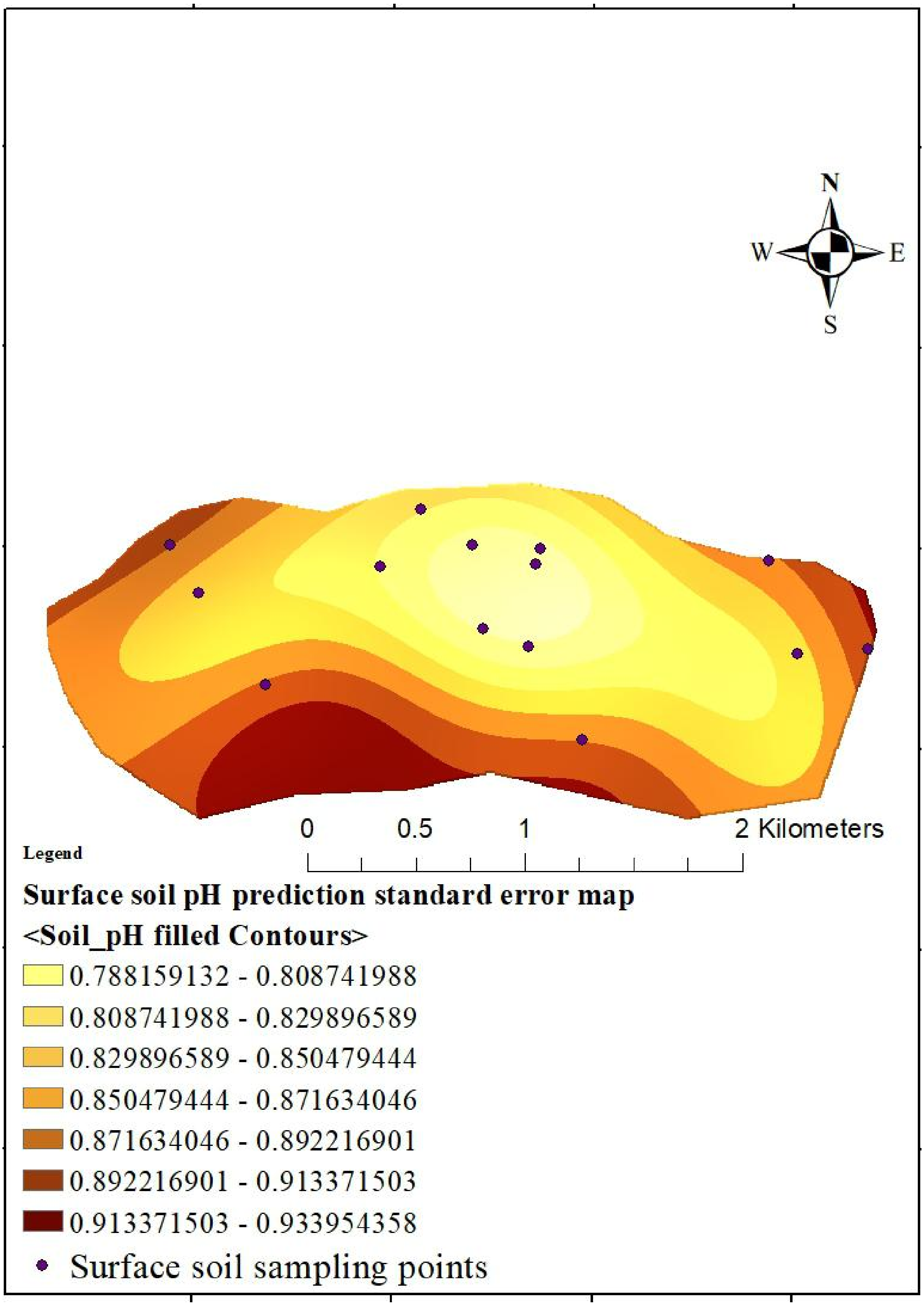

Figure 5. Spatial prediction of standard error surface (0-20 cm) soil pH of the water.

