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QUANTIFYING SOIL NUTRIENT BALANCE AND STOCK ON SMALLHOLDER FARMS AT AGEW MARIAM MICRO-WATERSHED IN NORTHERN ETHIOPIA

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MSc Thesis

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A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF COLLEGE OF AGRICULTURE AND ENVIRONMENTAL SCIENCES, BAHIR DAR UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE (MSc.) IN SOIL SCIENCE

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THESIS APPROVAL SHEET

As members of the Board of Examiners of the Master of Sciences (MSc.) thesis open defense examination, we have read and evaluated this thesis prepared by Mr. **Tilahun Esubalew Nigussie** entitled "**Quantifying Soil Nutrient Balance and Stock of Smallholder Farms at Agew Mariam micro-Watershed in Northern Ethiopia**". We hereby certify that the thesis is accepted for fulfilling the requirements for the award of the degree of Master of Sciences (M.Sc.) in **Soil Science**.

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DECLARATION

This is to certify that this thesis entitled “**Quantifying Soil nutrient balance and stock of smallholder farms at Agew Mariam micro-watershed northern Ethiopia**” was submitted in partial fulfillment of the requirements for the award of the degree of Master of Science in “**Soil Science**” to the Graduate Program of College of Agriculture and Environmental Sciences, Bahir Dar University by **Mr. Tilahun Esubalew** (ID. No. BDU1206796PR) is an authentic work carried out by him under our guidance. The matter embodied in this project work has not been submitted earlier for the award of any degree or diploma to the best of our knowledge and belief.

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DEDICATION

This study is wholeheartedly dedicated to those who are struggling against the terrorist Tigray people liberation front (TPLF) group to ensure the existence of the Amhara people, and to sustain the unity of Ethiopia.

LIST OF ACRONYMS AND ABBREVIATIONS

Ava. K	Available Potassium
Av. P	Available Phosphorus
BD	Bulk Density
BOA	Bureau of Agriculture
FAO	Food and Agricultural Organization of the United Nation
ISFM	Integrated Soil Fertility Management
IN1	Input from Inorganic Fertilizer
IN2	Input from Organic Fertilizer
IN3	Input through Atmospheric Deposition
IN4	Input through Nitrogen Fixation
OC	Organic Carbon
OM	Organic Matter
OUT1	Output through Crop Product
OUT2	Output through Crop Residue
OUT3	Output through Leaching
OUT4	Output through Gaseous Loss
OUT5	Output through Erosion
PPM	Parts Per Million
SWC	Soil and Water Conservation
USLE	Universal Soil Loss Equation

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QUANTIFYING SOIL NUTRIENT BALANCE AND STOCK ON SMALLHOLDER FARMS AT AGEW MARIAM MICRO-WATERSHED IN NORTHERN ETHIOPIA

By

Tilahun Esubalew

Advisors: Tadele Amare (Ph.D.) and Eyayu Molla (Ph.D.)

ABSTRACTS

Soil nutrient balance is used to evaluate the state of soil fertility, rate of nutrient depletion, sustainability of land productivity, the environmental wellbeing of an area, and to take appropriate management decisions. This study was conducted to quantify soil nutrient balance and stocks on smallholder farms at Agew Mariam watershed in northern Ethiopia in the 2020/21 main season. Inflows and outflows of nitrogen (N), phosphorus (P), and potassium (K) into, and out of barley, tef, and wheat farms were determined through, field measurement, laboratory analysis, USLE model, pedo-transfer functions, and interview questions. The total inflows of N on barley, tef, and wheat farms were 15.1, 12.5, and 10.5 kg ha^{-1} yr^{-1} respectively. P inflows on barley, tef and wheat were 0.7, 3.3, and 3.4 kg ha^{-1} yr^{-1} respectively. Thus K inflows values were similar for all farms 2.7 kg ha^{-1} yr^{-1}. The outflow of N was 81.8, 21.4, and 57.6 kg ha^{-1} yr^{-1} for barley, tef, and wheat respectively. The outflows of P from barley, tef, and wheat were 6, 1.8, and 5.3 kg ha^{-1} yr^{-1} respectively. Similarly, the total K outflows were 15.5, 6, and 8.7 kg ha^{-1} yr^{-1} from barley, tef, and wheat farms respectively The N partial balance of barley, tef, and wheat was -66, -9.8, and -50.7 kg ha^{-1} yr^{-1} respectively. The P balance was -5.9, 0.9, and -2.6 kg ha^{-1} yr^{-1} for barley, tef, and wheat respectively. Whereas, K balance was -12.3, -3.2 and -5.4 kg ha^{-1} yr^{-1} from barley, tef, and wheat respectively. The balance results revealed that N and K had negative values except for P in tef. The major paths of nutrient loss were via grain yield, crop residue removal, and leaching. The stock of N was 1295, 1510, and 1240 from barley, tef, and wheat kg ha^{-1}respectively while, the P stock was 63, 18.7, and 27.5, kg ha^{-1} from barley, tef, and wheat farms respectively. Similarly K stock was 1092.7, 1059.4, and 1090.6 kg ha^{-1} from barley, tef, and wheat cropping systems respectively. Reversing the imbalance between inflows and outflows via adding organic and inorganic fertilizers is critically essential.

Keywords: Barley, Inflow, Outflow, Tef, Wheat

CHAPTER 1. INTRODUCTION

1.1. Background and Justification

Soil fertility is a limiting factor for agricultural production (Lehmann *et al.*, 2003). However, in sub-Saharan Africa, it was declining and becoming the major cause of slow agricultural transformation, food insecurity, and rural poverty (Donovan and Casey, 1998; Sheldrick *et al*., 2003; Vanlauwe *et al*., 2015). The fertility of the soil is diminishing as a result of continuous cultivation without adequate input supply, poor land management, and soil erosion (Melku Dagnachew *et al.*, 2020). Ethiopian soil fertility depletion has been increased over time with yield levels (Stoorvogel *et al*., 1993; Van Beek *et al.*, 2016).

Large areas of sub-Saharan Africa are affected by nutrient depletion (Stoorvogel and Smaling, 1990), caused by many factors including food crop production with little or no use of organic and inorganic fertilizers (Heerink, 2005). Similarly, continual nutrient elimination via crop harvests with inadequate nutrient substitutes depletes the nutrients (Bekunda *et al.*, 2002). Continuous mono-cropping with one or two chemical fertilizer sources gradually causes soil fertility depletion (Abebe Zerihun and Deressa Haile, 2017). Hence, in sub-Saharan Africa (SSA) countries the agricultural productivity is low. But the overall agricultural production in the region has increased from the 1990s, primarily due to the expansion of the agricultural lands (Fuglie and Rada, 2013).

Soil erosion also deteriorates soil fertility (Segarra *et al*., 1991; Lal, 2009). Its economic impact is a serious problem in developing countries because of the lack of capacity to cope with it (Sanchez, 2002; Lulseged Tamene and Paul, 2008). The impact of soil erosion is manifested by soil degradation which is characterized by nutrient depletion and negatively affects agricultural sustainability (Brand and Pfund, 1998). Similarly, in Ethiopia, the decline in soil fertility related to soil erosion and land degradation is a constraint to agricultural productivity (Tolera Abera *et al*., 2009), food insecurity (Nyssen *et al*., 2007; Vlek *et al*., 2010), and sustainability (Eyasu Elias, 1998; Berhanu Gebremedhin and Swinton, 2003; Gebremedhin Kiros *et al*., 2014).

Soil fertility management is a serious issue for farmers and researchers as soil properties vary spatially and temporally (Rosemary *et al.*, 2017). This is because crop production and productivity improvement mainly depend on soil nutrient management (Koch *et al*., 2020). Besides, soil nutrient management is affected by wealth and off-farm incomes. But the cost of inorganic fertilizers in Africa is beyond the capacity of subsistence farmers (Eyasu Elias, 2002; Kasozi, 2005). As a result, poor nutrient management is a risk for sustainable agricultural production (Amare Haileslassie *et al*., 2006). To reverse such nutrient management practice immediate and proper corrective measures should be done on time in place. Integrated soil fertility management is one of the corrective measures to improve the negative balance of nutrients (Oenema and Pietrzak, 2002; Workineh Ejigu *et al*., 2021). Since long-term soil fertility management enhances productivity, environmental quality should be adopted, and sustainability (Goulding *et al*., 2008). The basic principle of maintaining soil fertility is replenishing annually removed nutrients from the field. Indeed, this becomes more relevant in the absence of the measures for adequate replenishment of the depleted nutrient pools through the removal of crop residues from agricultural fields (Sanyal *et al*., 2014).

Soil nutrient balance is the summation difference between nutrient input flows and output flows within a particular framework over a certain period (Stoorvogel and Smaling, 1990). On the other hand, it can be defined as the difference between the nutrients entering a farming system (mainly livestock manure and fertilizers) and the nutrients leaving the system (the uptake of nutrients for crop and pasture production). However, it does not express the current soil fertility level (Van Beek *et al.*, 2016). Nutrient balance is used to assess soil fertility changes, and understand nutrient depletion (Bindraban *et al.*, 2000; Roy *et al*., 2003). Simultaneously, it is used to identify the present status of agricultural cultivated fields, soil health levels and to take appropriate measures. This activity helps to sustain a healthy ecosystem service system and nutrition (Amare Haileslassie *et al.*, 2006), and it is a static tool to calculate the balance of nutrients in a specific year (Lesschen *et al.*, 2007).

Nutrient balances provide information about environmental pressures. A negative balance indicates a decline in soil fertility, while, a positive value indicates nutrient addition greater than removed from the soil. A surplus may cause a risk of pollution to soil, water, and air

(FAO, 2003). Thus, nutrient balance analysis is an indicator of soil whether soil fertility is being maintained, improved, or degraded (Stoorvogel and Smaling, 1990). Additionally, Soil nutrient balances can indicate nutrient use efficiency of the farming systems (Van der Pol, 1992; Stoorvogel, 2007; Cobo *et al*., 2010). Similarly, the partial nutrient balance serves as an indicator of management practices and the sustainability of the farm, and the systems (Jiri1 and. Mafongoya, 2018; Theodora, 2018).

In Ethiopia, many studies on nutrient balance showed a negative balance. According to Amare Haileslassie *et al*. (2005), the nutrient balance of Ethiopia is decreasing except in, areas covered by permanent vegetation cover and vegetable cropping systems. It showed the nutrient balances in the Amhara, Oromiya, and southern nation and nationalities regions, are strongly negative as compared with less intensively cultivated regions of (Afar and Somali). This was due to ineffective use of locally available nutrient resources, lack of proper soil and water conservation practices, and high cost of synthetic fertilizers (Eyasu Elias, 2002; Abebayehu Aticho *et al*., 2011). For instance, in the central highlands of Ethiopia, the nutrient balance value for tef based farming system had a net negative balance for Nitrogen and Potassium (Gebremedhin Kiros *et al*., 2014). Similarly, in the Tigray region, Northern Ethiopia, N, P, and K balance were found negative (Abrham Belete, 2014).

Soil nutrient stock is the accumulation of plant nutrients in the soil that can be available to plants from 5 to 10 years (Sanchez and Palm, 1996). This could be achieved through the application of integrated nutrient management principles that ensures a positive nutrient balance for a long time with sustainable crop production (Selim, 2020). Integrated soil fertility management practice is the core principle to reverse the current situation of nutrients in Ethiopia (Deugd *et al*., 1998; Tamirat Wato, 2019). Its success highly depends on the revenue and the interests of farm families to invest in soil fertility (Deugd *et al*., 1998). Therefore, prudent nutrients management strategies for better crop yield and sustainability are indisputable.

In the Waghimera zone of the Amhara Region, the rainfall is erratic and insufficient. Degraded steep slope, less vegetation cover, poor crop residue management, low organic and inorganic inputs resulted in poor soil fertility. Furthermore, the inappropriate design of soil water conservation (SWC) structures resulted in the decline of soil fertility that is reflected by shocking low crop productivity. As a result, in the study area, half of the communities (50%) were food insecure and under continuous refuge (BOA, 2018). On the other hand, there is a critical research gap on nutrient balance in this part of the country. Therefore, this study was initiated to identify the impact of current soil fertility management practices on soil nutrient status through the analysis of nutrient balances based on monitoring the inputs and outputs of the nutrients at the Agew Mariam watershed.

1.2. Statement of the Problem

Land degradation and nutrient depletion have been increasing and negatively affecting agricultural production and sustainability in different parts of Ethiopia (Fasile Kebede and Charles, 2009). Especially land degradation and decline soil fertility are becoming a serious problem in different parts of Amhara National Regional State (ANRS) Ethiopia. The problem is so serious in the eastern part of the regional state one of which is the Waghimera administrative zone where soil fertility decline is exacerbated by the mountainous, undulating land features and scattered vegetation cover. In particular, soil fertility decline is a common problem in the Agew Mariam watershed where this study was conducted. The mean annual soil loss of the Agew Mariam catchment was estimated to be 25 t ha^{-1} yr^{-1} (Gebrehana Girmay *et al*., 2020). Thus the production and productivity of crops are low in the watershed as illustrated in (Appendix 2) the yield of barley, tef and wheat were 2100, 550, and 1006 kg ha^{-1} respectively. Although soil and water conservation measures have been done by governmental and non-governmental organizations through community mobilization, the result is below the expectation. Farmers of the watershed also practiced applying a small amount of inorganic fertilizers, poor land use management practice, and continuous mono-cropping.

In addition, the most pressing problems in the Agew Mariam watershed are the absence of retaining crop residue management, inefficient use of locally available nutrient resources, poor adoption of the agroforestry practice, deforestation, and poor complimentary services such as extension, credit, marketing, infrastructure, and climatic factors such as drought and flood are still key problems of the study area and might be highly associated to negative nutrient balances. These factors minimize the adaptive capacity and aggravate the vulnerability of farmers to future changes, such as climate change, low production, and food insecure which negatively affect the performance of agricultural productivity and hydrological processes. So, knowledge of soil nutrient balance by quantifying the inputs and outputs at the watershed level is vital in the study area.

1.3. Objective

1.3.1. General objective

The general objective of this study was to quantify soil nutrient balance and stock of smallholder farms at Agew Mariam micro-watershed.

1.3.2. Specific objectives

The specific objectives of this study were;

- To quantify the inflows, outflows of N, P, K, and nutrient balance in the major crop types grown in the watershed.
- To estimate N, P, and K nutrient stocks on smallholder farms in the watershed.

1.4. Research Questions

The research was conducted to answer the following questions;

1. How much nitrogen, phosphorous, and potassium were inflows and outflows from the Smallholder farms of major crops at Agew Mariam watershed?
2. How much nitrogen, phosphorous, and potassium nutrient balance of the major crop in the watershed.
3. How much nitrogen, phosphorous, and potassium stock was existing in the smallholder farms of major crop types at the watershed?

1.5. Hypotheses

Soil nutrient balance is expected negative and the stock is declining under smallholder farms in the Agew Mariam watershed. Loss of essential plant nutrients, particularly N, P, and K through, soil erosion, crop residue, harvested crop product, gaseous loss, and leaching is high. Inputs addition of organic and inorganic fertilizers under the study area may be lower than outputs. That may lead to a negative nutrient balance and lower N, P, K nutrient stocks that lead to low nutrient reserve and hence causing current and future unsustainable production systems of agriculture. Therefore, quantifying soil nutrient stock, inputs in to and outputs from smallholder farms is a critical and a priority research to support development organizations and policymakers for their immediate, midterm, and long-term decisions to enhance the nutrient balance and stocks towards a positive trend that could finally improve the productivity of the farming system.

1.6. Significance of the Study

Quantifying soil nutrient balance and stock helps to examine the fertility management practices of smallholder farms in the Agew Mariam watershed of the Waghimera zone, Amhara Region. This research helps to generate information about the input-output flow of nutrients in the smallholder farming system of the study area. Furthermore, the study could play a significant role in estimating the primary macronutrient concentration of the farms. The amount of available plant nutrients of N, P, and K in the upper 0.2 m could be estimated further and this will help for additional research and development endeavors. Quantifying soil nutrient balance provides information about the state of soil fertility and environmental quality to take appropriate management measures.

Generally, a soil nutrient balance study is used to determine the amount and type of organic and inorganic fertilizers added and the sustainability of the farms. Computing and estimating inputs of nutrients through biological nitrogen fixation and atmospheric deposition of the major crops in the watershed could be used as parts of knowledge and skill for sustainable soil fertility management. Besides knowledge and skill will be developed on estimating nutrients lost through soil erosion, leaching, denitrification, volatilization, harvested crop product, and above-ground biomass yield. Then, the magnitude of nutrient depletion and its impact on agricultural production is critically important for catering agricultural developments in the study area on the farming systems of barley, tef, and bread wheat farmlands.

1.7. Scope and Limitation of the Study

This study mainly focused on smallholder farms at the watershed level. Quantification of soil nutrient inputs in to and outputs from agricultural cultivated lands was done annually for the rainy season. During this research work, there were many challenging issues occurred. It needs more time, labor, finance, and better equipment. Nutrient balance study needs more data, requires integrating of interviewed and focus-grouped data with direct measured and observed biological, laboratory analysis, pedo-transfer analysis, and model-simulated data are used. There are no previous studies on soil nutrient balance and total nutrient stock in the study area to compare and contrast the spatial and temporal trends with the current finding result.

CHAPTER 2. LITERATURE REVIEW

2.1. Concept of Nutrient Balance

In agricultural farmlands, nutrients are entered and left from the systems in different ways. Fertilization, atmospheric deposition, sedimentation, and biological nitrogen fixation are mechanisms of nutrient addition. Whereas, harvested crop yield, above-ground biomass residue removal, nutrient leaching, nutrient volatilization, nutrient denitrification, and soil erosion are means of outflows of nutrients. Nutrient balance is the summation difference between inputs and outputs (Smaling and Dixon, 2006). The inflows and outflows can be estimated through direct measurements, pedo-transfer functions, field surveys, group discussions, databases, and works of literature (Oenema and Heinen, 1999).

Nutrient balances values can be positive or negative. The negative nutrient balances show that in the system the outputs are larger than the inputs. This implies that the system is under nutrient deficiency and fertility status decline (Bindraban *et al.*, 2000). While excessive positive balance values indicate the nutrients environmental issues on the system are accumulating and have polluting risks on soil, air, and water (Cobo *et al.*, 2010). Nutrient balances are used to do gross evaluations of system sustainability for crop production, soil quality, and potential nutrient losses to the air and water. Nutrient balances can be done on national, regional, watershed, farm, and field scales (FAO, 2003). Nutrient budgets at the farm level serve slightly for different purposes. Nutrient flows into and out of fields, watersheds, regions, and countries are evaluated to determine if soil nutrient stocks are being depleted or enriched. Farm-level balances can be used as a daily management tool, whereas balances as a whole serve as indicators for policy-level management (Alley and Vanlauwe, 2009). Nutrient balances are also essential for understanding soil fertility decline, recovery, or pollution and for setting up new strategies dealing with soil management (Roy *et al.*, 2003). Furthermore, it is used for facilitating discussions with farmers about soil fertility issues and for policy recommendations (De Jager, 2005).

2.2. Soil Fertility Depletion

Soil nutrient diminution is a continuous process and occurred due to: soil erosion, poor land use policy, poor routine crop residue retention on fields, low addition of organic and inorganic inputs are the main constraint of agricultural production and productivity in sub-Saharan Africa. Continuous depletion of soil N, P, and K in most African countries and other least developed countries, coupled with low crop production levels, poses a real threat to agricultural sustainability and food security. Soil nutrient depletion caused by high production levels and decline in fertilizer use in recent decades in many developed countries is also a concern. Worldwide, soil fertility problems associated with human-induced nutrient depletion are expected to continue (Smaling *et al*., *2007).*

Soil fertility depletion is directly related to the increasing food demands. Protected and forest lands shifted to cultivation. Ethiopia is affected by soil nutrient depletion (Eyasu Elias *et al*., 1998; Amare Haileslassie *et al*., 2005). The study of Adugna *et al*. (2015), in western Ethiopia, revealed that the annual rate of soil loss is in the vary of 4.5 Mg ha^{-1} yr^{-1} in forestland and 65.9 Mg ha^{-1} yr^{-1} in cropland. The rate of soil loss in the cropland, which debts for about 69 percent of the whole soil loss in the study area is severe. Nutrient depletion causes low agricultural production and malnutrition (Amare Haileslassie *et al*., 2005). Soil erosion by water lowered soil quality by transporting surface soil nutrients and SOM selectively from the top to lower slope positions. Grain yields and aboveground biomass have been discovered to amplify from the higher to lower slope positions. In steep-slope areas, soil erosion was a predominant reason for soil degradation and grain yield discount (Zheng-An *et al.,* 2010). In the central highlands of Ethiopia, soil erosion is essential agricultural trouble that resulted from inappropriate land management practices (Gebremedhin Kiros *et al*., 2014).

Soil nutrient management practices for different land-use types by smallholder farmers could not support improving macronutrient stocks in the Jimma zone, of western Ethiopia due to the added nutrients were not sufficient to compensate for the loss (Abebayehu Aticho and Eyasu Elias, 2011). However, in the highlands of Ethiopia, the depletion of soil nutrients increased over time with a mild decrease in crop production (van Beek *et al*., 2016). Most Ethiopian soils have low nutrient contents particularly nitrogen and phosphorus (Assefa Workineh *et al.,* 2015). Research conducted by Hillette Hailu *et al*. (2015) showed in central highland Vertisols of Ethiopia due to either inherently low availability of nutrients in the soil or as a consequence of continuous intensive cropping without applying nutrient inputs, that lead both the fields and plants tissue analysis was low values of N, P, K, S, Zn, Mo, and Bo nutrients.