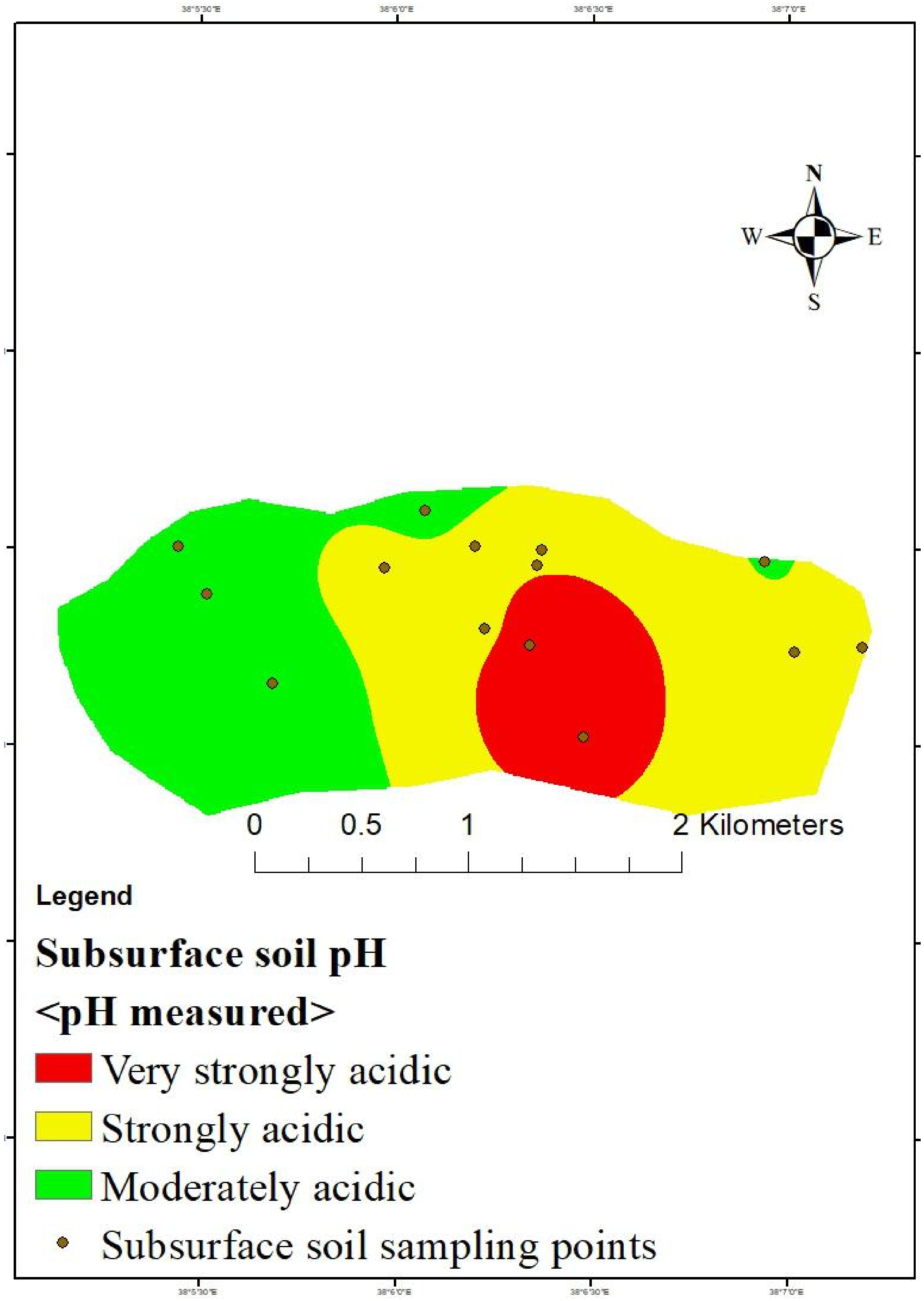

Figure 6. Spatial distribution of measured subsurface (20-40 cm) soil pH of the water.