2.3. Soil Fertility Management

Effective nutrient management is an indispensable component for sustaining environmental quality, food, fodder, and fiber production (Pathak *et al*., 2010). Establishing plot-level suggestions is an effective proper diagnosis of soil fertility-related constraints. Especially in the context of highly variable soil fertility conditions of African smallholder agriculture (Vanlauwe *et al*., 2014; Goulding *et al*., 2007). Soil fertility management has multiple approaches and supplying essential plant nutrients adequately, conserving soil from erosion, leaving crop residue in the farm, and adding organic fertilizers are some of the alternatives. A decline in soil fertility of Africa is a threat and that needs great attention (Smaling *et al*., 1997). Improving soil nutrient availability is a necessity for increasing crop productivity in SSA (Wortmann and Sones, 2017). Exhaustive land-use practices have a direct and fundamental impact on crop productiveness (Hailu Araya *et al*., 2011; Sanchez and Swaminathan, 2005). So far, many research findings showed that managing practice of soil fertility is poor in SSA including Ethiopia, due to lack of awareness, insufficient technology supply, poor institutional coordination, and extension services. There are different types of soil fertility management practices. Integrated soil fertility management is a set of soil fertility management practices that include the use of fertilizers, organic inputs, and improved germplasm adapted to local conditions, aimed at excessive agronomic use efficiency of the applied nutrients and improving crop productivity (Vanlauwe *et al*., 2010).

Soil fertility can be restored through maintaining and protecting from erosion as well as using organic and inorganic fertilizers (Fanuel Laekemariam and Kibebew Kibret, 2020). The use of the early maturing soybean variety as a precursor with FYM and phosphorous fertilizer in the short rainy season boasted the yield of the subsequent finger millet (Abebe Zerihun and Deressa Haile, 2017). ISFM through grain legumes and synthetic fertilizers enhance soil fertility, and increase crop yield by maximizing nutrient use efficiency, in southern Ethiopia.

ISFM significantly improves the sustainability of farming (Mulugeta Habte *et al*., 2018). In northern Ethiopia (Tigray) farmers practice crop rotation, animal manure application, planting multi-purpose trees, and compost as means of soil fertility management (Hailu Araya, 2010). Different authors propose integrated soil fertility management to prevent nutrient depletion (Vanlauwe *et al.,* 2010). Conservation Agriculture had a significant role in minimizing nutrient depletion (Jama and Pizarro, 2008; Giller *et al*., 2009). Mineral fertilizers alone couldn't lead to sustainable systems (Kraaijvanger and Veldkamp, 2014).

2.4. Soil Fertility Management Factors

2.4.1. Socio-economic factors

Soil fertility is affected by different resources access to farmers: including the relative value of land, land size, labor, capital endowments, and opportunities (Corbeels *et al.,* 2000). Establishing efficient and effective systems to supply fertilizers, seeds, and other Agri-inputs has a crucial role to improve soil fertility. But access and opportunities are poor in most developing countries due to the small size of the market, limited technical capacity of merchants, poor information network systems, high cost, and lack of a regulatory framework for quality control. Most countries in sub-Saharan Africa depend on imports of fertilizers to satisfy the needs of nutrients by the crops. That implies governments and all stakeholders including donors should secure an adequate and timely supply of foreign exchange and credit funds for importing fertilizers and domestic marketing (Tewodros Tefera *et al*., 2020).

The high cost of commercial fertilizer causes food insecurity by distracting the sustainability of agriculture in Ethiopia (Abebayehu Aticho *et al.,* 2011). There has been a difference in fertilizer consumption among the farm wealth categories, due to farmers' limitation of knowledge about fertilizer and lack of sufficient land (Yewubdar Melese, 2017). Improper agricultural management practices of low addition of fertilizers, improper soil and water conservation designs, steep slope land cultivation, deforestation, crop residues removal, use of animal manure for energy sources have a direct impact on the depletion of soil fertility and soil organic matter (Asefa Abegaz *et al*., 2005; Chilot Yirga, 2007). Unbalanced nutrient balances in agricultural soils can lead to land degradation and, eventually land abandonment (van Beek *et al*., 2018).

2.4.2. Biophysical factors

Biophysical properties such as climate, rainfall, slope length, and inherent properties of soil affect nutrient depletion of a specific area. Unfavorable climate, poorly managed environment, and inherently poor soils have a significant impact on soil fertility diminution. Water holding capacity and soil textural class have a direct relationship with susceptibility to soil erosion. Rainfall amount, duration, and intensity influence the fertility of the soil by erosion (Renard *et al*., 1997). In high rainfall areas, there is a soil acidity problem whereas, in low rainfall areas existence of salinity problem is limiting agricultural productivity. Soil that occurs under forest areas has good physical, biological, and chemical qualities. On the contrary, soil that occurs in less vegetation cover areas is less fertile and is characterized as poor (Salazar *et al*., 2009; Najera *et al*., 2015). Conservation tillage has a remarkable influence on reducing soil and water losses and maintaining soil productivity (Adelaide, 2012).

In some parts of Ethiopia, attention for soil fertility control is higher than erosion control because of soil fertility's immediate yield effects as compared to water erosion control (Zenebe Adimassu *et al*., 2013). Areas that receive a high amount of rainfall affect the biophysical environment of agricultural production in West African countries. The soils' natural fertility and water-retaining capacity are often low, and they are highly susceptible to wind and water erosion. The climate is highly variable and globally influenced by wind circulation patterns that determine drought, humidity, and aridity. Nutrient balances and consequently nutrient requirements are affected by biophysical (soil and climate) and management factors. In Ethiopian highlands, low agricultural productivity due to soil degradation is a serious challenge (Amare Haileslassie *et al*., 2006).

2.5. Nutrient Balance in Ethiopia

Quantification of smallholder farms soil nutrient balance at watershed level valuable to provide essential information on trends in nutrient depletion or accumulation. In Africa, nutrient balances are widely used as indicators of soil nutrient mining. However, it can be used to compare different systems and identify elements of the farming system where nutrient management can be improved or depleted (Phong *et al*., 2011). Moreover, it can be used to prepare nutrient management strategies. Nutrient input-output balances are regularly used as indicators for the sustainability of agricultural and land-use systems. Especially, full nutrient balances have been used as an indicator of sustainability concerning soil fertility (Amare Haileslassie *et al*., 2005). Partial nutrient balance also serves as an indicator of management practices and the sustainability of the farm, and the systems (Jiri1 and. Mafongoya, 2018; Theodora, 2018).

Estimating the balance between inputs and outputs of soil nutrients is used to avoid the negative impact on the environment. Minimizing excessive agricultural phosphorus can reduce the negative impact of phosphorus on the environment (Sharpley, 1995). Similarly, nutrient balance indicates nutrient use efficiency of farming systems (Stoorvogel, 2007; Fixen, 2009; Cobo *et al*., 2010). Additionally, phosphorus partial nutrient balances are important to identify areas of inefficiency, reduce the risk of nutrient loss from cropping systems, and ensure the availability and quality of future phosphorus resources (Syder and Bruulsema, 2007).

Soil nutrient balance serves as a warning sign for the sustainability of agricultural systems as far as soil fertility management concern (Eyasu Elias *et al*., 1998; Lesschen *et al*., 2007). In Africa, nitrogen and phosphorus nutrient balances are negative throughout the smallholder farming systems (Bekunda *et al.*, 2002; Ncube *et al*., 2009). Severe deficits of N, P, and K are found widely in harvested areas in both developing and least developed countries, particularly in the rice and wheat production systems in Asia, Central and South America, and Africa. When we think about nutrient balance as a land-quality indicator for the suitability of nutrients, no index can also be advocated as the most obvious. Most of the possible indices, the ratio of nutrient balance to nutrient shares can be considered as the tremendous one, on the other hand, it is not smooth to determine. However, easy to decide the ratio (IN 1+IN2)/ (general inputs) and the increased difficulty (OUT 1+OUT2)/ (overall outputs) had been labored out to a degree on this financial disaster but do no longer appear too promising (Stoorvogel, 2007).

Nutrient-budget and nutrient-balance techniques currently have been utilized widely. Research has been conducted by different scholars in many parts of Ethiopia to estimate, at plot, farm, watershed, and national level. The result revealed that mining primary macronutrients through harvested crop components, residue removal, leaching, gaseous loss, and soil erosion is shocking (Assefa Abegaze *et al*., 2003, 2005; Mekuanint Lewoyehu *et al*., 2020). The great occurrence of nutrient mining and soil fertility decline has been cautioned (FAO, 2003). The nutrient balance of Ethiopia varied from the -47 kg N, -7 kg P, and -32 kg K ha^{-1} yr^{-1} (Stoorvogel *et al*., 1993) to -122 kg N, -13 kg P, and -82 kg K ha^{-1} yr^{-1} (Amare Haileslassie *et al*., 2005 and 2006). Although, the field scale study for mixed farming in southern Ethiopia showed that N and P were in equilibrium or positive (Eyasu Elias *et al*., 1998). Full nutrient balance analyses in the central highlands of Ethiopia indicate there is an accumulation of P in enset-based farming systems. In contrast, in tef-based systems, P was slightly depleted (Amare Haile Selassie *et al*., 2005).

Based on Nandwa (2003), Ethiopia lost more than 60 kg N, P, and K ha^{-1} yr^{-1}. On the other hand, according to Stoorvogel *et al*. (1993), the nutrient balances of Ethiopia were estimated to be -41, -6, and -26 kg ha^{-1} yr^{-1} NPK respectively. Amare Haileslassie *et al.* (2005) reported that the partial nutrient balance is showing positive for the Tigray Region of Northern Ethiopia (+10, +6, +10) kg ha^{-1} yr^{-1} N, P, and K respectively. But negative for Amhara (-1, +6 and -2) while positive at country level (+10, +11, +7) kg ha^{-1} yr^{-1} N, P, and K respectively. Similarly, in the central highlands of Ethiopia the partial nutrient balance value for tef based farming system was -28 kg N ha^{-1} yr^{-1}, -87 kg K $ha^{-1}yr^{-1}$ for barley; -21 kg N ha^{-1} yr^{-1}, -23 kg K ha^{-1} yr^{-1} for wheat; -9 kg N ha^{-1} yr^{-1}, -11 kg K $ha^{-1}yr^{-1}$ for tef; -71 kg N ha^{-1} yr^{-1}, -81 kg K $ha^{-1}yr^{-1}$ (Gebremedhin Kiros *et al*., 2014). On the contrary, the field level analysis of nutrient flow shows that soil fertility is maintained and increasing in nutrient content at enset-garden, darkoa, and taro fields in Kindo Koisha farms in the southern part of Ethiopia (Eyasu Elias *et al*., 1998). On the other hand, the over-application of fertilizers resulted in a positive P balance (Paramasivam *et al.,* 2017).

Limited applications of fertilizers, crop residues removal, manures, and socio-economic problems are causes of nutrient depletion in Ethiopia (Assefa Abegaz, 2005; Assefa Abegaz *et al*., 2007). The study of partial or full nutrient balance at any level has large variations between farms, plots, and across land-use and a little variation between districts (Van den Bosch *et al*., 1998; Onwonga and Freyer, 2006). Ethiopian poor farmers' interest is getting high net profit on their input with little risk while rich farmers may endeavor to maximize profit per hectare (Negash Demissie and Israel Bekele, 2017). A deep sensible appreciation of the depletion of plant nutrients from soils helps to apprehend the use of soil degradation and may additionally be beneficial in devising nutrient management strategies.

2.6. Nutrient Inflow

Inflows of nutrients are necessary for farming systems as they are critical in maintaining and raising crop and forage productivity (Balesh Tulema, 2005). However, a buildup of surplus nutrients over the immediate crop and forage needs can lead to nutrient losses. A nutrient loss is not only a possible cause of economic inefficiency in nutrient use by farmers (Smaling *et al*., 1996). But also a source of potential harm to the environment, through water pollution or air pollution by greenhouse gas emissions (Ncube *et al*., 2009).

2.6.1. Organic inflows

Organic inputs like - farmyard manure, compost, green manures, and animal dungs are important inflows that contain essential plant nutrients and improve soil fertility (Workneh Bedada, 2015). Among them, compost is a microbial (biological oxidation) process through which fresh organic matter is transformed into a stable organic fertilizer product (de Bertoldi *et al*., 1983). Compost is used as a source of plant nutrients, improves crop productivity, and improves soil physic-chemical properties (Vanlauwe *et al*., 2011). Similarly, through manure addition replenishing soil fertility is a conventional habit of most Ethiopian farmers' (Eyasu Elias *et al*., 1998).

Manure is one of the key inputs to improve soil fertility for many farmers of Ethiopia. It is used as fertilizer to enhance soil fertility in many parts of Africa including Ethiopia. Many studies conducted in Ethiopia showed that manures had a residual effect on soil (Belay Tegene, 1998; Eyasu Elias, 2002). Its effect depends on the quantity and quality applied. However, accessibility to it depends on the number of livestock and the availability of labor to transport it to the fields (Eyasu Elias, 2002). But, today there is high computation to use as a source of household energy source (Aseffa Abegaze, 2005).

2.6.2. Mineral fertilizer

The application of synthetic fertilizers enhances crop yields, soil pH, organic C, total N, and available N (Zhong *et al*., 2010). In Ethiopia using synthetic fertilizers had started in the early 1970s (Murph*y,* 1968*).* For the last three decades, Ethiopian agriculture has been mainly dependent on urea and di-ammonium phosphate (DAP) fertilizer sources. Hence, Ethiopia has imported millions of metric tone N and P sources of fertilizers to increase agricultural production (G/Michael Yohannes, 1999; Eyasu Elias, 2002). However, the real practice shows that farmers are not applying the optimum required amounts of mineral fertilizer. According to FAO (2020) report, only 33% of Ethiopian farmers use chemical fertilizers. Most of the mineral fertilizer is used in irrigated fields (Aseffa Abegaze, 2005). The cost of chemical fertilizers is one of the challenges to farmers to purchase (Eyasu Elias, 2002; World Bank, 2007; Tewodros Tefera *et al*., 2020).

2.6.3. Atmospheric deposition

Atmospheric deposition is the accumulation of materials, nutrients, gas, smoke, ashes, oxides, acids and particles on land from the air. Primary macronutrients accumulated in the soil from rainfall. Atmospheric deposition is the process, long recognized by scientists, whereby precipitation (rain, snow, and fog), particles, aerosols, and gases move from the atmosphere to the earth's surface (Martinez *et al*., 2017). It is a major important source of nutrients for ecosystems that are deposited on plants and soil from the atmosphere (Pan and Wang, 2015). The input nutrients of atmospheric deposition are nitrogen, phosphorous, potassium, calcium, magnesium, sulfur, zinc, lead, copper, molybdenum, sodium (Huang *et al*., 2009; Tipping *et al*., 2014).

2.6.4. Biological nitrogen fixations

Nitrogen is an essential plant nutrient that limits plant growth and production and it accounts for about 2 % of the total plant dry matter that enters the food chain (Wagner, 2011). Biological nitrogen fixation (BNF) is the process whereby atmospheric nitrogen is reduced to ammonia in the presence of nitrogenize. Nitrogenase is a biological catalyst found naturally only in certain microorganisms such as the symbiotic Rhizobium and Frankia, or the free-living Azospirillum and Azotobacter and blue-green algae (Santi *et al*., 2013).

Biological nitrogen fixation (BNF) is the process in which nitrogen gas (N_2) from the atmosphere is incorporated into the tissue of certain plants. This fixation is a specialized prokaryotes organism; they utilize the enzyme nitrogenase to catalyze the conversion of atmospheric nitrogen (N_2) to ammonia (NH_3). Plants can readily assimilate NH_3 to produce the aforementioned nitrogenous biomolecules (Carvalho *et al*., 2019). The biological nitrogen fixation process is carried out by two main types of microorganisms: those are live together with plants in close symbiotic association and free-living" or non-symbiotic. The nitrogen fixation provides Earth's ecosystems with about 200 million tone N per year (Hoffman *et al*., 2014).

2.7. Nutrient Outflow

Essential plant nutrients are lost in different ways (Storvoogel and Smaling, 1993; Bindraban et al., 2000). The outflows occur in the form of harvested crop product, removal of straw yield, leaching, gaseous loss, and soil erosion (Stoorvogel and Smaling). The amount varies depending on crop type, soil type, agronomic practices, and plant nutrient uptake (Brady and Weil, 2002). Nitrogen outflows through five paths such as grain and straw yield, volatilization, denitrification, leaching, and soil erosion. While phosphorous is lost by grain yield, straw removal, and soil erosion. Potassium is also exported from the soil via crop yield, straw removal, leaching, and soil erosion (Storvoogel and Smaling, 1993). When the outflows are greater than the inflows it will result in a negative nutrient balance (Drechsel *et al*., 2001). The outflow mainly occurred by soil erosion and is a serious problem all over the world because it negatively affects the economic sector (Mekuanint Lewoyehu *et al*., 2020). Application of homogeneous fertilizer for a long time alters soil fertility (Aklilu Amsalu, 2015). There was the removal of soil nutrients by continuous cropping, especially; in irrigated areas. Poverty is linked with population to land and soil nutrient depletion and P extraction is increased due to overpopulation and continuous cropping systems. According to Abebayehu Aticho *et al*. (2011) outflow of NPK is higher than inflow in the Jimma zone of Ethiopia.

2.7.1. Crop residues

Crop residues are the above-ground biomass of plants remaining in the field after grains, and tubers have been collected. It can be used for the production of solid biofuels, such as briquettes, pellets, and charcoal, and can also be burnt directly for heating and cooking food (Shanahan *et al*., 2004). Crop residues play a significant role in sustaining and improving the chemical, physical, biological properties, and soil processes of the soil (Eyasu Elias, 2002; Carvalho *et al*., 2016). When incorporated into the soil it can directly recycle nutrients. Similarly, it is used for soil protection and soil fertility improvement (Smith and Elliott, 1990). Normally in Ethiopia, crop residues are removed for animal feed (Hailu Araya and Edwards, 2006; Eyasu Elias, 2002). But according to a study by Eyasu Elias (2002), about 42 percent of farmers in Kindo Koisha southern, Ethiopia apply crop residues for improving their soil fertility. While others immediately plow fields to protect the roaming of animals due to the free-range grazing practices (Hailu Araya and Edwards, 2006). Agricultural potential for organic matter sources depends on residue production from annual and perennial crops and manure application (Smil, 1999; Wang *et al*., 2019). Residue removal is a cause of poor soil fertility and N depletion (Gebremedhin Kiros *et al*., 2014). Also, the loss of K through straw residue removal leads to deficiency of K. Since straws had a high K concentration (Lupwayi *et al*., 2005; Jiang *et al*., 2018).

2.7.2. Leaching

Leaching is the loss of soluble essential plant nutrients and colloids from the top layer of soil by percolating perception. In other words, leaching is an important balance between preventing salt accumulation and removing nutrients from the soil. In dry soils of semi-arid regions salts can accumulate in the top horizons of the soil (Lehmann *et al*., 2003). Leaching in this review is defined as the removal of nutrient substances from the soil by the action of aqueous solutions, such as rain, dew, mist, and fog (Tukey, 1970). Leaching in the soil is highly dependent on the characteristics of the soil, which makes modeling efforts difficult. Most leaching comes from the infiltration of water. Nitrogen and potassium nutrients are easily leached from the soil by rainfall precipitation, but phosphorous withstand this phenomenon (Iyer, 2002).

2.7.3. Gaseous loss

The gaseous losses of nitrogen (N) primarily occur through ammonia (NH3) volatilization and nitrification-denitrification processes (Erisman *et al*., 2007). Though, the gaseous loss of N is affected by agricultural systems, crops types, soils, climates, fertilization, and management practices (Cai *et al*., 2002). The loss of N via denitrification was ranging (0-239) kg N $ha^{-1}yr^{-1}$ mainly occurring in irrigated and nitrogen-fertilized soils (Barton *et al*. 1999). But N loss in forest soil through denitrification was 1.9 kg N $ha^{-1}yr^{-1}$ and in cultivated lands, it extended 13 kg N $ha^{-1}yr^{-1}$ (Barton *et al*. 1999). The soil N loss is facilitated by high temperature and water contents (Sanchez *et al*. 2001). In the same way, the amount of nitrogen lost by denitrification depends on how long the soils are saturated. When the temperature is between 13-16^0C losses are about 2% day^{-1}. As the soil warms the loss increases up to 5% day^{-1}. Similarly, soil tillage practice also affects N loss (Potter, 2006).

2.7.4. Soil erosion

Soil erosion is the removal of soil with mineral nutrients by wind, water, gravity, and ice. It is the upper layer's gradual slow process movement and transport of the soil. Soil erosion is a complex process that depends on soil properties, ground slope, vegetation cover, rainfall amounts, and intensity (Wuepper *et al*., 2020). Also, it is at an alarming rate causing a serious loss of topsoil. The loss of soil from farmland may be reflected in reduced crop production potential, lower surface water quality, and damaged drainage networks (Apollo *et al*., 2018). Soil loss causes food insecurity and livelihood income as well as, retarded in Ethiopia (Bekele Tsegaye, 2019).

Rapid population growth, cultivation on steep slopes, clearing of vegetation, and overgrazing are the main factors that accelerate soil erosion in Ethiopia. Soil erosion and nutrient depletion in Ethiopia became a serious threat to agricultural productivity (Fassil Kebede and Charles, Y., 2009). Smallholder farmers can’t afford mineral fertilizers to replace the lost nutrient from their farmlands (Eyasu Elias, 2002). Management options should be taken to ensure the long-term sustainability of agricultural systems and to avoid irreversible losses (Fassil Kebede and Charles, 2009). Soil erosion is one of the major causes of soil degradation along with soil compaction, low organic matter, destruct soil structure, poor internal drainage, salinization, and soil acidity problems (Awdenegest Mogesand Holden, 2007).