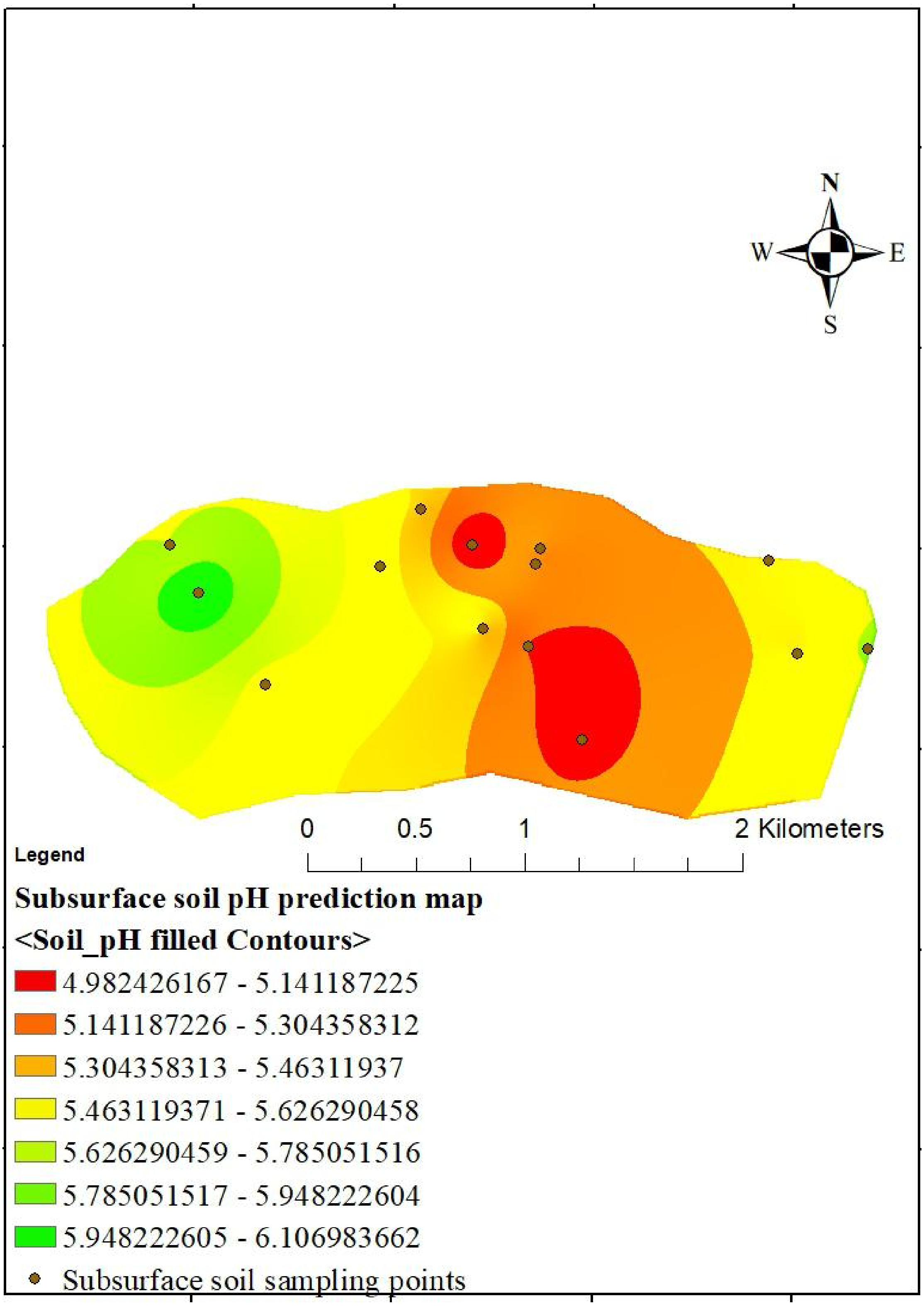

Figure 7. Spatial prediction of subsurface (20-40 cm) soil pH of the water.

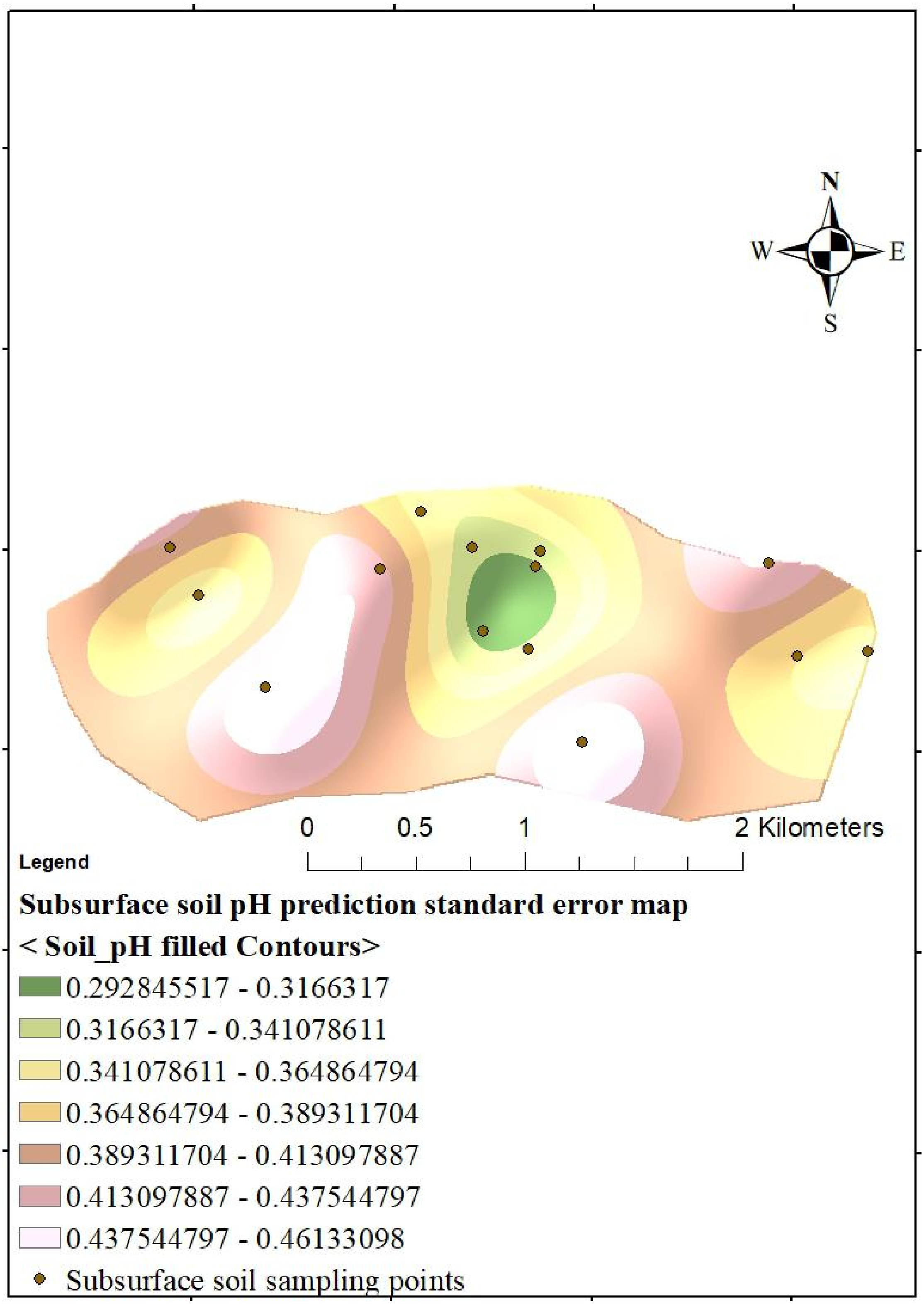

Figure 8. Spatial prediction error of subsurface (20-40 cm) soil pH of the water.

5. CONCLUSION AND RECOMMENDATIONS

This study has demonstrated the application of Geostatistical procedures to the mapping spatial variability of soil acidity and evaluation of physico-chemical soil properties in the Dewoshe sub-watershed area. In this study area most of the physico-chemical soil properties has varied from crop types to soil depths. It might be due to variation in slope gradient, elevation, crop patterns, parent material, land use type and soil management practices. The kriging model that was developed found to be a strong and medium spatial autocorrelation on nugget to sill ratio in prediction of surface and subsurface soil depths. Model validation and assessment revealed fair performance in the generation of predicted values with acceptable prediction errors. Therefore, the generated soil map can serve as a proxy for soil pH in Dewoshe sub-watershed area. Where evidence of spatial variability structure and quantitative estimates of uncertainty are reported imagery. Thus, the map produced can be used as guide for various uses, including identifying lime application rates according to spatial variability of soil pH. However, to more precisely understand what is driving soil pH variability in this system, further research should be done to include data sets representing factors of soil formation.

Generally, soils of the study area have strong to slightly acidic soil pH of the water very low and medium contents of OM, low to high contents of TN, very low and low available P, medium and high CEC, low and medium exchangeable Ca and Mg, very low to medium exchangeable K and low exchangeable Na.

The lower value of chemical soil properties in both crop types indicates that nutrients should be replenished to increase their content for optimum and sustainable crop production in the area. Above all maintenance of soil OM should get much attention since lower values were recorded for about 72% (i.e. in both crop and depths types) of the study area although it plays a vital role for improvement of both physico-chemical soil properties. Therefore, creating public awareness about integrated and sustainable soil fertility management through maintenance of SOM in particular has to be done. Well organized integrated watershed management practices have to be implemented. Environmentally and socially acceptable integrated nutrient management practices such as agro-forestry systems, crop rotation, use of organic inputs (compost and FYM), chemical fertilizers, cultivation of acid tolerant plants, covering the surface with non-acidic soil, the use of organic fertilizers, use appropriate farm management practices, avoid continues use of acid forming inorganic fertilizers, protect the removal of agricultural by products (crop residues) and continuous crop harvest, making trace, soil bund, steep sloppy landscapes covered by forest land, and grass land, applying lime requirements on cereal crops up to optimum level of nutrients, but not only cereal crops Enset crop should be needed fertility improvement by increase livestock production and decreasing Enset farm away from households and improved crop varieties that can be adapted to local farming situations should be implemented for sustainable agricultural crop production growth in the study area. However, soil analysis by itself cannot go further than the identification of soil nutrients status due to intricate nature of soil. Therefore, the nutrient supplying powers of the soils and demanding levels of the plants need further correlation and calibration work to come up with conclusive site soil crop specific fertilizer recommendation with appropriate rate.

For the mapping spatial variability of soil acidity the detrimental effects of slope gradient are higher at steep, moderately steep and strongly sloping areas as compared to sloping, gently sloping, very gently sloping and nearly level sloping in the study areas. The decline in quality of soil pH in the study area from steep, moderately steep and strongly sloping areas to sloping, gently sloping, very gently sloping and nearly level sloping were presumed to be due to past soil erosion and high velocity runoff effect that removed the clay particles or control the infiltration of clay soil in to the subsurface, soil organic matter and other plant nutrients. Therefore, the soil pH improvement in the study area should focus a treatment of it that could improve the organic matter and nitrogen levels of the soils and special management practices such as terracing, make soil bund, covering by forest trees, used for grass land, and proper land levelling are required to improve the effects of high slope gradient on soil pH for improving a sustainable crop production. But, not only soil pH for physico-chemical soil properties should be necessary the above recommendation.