The annual rate of soil loss in the country is higher than the annual rate of soil formation. Annually, Ethiopia losses over 1.5 billion tones of topsoil from the highlands by erosion which could have added about 1.5 million tones of grain to the country's harvest every year (Lulseged Tamene and Vlek, 2008). This indicates that soil erosion is a very serious threat to food security and requires urgent management intervention. In Ethiopia, the amount of soil lost with plant nutrients due to erosion is very high (Gebreyesus Brhane and Vlek, 2013). Soil erosion is among the most serious mechanisms of land degradation and contributes to soil fertility decline (Oldeman, 1994).

2.8. Total Nutrient Stocks in the Soil

Total nutrient stock is the accumulation of essential plant nutrients in the soil that can be available to plants from 5 to 10 years (Sanchez and Palm, 1996). Soil nutrient stock is the summation of total input from crop residue, applied fertilizer, biological nitrogen fixation, and atmospheric deposition. Nutrients can be stored (accumulated) in the soil when the quantity of inputs is greater than the quantity of the outputs (Smaling *et al.*, 1996). The nutrients are stored in the forms of dynamic and inert. Dynamic soil nutrient reserve is a fraction of soil organic matter with readily available nutrients stored in a relatively active form. While inert soil nutrient reserve is a fraction of organic matter which does not easily release its nutrient (Defoer *et al*., 2000).

The stock of soil nutrients is varied among different land-use types and farmlands. Soil nutrient stock to balance ratio is used to assess the sustainability of agricultural lands (Defoer *et al*., 2000; Umeh and Onyeonagu, 2014; Bahr *et al*., 2015). Sustainable on-farm agricultural production can be achieved only through, enough nutrient biomass or residue retention (Nandwa and Bekunda, 1998). The stock of soil nutrients is an indicator of soil quality as there is a change in land cover and land clearance processes. Besides, soil nutrient balance plays a significant role in monitoring and controlling soil fertility decline and nutrient use optimization as well as, natural resource management assessment (Hartemink, 2006).

CHAPTER 3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1. Location

The study was conducted in the Agew Mariam watershed, Wagehimera Administrative zone, Amhara National Regional State, Ethiopia in the 2020/21 main crop season. It is located from 38^0 53'14''to 38^0 56'15'' longitude and 12^0 31'40'' to 12^0 32' 33'' latitude with an altitude of 2104 to 2361 meters above sea level. It is located at a distance of 720 km north of Addis Ababa and 20 km south of Sekota town in Sayda kebele of Sekota district (Fig.3.1). Waghimera zone is one of the 14 administrative zones in Amhara National Regional State.

The watershed was delineated in 2016 by Sekota Dryland Agricultural Research Center as a model watershed for agricultural technology generation, adaptation, and dissemination. It has an area of 147 hectares. The watershed was treated with soil and water management intervention measures in 2019. It is a gauged watershed with a weir and has a metrological station.

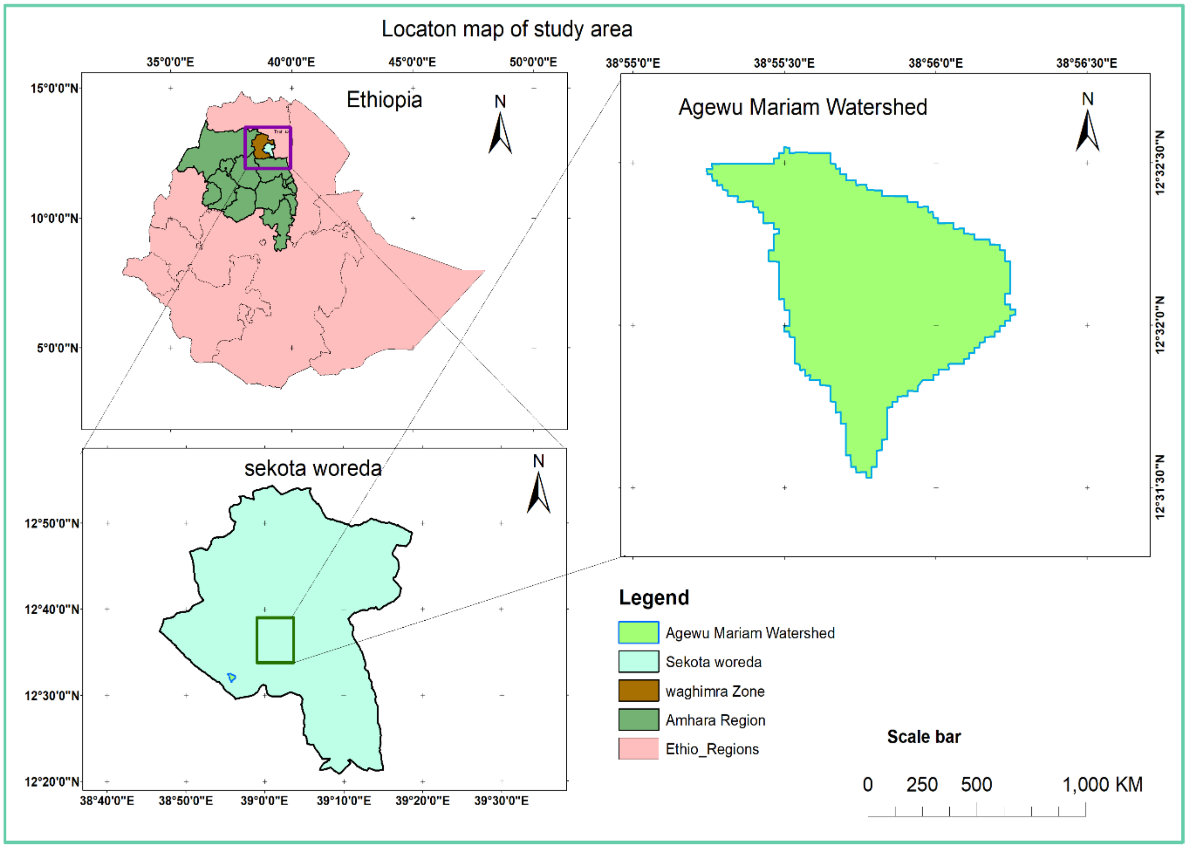

Figure 3. 1. Location map of the study area, Agew Mariam watershed

3.1.2. Topography and climate

The study area has undulating and mountainous topographic features. Most of the areas are steep slopes. About 69% of the watershed has a slope range that varies from 15 - 50%, 8% of the area has a slope range of 0 – 8 %, 20 % of the area has a slope range of 8 – 15 %. While 3% of the watershed is characterized by a slope above 50% (Yonas Reda *et al*., 2018). The study area has a uni-modal pattern of rainfall that extends from the beginning of July to early September. The mean annual rainfall was 590 mm, while the mean annual minimum and maximum temperatures were 13 °C and 27 °C respectively from 2000-2020 years (Agew Mariam and Kombolcha metrological station) (Figure 3.2). The area belongs to dry semi-arid midland (Gebrehana Girmay *et al*., 2020).

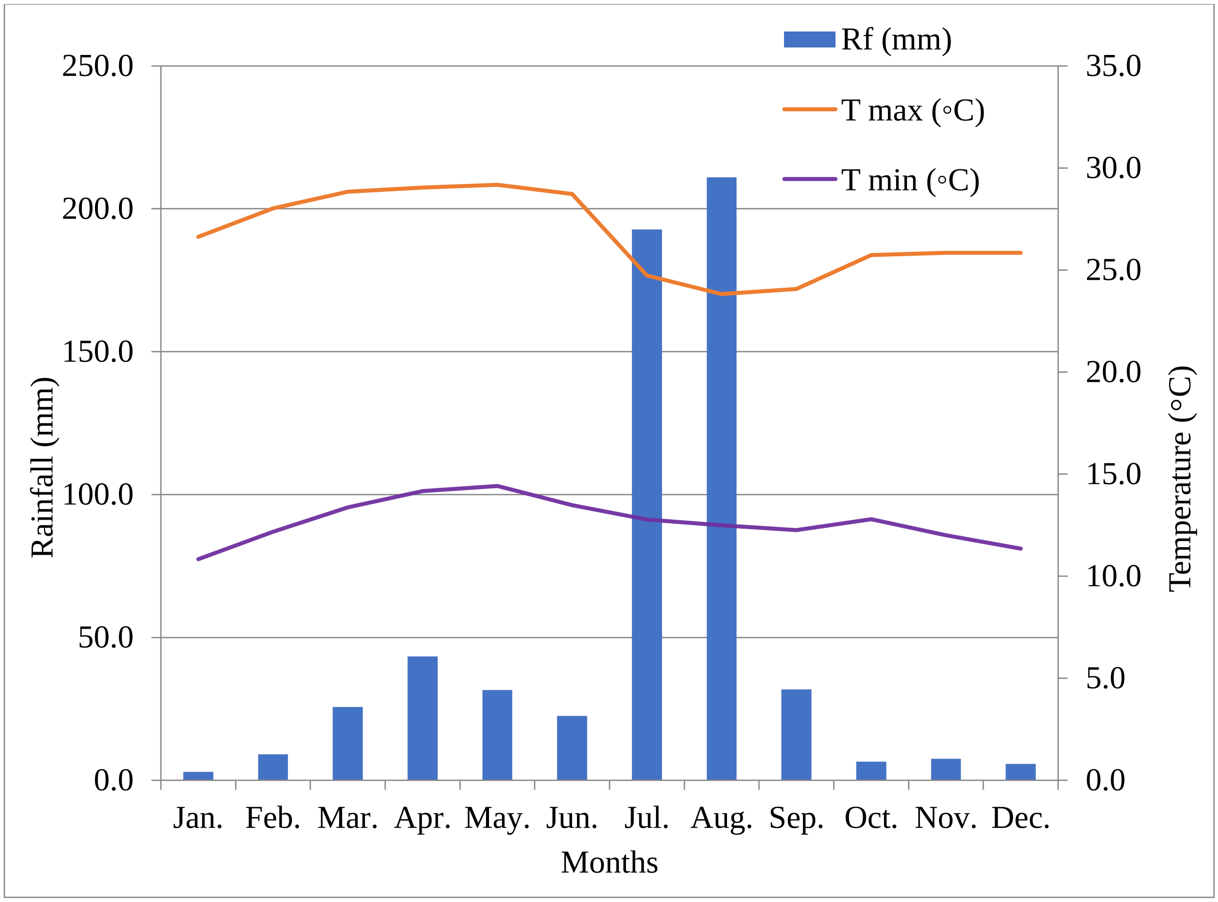

Figure 3. 2. Monthly minimum and maximum temperature and rainfall of the study area

3.1.3. Soil type

The soil types of Sekota district including the Agew Mariam watershed have Nitisols, Vertisols, eutric Regosols, and eutric Cambisols soil types. Soil nutrient depletion due to erosion challenges the land quality of agricultural production.