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7. APPENDIX

Appendix Table 1. Mean square value of physical soil properties due to crop types, soil depths and their interaction effect in the Dewoshe sub-watershed area.

Source of variation	Degree of freedom	Bulk density (g cm-^{3})	Total porosity (%)	Sand (%)	Silt (%)	Clay (%)
Replication	6	0.044**	62.369**	17.5^{NS}	14.405^{NS}	5.619^{NS}
Crop types	1	0.171**	240.14**	1.75 ^{NS}	0.321 ^{NS}	1.286 ^{NS}
Soil depths	1	0.104**	155.57**	132.89*	0.893 ^{NS}	96.571**
Cp*SD	1	0.025*	36.571*	6.036 ^{NS}	1.75 ^{NS}	9.143^{NS}
Error	18	0.002	2.289	11.976	6.849	3
R-square		0.95	0.95	0.53	0.42	0.72
CV%		3.28	2.84	9.42	6.25	8.16

* - significant at P=0.05; ** - significant at P=0.01; NS=Non-significant at P=0.05; Cp – crop type; SD - soil depths; Cp*SD - interaction of Cp and SD.

Appendix Table 2. Mean square value of chemical soil properties due to crop types, soil depths and their interaction effect in the Dewoshe sub-watershed area.

Source of variation	Degree of freedom	pH-H2O	pH-KCl	ΔpH	%OC	%OM	%TN	C:N	Av.P (mg/kg)
Replication	6	0.679**	0.617*	0.019^{NS}	0.625**	1.86**	0.0043**	9.32^{NS}	6.5*
Crop types	1	5.403**	6.413**	0.043^{NS}	9.97**	29.54**	0.090**	26.46*	256.45**
Soil depths	1	0.043^{NS}	0.366*	0.158*	7.05**	20.98**	0.038**	35.57*	74.65**
Cp*SD	1	2.118**	2.52**	0.018^{NS}	4.456**	13.19**	0.017**	25.54*	64.69**
Error	18	0.039	0.070	0.026	0.1467	0.436	0.001	4.55	2.37
R-square		0.943	0.911	0.42	0.90	0.90	0.905	0.64	0.91
CV%		3.57	5.55	21.84	33.03	33.03	22.56	29.03	43.9

* - significant at P=0.05; ** - significant at P=0.01; NS=Non-significant at P=0.05; pH (H_2O) = Power of Hydrogen in the water solution; pH (KCl) = Power of Hydrogen in the Potassium Chloride solution; ΔpH = Change of power of Hydrogen; OM(%) = Percent of Organic Matter; TN (%) = Percent of Total Nitrogen; C:N = Carbon-Nitrogen ratio; Av.P (mg/kg) = Available Phosphorus in milligram per kilogram; Cp=crop types; SD=Soil depths; Cp*SD=Interaction of Cp and SD.

Appendix Table 3. Mean square value of exchangeable bases, CEC, and exchangeable acidity due to crop types, soil depths and their interaction effect in the Dewoshe sub-watershed area.

Source of variation	Degree of freedom	Ca	Mg	K	Na	PBS	CEC Soil	Ex.Ac	Ex.Al	Ex.H
Replication	6	1.011**	0.447**	0.064*	0.00834**	28.54 ^{NS}	86.655**	1.758*	0.038*	1.492*
Crop types	1	15.451**	6.48**	0.458**	0.0165**	12.8 ^{NS}	505.75**	16.6**	0.070*	14.515**
Soil depths	1	1.286*	1.164**	0.028^{NS}	0.0024^{NS}	16.02 ^{NS}	141.75*	2.218*	0.016^{NS}	1.862^{NS}
Cp*SD	1	0.051^{NS}	0.345*	0.002^{NS}	0.000057^{NS}	54.04 ^{NS}	38.893*	2.401*	0.121**	1.445^{NS}
Error	18	0.053	0.029	0.007	0.00059	16.39	7.242	0.441	0.011	0.462
R-square		0.96	0.952	0.872	0.867	0.46	0.90	0.79	0.68	0.76
CV%		5.061	17.91	32.15	30.56	14.07	12.88	25.68	76.48	27.77

* - significant at P=0.05; ** - significant at P=0.01; NS=Non-significant at P=0.05; Cp -crop type; SD - soil depths; Cp*SD - interaction of Cp and SD; Ex.Ac=Exchangeable Acidity; Ex.Al=Exchangeable Aluminium and Ex.H=Exchangeable Hydrogen.

Appendix Table 4. Rating of soil pH in the water (Forth and Ellis, 1997), OM and TN (Tekalign, 1991), pH in KCl (FAO, 2012), Av.P (ppm) (Barber, 1984), and CEC (Hazelton and Murphy, 2007).

	pH			Av.P (ppm) /mg/kg	OM	TN	CEC	
H_2O	Rating	KCl	Rating		%OM	%TN	CEC (cmolc kg-1)	Rating
< 4	Extremely acidic	< 4.5	Extremely acid	<5	< 0.86	< 0.05	<6	Very low
4.5-5.0	Very strongly acid	4.5-5.5	Very acid	5-10	0.86-2.59	0.05-0.12	6-12	Low
5.1-5.5	Strongly acidic	5.5-7.2	Acid to neutral	10-25	2.59-5.17	0.12-0.25	12-25	Medium
5.6-6	Moderately acidic	7.2-8.5	Carbonbate rich soil	25-50	> 5.17	> 0.25	25-40	High
6.1-6.5	Slightly acid	>8.5	Alkaline	>50			> 40	Very high
6.6-7.3	Neutral							
7.4-7.8	Slightly alkaline							

Appendix Table 5. Rating of exchangeable cations (FAO, 2006a), and PBS (Hazelton and Murphy, 2007) in the Dewoshe sub-watershed area.

Rating	Exchangeable cations (cmolc kg-^{1})				
	Ca	Mg	K	Na	PBS
Very high	> 20	> 8	> 1.2	> 2	>80
High	10-20	3-8	0.6-1.2	0.7-2	60-80
Medium	5-10	1-3	0.3-0.6	0.3-0.7	40-60
Low	2-5	0.3-1	0.2-0.3	0.1-0.3	20-40
Very low	< 2	< 0.3	< 0.2	< 0.1	0-20

Appendix Table 6. Slope gradient classes (FAO, 2006a), points for spatial variability of soil acidity mapping in the Dewoshe sub-watershed area.

Crop types	**Slope gradient class**		
Cereal crops	Slope Class (%)	Land form description	Current slope (%)
1	0.5-1	Nearly Level	0.85
2	1-2	Very gently slopping	1.60
3	2-5	Gently slopping	4
4	5-10	Slopping	9
5	10-15	Strongly slopping	13
6	15-30	Moderately steep slopping	21
7	30-60	Steep slopping	37
Enset crop			
8	0.5-1	Nearly Level	0.70
9	1-2	Very gently slopping	1.30
10	2-5	Gently slopping	3
11	5-10	Slopping	7
12	10-15	Strongly slopping	12
13	15-30	Moderately steep slopping	19
14	30-60	Steep slopping	34

Appendix Table 7. Geographical coordinates of the Dewoshe sub-watershed area.