3.1. Population size

According to Yonas Reda *et al*. (2018).The number of households was 259 and the total population was 1113 in the study area (Table 3.1).

Table 3. 1. Total population and households in the study area

Villages	Household heads			Total population		
	Male	Female	Total	Male	Female	Total
Tachgishman	55	8	63	153	146	299
Likan	33	6	39	86	98	184
Walka	63	11	74	179	146	325
Keymeret	21	5	26	50	60	110
M/ chilkiw	43	14	57	79	116	195
Total	215	44	259	547	566	1113

Source: (Yonas Reda *et al*., 2018)

3.1.4. Land use and farming system

The four major land-use types in the Agew Mariam watershed are, cultivated land (71.4 %), bushland (19.7%), area closure (8.2%), and residence (0.7%) (Yonas Reda *et al.,* 2018). Most of the upper and lower parts of the watershed are cultivated land. While the middle hillside parts are covered with natural vegetation mainly dispersed bushes and shrubs. In the watershed, the farmlands are fragmented and smaller in size (around 0.75 ha per household) (BoA, 2018). The farming system is characterized by subsistence mixed crop production and livestock husbandry. The major grown crops are Bread wheat (*Triticum aestivum L.)*, sorghum (*Sorghum bicolor L.)*, teff *(Eragrostis tef (Zucc.*) Trotter), barley (*Hordeum vulgar L*), and faba bean (*Vicia faba* L.). The area has a high potential for livestock production including cattle, apiculture, poultry, goat, sheep, and donkey.

3.2. Methods

3.2.1. Approach of the Study

The study had two parts, soil nutrient balance and stock quantification on smallholder farms of the major crop types. Nitrogen, phosphorous, and potassium balance estimation was done based on the Stoorvogel and Smaling (1990) model. The model has four inflows and five outputs. The inflow sources of N, P, and K were mineral fertilizer, organic fertilizer, atmospheric deposition, and biological nitrogen fixation. Similarly, the outflow paths were harvested crop yield, harvested crop residue removal, leaching, gaseous loss, and soil erosion. So that, soil nutrient balance was calculated by subtracting the summation of outflows from the summation of inflows.

3.2.2. Sampling Design and Sample Size

The study watershed was selected purposively for the integration and buildup of the database as the watershed is used as a model for technology generation, adoption, and dissemination for Sekota Dryland Agricultural Research Center. The watershed represents the Sekota district in; biophysical resources, farming practices, crop varieties, socio-economic status, and topographic features. The sampling crop farmlands was selected in purposive random sampling techniques, considering slope class levels (lower, middle, and upper), socio-economic status (poor, medium, rich) wealth categories, soil fertility level, and management activities. Totally 23 representative farms were selected. Among them 10 wheat, 3 barley, and 10 tef farm fields.

3.2.3. Data Collection

Essential data for this research were collected from different sources. Some of the inflows and outflows were measured directly in the field. the outflows through harvest crop product (OUT1) and crop residue removal (OUT2) were measured directly from the entire whole fields, but samples for laboratory analysis were taken using 1m X 1 m quadrant (Appendix 3.3 and Appendix 3.4). About one kg of composite soil sample was collected by auguring diagonally ten subsamples from the three major crop cultivated lands at a depth of 0.2 m for the analysis of N, P, and K contents, soil SOC, and soil separate particles. Additionally, undisturbed soil samples were collected from the selected crop type using a core sampler for the analysis of bulk density. Moreover, rainfall data is also recorded in each rainy event.

Important supportive data of universal soil loss equation model like soil structural shape, size, steepness, slope length, and soil sampling depth were collected and recorded directly in the field. Moreover, inflows of N and P through mineral fertilizers and organic were determined by interview, focus group discussions were conducted with purposively selected farmers to identify major cropping systems, crop rotation practice, type of input and outputs, type of major crops, amount of crop residues left on the farms, crop production potential and challenges of crop production (Appendix.1). Similarly, soil N, P, and K nutrient stocks estimation inputs data of nutrient contents, bulk density, and sampling depth were collected in the field survey. (Appendix 3.5. and Appendix 3.6) based on Bond's (2010) equation.

3.3. Materials Used

Materials that were used at fields for the collection of indispensable input data of this study were:

- Tape meter: to measure slope length and soil sampling depth,
- Clinometer: to measure slope gradient of the sampled sites,
- Polythene plastic: used for handling of the collected soil sample,
- Global Positioning System (GPS) Garmin: used for collecting coordinate points, and areas of sampling sites,
- Hanging balance: to measure aboveground biomass, total grain yield, and straw amount,
- Quadrant: used to take plant samples uniformly from a certain measurable field,
- Sack: used for holding straw and grain yield plant samples,
- Core sampler: to take an undisturbed soil sample from the field for the analysis of bulk density,
- Auger: it was used to take disturbed soil samples,
- Hoe/Spade: to dig farms for soil structure identification.

3.4. Quantification of Inflows

The quantification of inputs is summarized in Table 3.2, and the details of each input are presented below.

3.4.1. Mineral fertilizers

The amount and type of mineral fertilizers added for each crop type in the watershed were identified through interviews. The input of added N and P content converted from NPSZnB into corresponding total N and P in kg ha^{-1} by multiplying the amount of P_2O_5 by 0.44. But, the total quantity of applied commercial urea fertilizer was changed into elemental nitrogen amount. The total amount of fertilizer added to the farms was illustrated in appendix 2.

3.4.2. Organic fertilizers

The amount of nutrient inflows from organic fertilizers (compost, farmyard manure, and animals' manure) that were added to the farmlands planned was estimated through field surveying, interview, and group discussion. The representative samples were taken before incorporating the organic inputs into the farm fields, for the analysis of N, P, and K content by their appropriate standard laboratory procedures. However, farmers didn`t add any organic input sources to farmland far away from their homes. They usually use the organic inputs to their backyard plot crops.

3.4.3. Atmospheric deposition

The input of N, P, and K from atmospheric deposition was quantified by collecting all rainfall data for each rainfall event from the rain gauge station and the rainfall amount of the season was 830 mm. The nutrient content was estimated using the pedo-transfer function according to Stoorvogel and Smaling (1998) formula:

$$IN3\ N = 0.14P^{1/2}$$

$$IN3\ P = 0.023P^{1/2}$$

$$IN3\ K = 0.092P^{1/2}$$

Where P is the mean annual rainfall (mm yr^{-1}).

3.4.4. Biological nitrogen fixations

According to Sheldrick *et al*. (2003), report 50 – 70% of pulses N requirement fixed by symbiotic association. Also, non-symbiotic N-fixation accounts for 40% of the plant's N requirement (Boddey and Dobereiner, 1996). Cereal crops benefited nitrogen from the biological nitrogen fixation process through non-symbiotic associations by blue-green algae and free-living bacteria, most particularly Azotobacter, Beijerinckia, and Clostridium (Santi *et al*., 2013). Biological nitrogen fixation inputs can not be quantified by direct measurement. So, it was estimated by pedo-transfer functions using reassign equation developed by Stoorvogel and Smaling (1998).

$IN4 = 0.5 + 0.1P^{1/2}$

Where P is the annual rainfall (in mm).

Table 3. 2. Methods of nutrient input quantification

Input	Methods of quantification
1. Mineral fertilizer	Interview
2. Organic fertilizer	Interview, field survey
3. Atmospheric deposition	Field measurement and pedo-transfer function
4. Biological nitrogen fixation	Field measurement and pedo-transfer function

Source: (Stoorvogel and Smaling, 1990; FAO, 2003)

3.5. Quantification of Outflows

The output of primary macronutrients from the farmland of the upper, middle, and lower slope of the watershed was assessed by direct field measurement, USLE model, and using pedo-transfer functions. The output of NPK: via crop product (OUT1), crop residue (OUT2), and soil erosion (OUT5) estimated by direct field measurements, laboratory analysis, and using the USLE model. Although, the remaining outputs leaching and gaseous losses were estimated by pedo-transfer functions (FAO, 2003). The summary of the outputs methods is indicated in detail below (Table 3.5).

3.5.1. Harvested crop product

Nutrient outflows from each major crop farmlands through harvest crop yields was estimated by measuring the total grain yields, and samples for laboratory analysis were taken using 1m x 1m quadrant walking a certain distance diagonally within the farmlands. The grain yield of the sample crop types was adjusted by the standard moisture correction factor. Then the collected sample was analyzed for N, P, and K contents based on their appropriate standard laboratory procedures. The total amount was calculated based on FAO (2003) formula.

$$\text{Outflow } 1 = \Sigma \left(\frac{\text{Area X nutrient content x yield}}{\text{total area}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

N = Y*N = (kg N ha^{-1}) ……………………………………..............…………………(3.2)

P = Y*P = (kg P ha^{-1}) …... …………………………………......................................(3.3)

K = Y*K = (kg K ha^{-1}) …………………………………………………………………….(3.4)

Where, Y = yield (kg ha^{-1}), N = N content of crops (% harvested product); P = P content of crops (ppm harvested product), and K = K content of crops (ppm harvested product).

3.5.2. Harvested crop residues

The N, P, and K outflows from the cultivated land through harvest crop residue removal was calculated with the same procedure of harvest crop yield based on the FAO (2003) formula.

$$\text{Outflow2} = \Sigma \frac{(\text{Area X nutrient content x yield})}{\text{total area}} \; x \text{ \% removable factor} \ldots\ldots\ldots\ldots (3.5)$$

N = R * N = (kg N ha^{-1}) …………………………………………………….................(3.6)

P= R * P = (kg P ha^{-1}) ……………………………………………………………...............(3.7)

K= R * K = (kg K ha^{-1}) …... (3.8)

Where, R = amount of residues (kg ha^{-1}); N = N content of crops' residues (kg N kg^{-1} harvested product); P = P content of crops residues (kg P kg^{-1} harvested product); K = K content of crops residues (kg K kg^{-1} harvested product.

3.5.3. Leaching

The loss of nitrogen and potassium through, leaching from tef, barley, and bread wheat farms were quantified using the empirical quantitative relations (transfer functions) and assumptions based on secondary data from a variety of sources. While P is not leached since it is highly bounding with soil particles (Laird *et al*., 2010). Leaching (OUT3) of N and K were calculated using the formula of (Stoorvogel and Smaling, 1990).

OUT3N = 2.3+ (0.0021 + 0.0007 * F) * P+0.3 * IN1+IN2-0.1 * TNU …………………(3.9)

OUTK3 = (0.6+ (0.0011 + 0.002 * F) * P+0.5 * (IN1+IN2)-0.1* TKU)/1.2……………(3.10)

Based on (Sharma *et al*. (2012) TNU and TKU (kg ha^{-1}) = nutrient content % X yield (kg ha^{-1}) /100……………………………………………………………………………………..(3.11)

Where, p: annual rainfall, F: soil fertility class (1= low; 2 = moderate; 3 = high), IN1+IN2: mineral fertilizer and manure applied (kg ha^{-1} yr^{-1}) and TNU, TKU: total N and K uptake (kg ha^{-1} yr^{-1}), respectively.