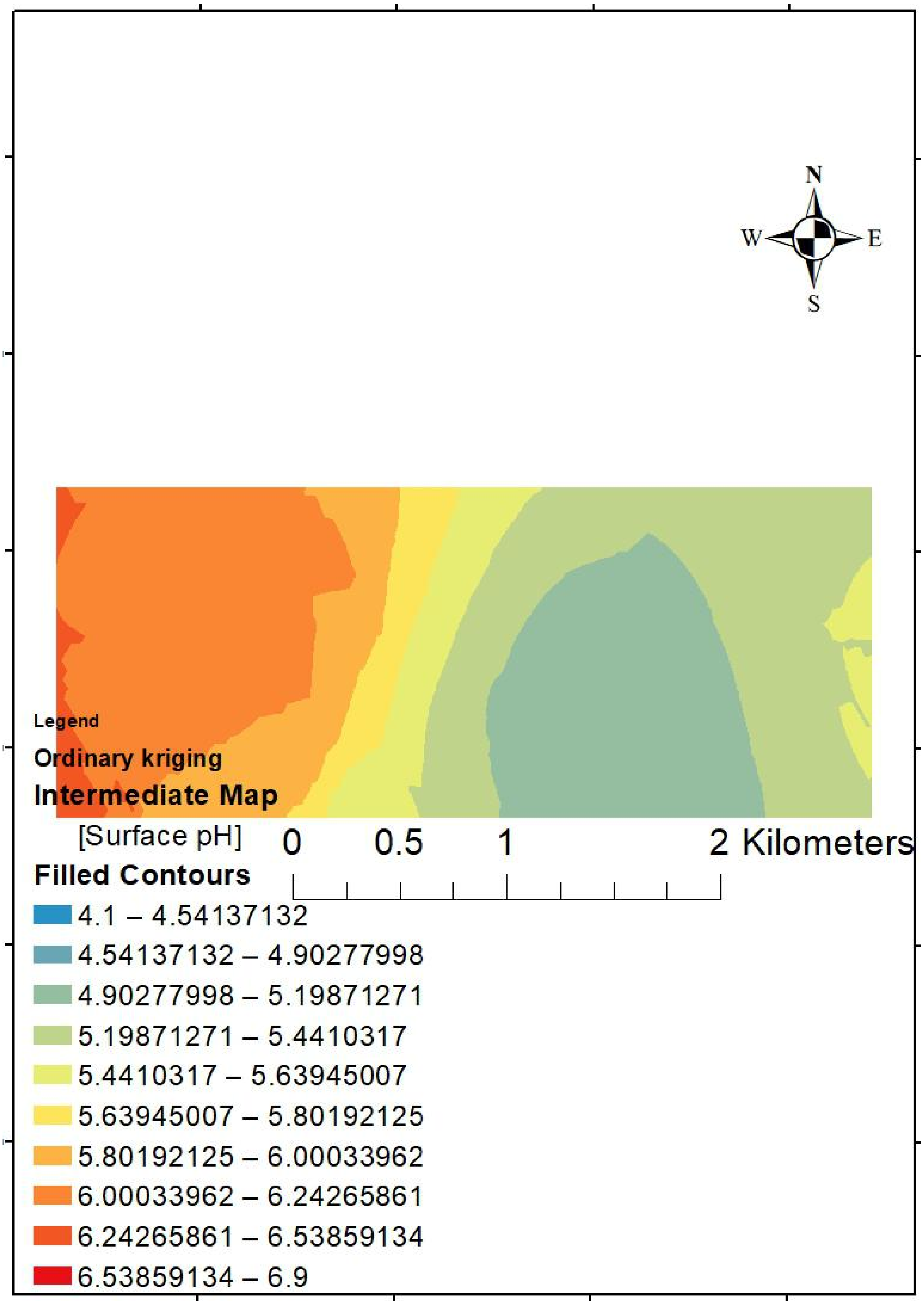
Crop types	Slope class	Garmin UTM Points		Points in degree, minutes and seconds		Altitude (masl)
Cereal crops		Latitude	Longitude	Latitude (Northing)	Longitude (Easting)	
1	0.5-1	399931	886881	N8°01´20.53´´	E38°05´30.91´´	2925
2	1-2	402549	887032	N8°01´25.64´´	E38°06´56.41´´	3018
3	2-5	402685	886605	N8°01´11.75´´	E38°07´00.88´´	3030
4	5-10	401189	887103	N8°01´27.85´´	E38°06´11.98´´	2948
5	10-15	401502	887085	N8°01´27.27´´	E38°06´22.22´´	2967
6	15-30	401447	886638	N8°01´12.73´´	E38°06´20.43´´	2993
7	30-60	401696	886206	N8°00´58.67´´	E38°06´28.6´´	2987
Enset crop						
8	0.5-1	400240	886462	N8°01´06.91´´	E38°05´41.02´´	2942
9	1-2	399799	887102	N8°01´27.73´´	E38°05´26.59´´	2929
10	2-5	400953	887269	N8°01´33.25´´	E38°06´04.25´´	2962
11	5-10	403006	886626	N8°01´12.43´´	E38°07´11.36´´	3011
12	10-15	401482	887013	N8°01´24.93´´	E38°06´21.55´´	2971
13	15-30	400766	887003	N8°01´24.56´´	E38°05´58.16´´	2945
14	30-60	401237	886717	N8°01´15.27´´	E38°06´13.57´´	2981

Appendix Table 8. Slope class and crop types of the sampling points in the Dewoshe sub-watershed area.

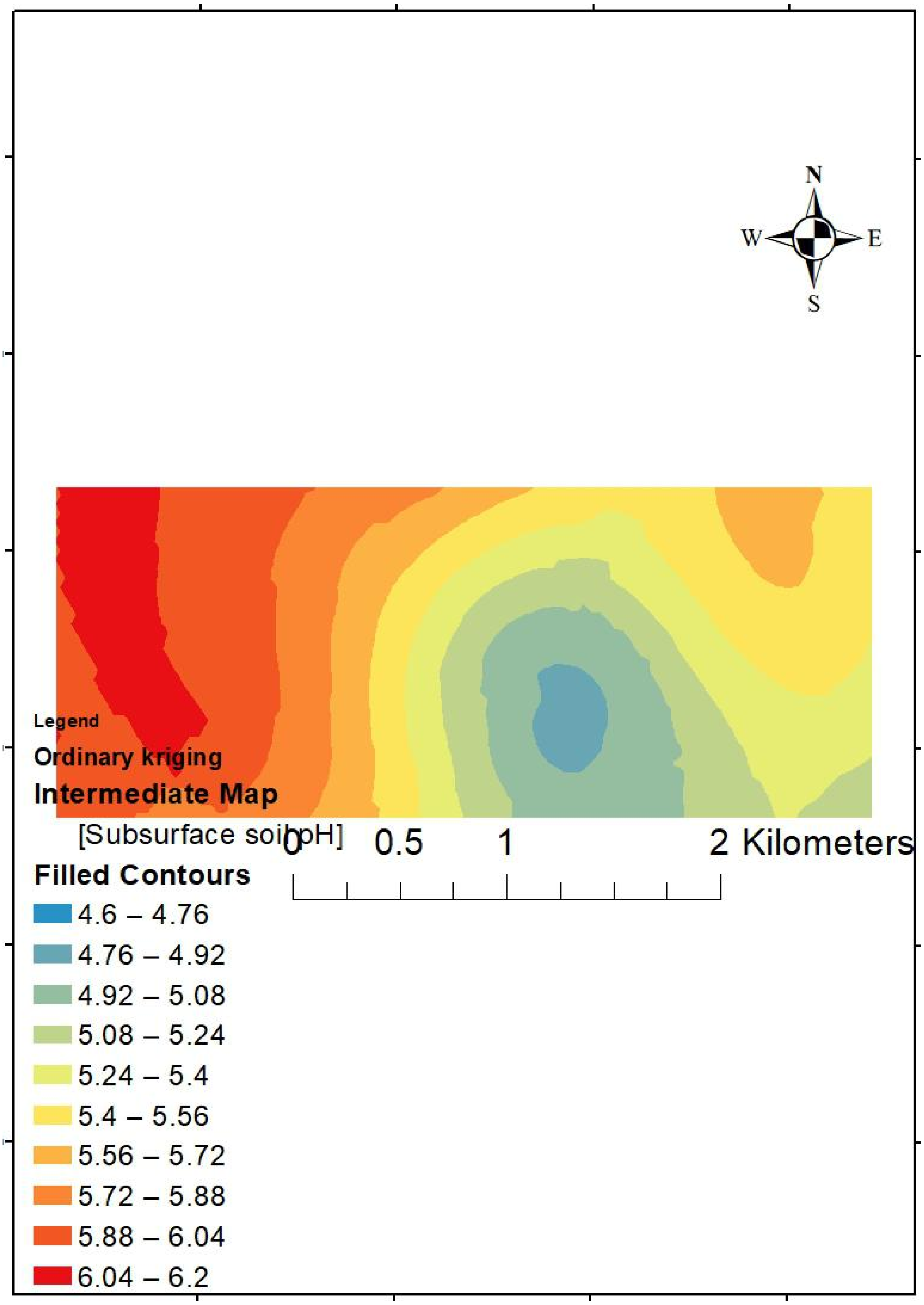
Slope class	Dominant previous crop in summer	Dominant previous crop in spring season	Dominant current crop
0.5-1	Barley	Potato	Wheat
1-2	Barley	Potato	Barley and Wheat
2-5	Wheat	Potato	Barley
5-10	Barley	Potato	Barley
10-15	Barley	No	Barley
15-30	Barley	No	Barley
30-60	Barley	No	Barley

Source: Currently crop observed by farming areas, and previous crop in spring season have been asked by land owner (farmers).

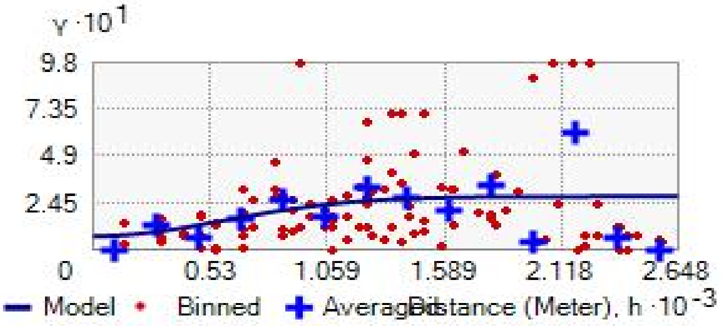
Note: - Enset crop is the perennial and continues to grow on the field for decades.



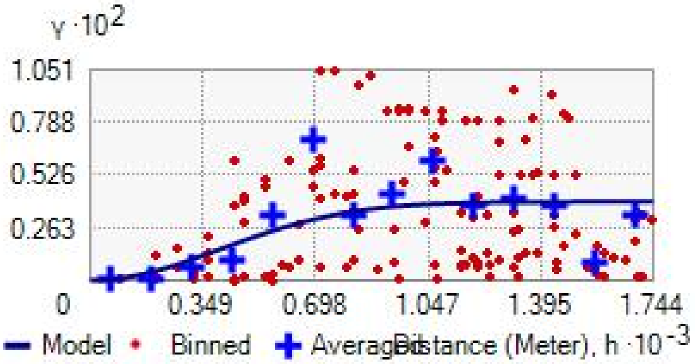
Appendix Figure 1. Intermediate semi-variogram map in surface (0-20 cm) soil pH of the water.



Appendix Figure 2. Intermediate semi-variogram map in subsurface (20-40 cm) soil pH of the water.



Appendix Figure 3. Isotropic semi-variograms and Guassian model for surface soil (0-20 cm) pH of the water.



Appendix Figure 4. Isotropic semi-variogram and Spherical model for subsurface soil (20-40 cm) pH of the water.