3.5.4. Gaseous loss

Gaseous loss of nitrogen in the form of denitrification, nitrification, and ammonium volatilization that can result in the release of NH_3, NO, N_2O, and N_2 to the atmosphere from smallholder farms of tef, barley, and bread wheat calculated by using empirical quantitative transfer functions and assumptions based on secondary data from a variety of sources like leaching. Gaseous loss (OUT4) of nitrogen in denitrification and volatilization form from agricultural fields estimated based on the model developed by (Stoorvogel and Smaling, 1990).

OUT4 = (0.025+0.000855*P + (0.01725*(IN1+IN2) + 0.117)) + (0.113 * IN1+IN2)…..(3.12)

Where, p = annual rainfall; IN1 + IN2: mineral fertilizer and manure applied (kg ha^{-1} yr^{-1}) respectively.

3.5.5. Soil erosion

The output of N, P, and K from barley, tef, and wheat farms of the upper, middle, and lower slope of the watershed by runoff and sediment was measured from tef, barley, and bread wheat in the 2020 rainy season. The amount of nutrients outflowed by soil erosion in the form of runoff and sediment was estimated using the universal soil loss equation (USLE) model Wischmeier and Smith (1978) with:

A= R * K * LS * C * P…………………………………………………………………….(3.13)

Where *A* is the annual soil loss (T ha^{-1} yr^{-1}), *R* is the rainfall erosivity factor in megajoule millimeters per hectare per hour per year (MJ mm h^{-1} ha^{-1} yr^{-1}), *K* is the soil erodibility factor (Mg ha^{-1} MJ^{-1} mm^{-1}), *LS* is the slope length factor (dimensionless), *C* is the management factor (dimensionless), and *P* is the conservation practice factor (dimensionless). The *R* factor is calculated using the regression equation developed by Hurni (1985) with:

$$R = -8.12 + 0.562P \quad (3.14)$$

Where *R* is the erosivity factor and *P* is the annual rainfall (mm yr^{-1}).

The *K* factor is defined as the rate of soil loss per unit of R-factor on a unit plot was calculated from soil properties of texture, organic matter, structure, and permeability. Analysis of the physical and chemical properties of the soil samples was performed based on the standard laboratory procedures. Soil structure was identified under field conditions with the help of a soil structure assessment kit to determine soil structural class code, shape, and size which was adopted from the USLE nomograph (Hailu Kendie and Klik, 2015). The structural class code was determined based on the observed shape and size of soil structure as adopted from the USLE (Wischmeier and Smith, 1978). The permeability class codes were encoded from the textural triangle class observation (Renard *et al*., 1996).

Particle size distribution was analyzed using the hydrometer method (Loveland *et al*., 2000). The hydrometer method of silt and clay measurement relies on the effects of particle size on the deferential settling velocities within the water. Whereas organic carbon and organic matter contents were determined by the wet combustion method of Walkley and Black as outlined by (Van Ranst *et al*., 1999). Soil erodibilty factor calculated using (Foster *et al*., 1991; Pongsai *et al*., 2010) equation. Which is:

$$K = 2.77 * 10^{-7} (12 - OM) M^{1.14} + 4.28 * 10^{-3} (S - 2) + 3.29 * 10^{-3} (P - 3) \quad (3.15).$$

$$M = ((100 - C) (L + Armf)) \quad (3.16).$$

Based on USDA-Agricultural Research (2008):

$$Armf = [0.74 - (0.62psd/100)] * psd \quad (3.17).$$

Where *C* is % of clay (<0.002mm), *L* is % of silt (0.002- 0.05mm), *Armf* is % of very fine sand (0.05-0.1mm), *OM* is the organic matter content (%), *p* is a code indicating the class of permeability, and S is a code for structure size, and psd is the percent of sand.

Slope steepness (S) and slope length (L) of each sample site were measured using a clinometer and tape meter respectively and their values are presented in (appendix 3). Slope length (L) was measured horizontally from origin of runoff point to deposition point and slope gradient was measured over 10 m distance in the direction of perceived maximum slope. Slope length is defined as the horizontal distance from the origin of overland flow to the point where deposition begins or where runoff flows into a defined channel (Renard *et al*., 1997).

Based on Kennedy's (2012) equation:

$LS = [0.065 + 0.0456 \text{ (slope)} + 0.006541 \text{ (slope)}^2] \text{ (slope length} \div \text{constant)}^{NN}$ ……..(3.18).

Where: slope = slope steepness in %.

Slope length = length of slope in m (ft).

Constant = 22.1 metric (72.5 Imperial).

Where, the value of NN is depending on slope as illustrated in Table 3, for Slope < 1 0.2, for 1≤ slope < 3 is 0.3, for 3≤ slope< 5 is 0.4 and for slope ≥ 5 is 0.5.

Table 3. 3. NN value depend on the slope table below

S	< 1	1≤ slope < 3	3≤ slope< 5	≥ 5
NN	0.2	0.3	0.4	0.5

Cover and management factor (C): The C-factor is defined as the ratio of soil loss from farmlands with specific vegetation to the corresponding soil loss from continuous follow; on the other hand, C- factor is the combined effect of all the interrelated cover, crops, and crop management variables on soil erosion rate. It is the most important factor required for land-use policy decisions as it represents conditions that can be most easily managed to reduce erosion (Wischmeier and Smith, 1978). According to Hurni (1988), cereal cultivated land has a 0.17 C – factor value.

The conservation practices factor (p-values): It is the effects of practices that will reduce the amount and rate of soil erosion. It depends on the type of conservation measures implemented and requires mapping of conserved areas for it to be quantified (Renard *et al*., 1997). Additionally, the support practice factor (P) represents erosion prevention practices such as contouring, strip-cropping, and terracing to reduce the amount of erosion by the runoff. P-factor is the ratio of soil loss by a particular support practice to that of straight-row farming up and down the slope. The agricultural lands are classified into six slope categories and assigned P-values. Land use or farming system affect soil erosion (Pham *et al*., 2018). The P-value ranges from 0 to 1 depending on the soil management activities employed in the specific plot of land (Wischmeir and Smith, 1978; Bewket and Teferi, 2009). Based on Wischmeier and Smith's (1978); Shi *et al*. (1999) principle as shown below in Table 3.4, the P-values of agricultural farmlands were.

Table 3. 4. P-value of agricultural farmland based on land use type and slope

Slope class	P-value
0- 5	0.11
5 - 10	0.12
10 - 20	0.14
20 - 30	0.22
30 - 50	0.31
50 -100	0.43

Nutrients that were lost by soil erosion were analyzed by collecting composite soil samples from barley, tef, and wheat farmlands at depth of 0.2 m. The amounts of N, P, and K were analyzed in the laboratory-based on their standard procedure. Finally, the amount of N, P, and K lost through soil erosion were estimated by using the Berhane Lemma *et al*. (2017) equation.

Nutrients loss (kg) = soil loss (kg ha^{-1} yr^{-1}) X % of the nutrient content of the soil X field size (ha)……………………………………………………………………………………..(3.19).

Loss of N (kg ha^{-1} yr^{-1}) = total soil loss (kg ha^{-1} yr^{-1}) X N content of soil (kg kg^{-1}) X field size (ha)……………………………………………………………………………………..(3.20)

Loss of P (kg ha^{-1} yr^{-1}) = total soil loss (kg ha^{-1} yr^{-1}) X P content of soil (kg kg^{-1}) X field size (ha)………………………………………………..…………………………………(3.21)

Loss of K (kg ha^{-1} yr^{-1}) = total soil loss (kg ha^{-1} yr^{-1}) X K content of soil (kg kg^{-1}) X field size (ha)……………………………………………………………………………………...(3.22)

Table 3. 5. Methods of nutrient output quantification

Output	Methods of quantification
1. Harvested crop product	Field measurement, laboratory analysis
2. Harvested crop residue	Field measurement, laboratory analysis
3. Leaching	Pedo-transfer function, laboratory analysis for nutrient uptake
4. Gaseous losses	Pedo-transfer function, rainfall data record
5. Erosion	USLE model, laboratory analysis, and field survey

Source: (Stoorvogel and Smaling, 1990; FAO, 2003)

3.6. Partial soil nutrient balance

Partial soil nutrient balances of smallholder farms of barley, tef, and wheat were quantified by estimating nutrients entering into the farm through organic and inorganic fertilizers and subtracting nutrients lost by harvested crop grain yields and crop residue removal *(*Zingore *et al., 2007).*

Partial balance of N (kg ha^{-1} yr^{-1}) = (N content of (mineral fertilizer + organic fertilizer) – (crop
grain yield + crop residue removal))…………………………………………..……….(3.23)

Partial balance of P (kg ha^{-1} yr^{-1}) = (P content of (mineral fertilizer + organic fertilizer) – (crop
grain yield + crop residue removal))…………………………………………………(3.24)

Partial balance of K (kg ha^{-1} yr^{-1}) = (K content of (mineral fertilizer + organic fertilizer) – (crop grain yield + crop residue removal))…………………………………………….(3.25)

3.7. Estimating Soil Nutrient Stock

Soil nutrient stock of smallholder farms of Agew Mariam watershed estimated through taking representative soil samples from barley, tef, and wheat parcels. Composite soil sample one kg crop^{-1} collected from ten subsamples randomly 0.2 m depth through auguring for analysis of N, P, and K content, SOC, and soil separate particles. Moreover, undisturbed representative soil samples were collected by core sampler within a depth of 0.2 m for the determination of bulk density. Finally, the nutrient stock of barley, tef, and wheat smallholder farms of the watershed was analyzed based on the Bond (2010) equation.

The stock of N, P, and K (kg ha^{-1}) = bulk density (kg m^{-3}) X soil sampling depth (m) X respective concentration (kg kg^{-1}) X area (10^4 m^2) of N, P, and K……………………(3.26).

where:

The stock of N = bulk density X sampling depth X concentration of N X area.

The stock of P = bulk density X sampling depth X concentration of P X area.

The stock of K = bulk density X sampling depth X concentration of K X area.

3.8. Data Analysis

3.8.1. Soil sample analysis

The collected composite soil samples were analyzed at Sekota Dryland Agricultural Research Center and Amhara Design and supervision works Enterprise soil laboratory (ADSWE). The soil was air-dried and sieved through a 2 mm sieve for NPK and textural class analysis, but for SOC analysis it was sieved at 0.5 mm. Soil organic carbon was determined following the wet digestion method as described in Walkley and Black (1934). Total nitrogen was determined by the Kjeldahl method (Sahlemedhin and Taye, 2000). Available potassium determined by Morgan's solution and K in the extract was measured by a flame photometer (van Reeuwijk, 1992). Available phosphorus was determined following the Olsen method (Dean and Olsen, 1965). Soil bulk density is the weight of a dry soil per unit of soil volume and its values were calculated based on the core method. Drying undisturbed soil samples by oven dry at 105^0 C for 24 hours, then divided the dry soil by its volume (FAO, 2020). Soil texture was analyzed through the hydrometer method (Bouyoucos, 1962; Beverwijk, 1967).

3.8.2. Plant sample analysis

The plants harvested manually on their maturity dates were preferred by the farmers. The samples were collected by throwing the quadrant randomly by walking a certain distance diagonally within the field. Fresh crop biomasses were weighed using hanging balance to know the total biomass amount. Crop grain yield was from barley, tef, and wheat farms collected and the weight was measured. Representative straw samples were taken into oven-dry at 65^0 C for 72 hours to avoid moisture contents. After drying the actual straw yields were calculated in equivalence ratio. Grain yields are also adjusted by moisture content factor using a moisture tester. Then both straw and grain were taken for laboratory analysis (Olson, 1963). Plant tissue (grain and straw) was air-dried and grinded to pass through a 0.15 mm mesh (Robinson, 1994; Okalebo *et al*., 2002).

Most plant analysis techniques involve ashing or wet digestion of the tissues to destroy the organic components to acquire a solution of inorganic ions. These methods are used for the determination of nutrient elements infiltrates from each solution or digests are the same as for soil extracts. The concentrations of the total nitrogen in the plant were determined by micro-Kjeldahl digestion, distillation, and titration method (Walkley and Black, 1934; Bray and Kurtz, 1945). Organic nitrogen was oxidized into ammonium by acid hydrolysis with H_2SO_4 together with the reagent potassium sulfate to raise the temperature and to hasten the rate of decomposition, copper sulfate and selenium powder were used as catalyst (Bray and Kurtz, 1945). Phosphorous and potassium concentration in the plant were measured by spectrophotometer and flame photometry respectively and determined with the procedure described by (Thomas *et al.*, 1967).

3.8.3. Statistical data analysis

Soil nitrogen, phosphorous, and potassium full, and partial balance (kg ha^{-1} yr^{-1}) of barley, wheat, and tef farms were done by subtracting the summation of outflows from the summation of inflows based on (Stoorvogel and Smaling, 1990) model. Furthermore, the stock was also quantified by multiplying the corresponding crop field bulk density with its sampling depth and nutrient concentration of N, P, and K (Bond, 2010). Finally, Field surveyed, pedo-transfer derived, model stimulated, laboratory analyzed soil and plant samples data of each inflows, outflows, and stored were summarized using Microsoft Excel spreadsheets. Additionally, to compare nutrient balances and stocks among crop types and nutrients statistical analysis was done using SAS software version 9.0, and the mean separation was analyzed by using 5% least significance difference (LSD).

CHAPTER 4. RESULTS AND DISCUSSION

4.1. Inflow of Nutrients

Cereals barley, tef, and wheat were the major crops in the Agew Mariam watershed. The addition of nutrients into the farms from mineral and organic fertilizers sources was very low. Only a few farmers (30.4%) use inorganic fertilizers for the production of tef, barley, and wheat which was ratified by this research through interviews. The farmers applied only synthetic fertilizers in the form of NPSZnB and urea for the production of field crops. The average nutrient rate used for barley, tef, and bread wheat in kg ha^{-1} is indicated in Table 4.1. These amounts could not meet the crops' optimum requirement of nutrients for better production. The recommended amount of nitrogen and phosphorous for tef and wheat to the area were 92 and 10 kg ha^{-1} N and P respectively (Ewunetie Melak *et al*., 2021 in press). However, the crops in the study area had no responses to K on crop yields (Tilahun Esubalew and Workat Sebnie, 2018). But, this statement disagrees with the findings of Wassie Haile and Tekalign Mamo's (2013) in Chencha and Hagere Selam in Southern Ethiopia K had responses on wheat yield.

Most of the farmers in the study area could not afford the money to purchase and use mineral fertilizers in their farms. The reasons were high poverty levels, lack of reliable credit services, and the ever-increasing cost of mineral fertilizer affect farmers' fertilizer usage. According to Eyasu Elias (2002) and Tewodros Tefera *et al*. (2020), the above-mentioned problems similarly affect the farmers. Unreliable, and erratic rainfall is another factor since in dry areas these fertilizers had a negative impact on crop production (World Bank, 2007). The result of this study was similar to the findings of Gebremedhin Kiros *et al*. (2014) and Shimbahri Mesfin *et al.* (2020) who reported that poor farmers purchase lower amounts of chemical fertilizers compared with the rich.

Based on the results of the interview, and group discussion, farmers did not apply organic fertilizers (farmyard manure and compost) to their barley, tef, and wheat farms. Since the number of animals per household is very low in number for the production of excess farmyard manure. The smaller amount of farmyard manure produced per household is mostly used around the homesteads plots and as fuelwood. So that, there were no input flows of N, P, and

K from organic sources to the major cereal field crops. However, applying compost and animal manure had a significant effect on improving soil fertility level and crop productivity (Belay Tegene, 1998; Eyasu Elias, 2002; Workneh Bedada, 2015). The availability of organic sources' of fertilizers depends on livestock number and family labor size for transporting to the farmlands (Eyasu Elias, 2002). However, currently, in the study area as well as in the rest of the country, farmyard manure is used as a source of energy (Asefa Abegaze, 2005).

The inflow addition of N, P, and K from atmospheric deposition (IN3) was calculated by using rainfall data of the season (830 mm). Based on this barley, tef, and wheat farmlands received the same amount of N, P, and K (4.03, 0.66, and 2.65) kg ha^{-1} yr^{-1} respectively. Although the cereals barley, tef, and wheat are not leguminous crops, all of these crops benefited from the nitrogen fixation process. According to Santi *et al.* (2013), many cereal crops benefited from nitrogen from the non-symbiotic associations. This is performed by blue-green algae and free-living bacteria, most particularly Azotobacter, Beijerinckia, and Clostridium, or by N-fixing trees that are cleared out on the field (*Rhizobia* and *Actinomycetes* spp.) (Abebayehu Aticho *et al*., 2011). The value of nitrogen added to the farms of major crops through nitrogen fixation (IN4), was 3.38 kg ha^{-1} yr^{-1}. This value was similar to Melese Gezie's (2019) results of tef and wheat farms received 4 kg N ha^{-1} yr^{-1}.

The total inflows additions for the barley were 15.08, 0.66, and 2.65, for tef 12.47, 3.24, and 2.65, and also for wheat 10.52, 3.39, and 2.65 kg ha^{-1} N, P, and K respectively. As indicated in (Table 4.1) below. The major sources of inputs were mineral fertilizer, atmospheric deposition, and biological nitrogen fixation for N. However, the overall inflows were very low and alarming. This shows the inflow amounts of N and P were not equivalent to the recommended amount of 92 and 10 kg ha^{-1} N and P respectively. This was due to socio-economic factors (credit service, lack of potential, lack of animals, cost of fertilizer, manure transportation problems, and competitive use of animal dung for energy source) and physical factors and erratic rainfall, that made farmers reluctant to use mineral fertilizers (Eyasu Elias, 2002).

Proper nutrient management is very critical to increase crop production and sustain soil productivity (Negash Demissie and Esrael Bekele, 2017). Although, the Fertilizer application in Ethiopia is above the average in sub-Saharan Africa, but its nutrient use efficiency is much lower than in other countries (Gete Zelleke *et al*., 2010). In Ethiopia, smallholder farms get only 30–40% fertilizer (Spielman *et al*. 2011). As a result, cereal yields and fertilizer use are low in Ethiopia (Daniel Zerfu and Larson, 2010). Similarly, the value of nutrient input addition in the study area was low even as compared with other areas (Melese Geze, 2019; Amare Haileselassie *et al*., 2005, 2006; Van Beek *et al*., 2016). This may be related to the poor dissemination of mineral fertilizers to the study area (Table 4.1, and Appendix 2).

Table 4. 1. Nutrient inflows into the farmlands of the study watershed

Crop field	IN1		IN2			IN3			IN4	Total		
	N	P	N	P	K	N	P	K	N	TNIN, TKIN		TPIN,
Barley	7.7	0	0	0	0	4.03	0.66	2.65	3.38	15.1	0.7	2.7
Tef	5.1	2.6	0	0	0	4.03	0.66	2.65	3.38	12.5	3.3	2.7
Wheat	3.1	2.7	0	0	0	4.03	0.66	2.65	3.38	10.5	3.4	2.7

Where IN1 refers to inputs from mineral fertilizer, IN2 stands for inputs from organic fertilizer, IN3 represents input from atmospheric deposition, and IN4 refers to inputs from biological nitrogen fixation, while TNIN refers to total N inputs, TPIN represents total P inputs and TKIN represents total K inputs.

4.2. Outflow of Nutrients

The amount of nitrogen, phosphorous, and potassium lost via harvested crop yield from barley were 40.1, 3.8, and 3.1, from tef 6.2, 0.6, and 0.6, from wheat 22.5, 2.4, and 1.3 kg ha^{-1} yr^{-1} respectively (Table 4.2). The magnitude differs among crop types due to their production potential and nutrient uptake (Fresew Belete *et al*., 2018; Sarkar *et al*., 2020; Shawl Assefa *et al*., 2021). The outflows of N, P, and K by crop residue removal from barley were 33.6, 2.2, and 9.2, from tef 8.7, 1.2, and 2.6, and wheat 31.3, 2.9, and 4.1 kg ha^{-1} yr^{-1} respectively. The loss of K through straw residue removal is greater than grain yield since straws had a high K content (Lupwayi *et al*., 2005; Jiang *et al*., 2018; Shawl Assefa *et al*., 2021). Whereas, the straw of cereal crops had lower N and P contents than grain (Melese Gezie, 2019; Shawl Assefa *et al*., 2021). The outputs of N and K via leaching were 5.3 and 2.6 for barley, 4.7 and 2.6 for teff, and 1.5 and 2.6 for wheat kg ha^{-1} yr^{-1} respectively. Nitrogen lost by gaseous losses of volatilization and denitrification were 1.9, 1.5, and 1.3 kg ha^{-1} yr^{-1} for barley, tef, and wheat respectively. Soil erosion was one of the biggest challenging threats for the removal of essential plant nutrients (Amare H/Selassie *et al.*, 2005, 2006; Nigussie Haregeweyn *et al*., 2015; Berhane Lemma *et al*., 2017; Melese Gezie, 2019).

The amounts of nitrogen lost from the farmlands through erosion were 0.9, 0.3, and 1 kg ha^{-1} yr^{-1} for barley, tef, and wheat respectively. The loss of phosphorous from barley, tef, and wheat were 0.02, 0.01, and 0.03 kg ha^{-1} yr^{-1} respectively. Whereas the outputs of potassium were 0.6, 0.2, and 0.74 kg ha^{-1} yr^{-1} from barley, tef, and wheat farms respectively. There were magnitude differences among croplands as shown in Table 4.3 below. The differences were due to differences in slope steepness and length, soil erodibility factor, management practice, and nutrient contents of the soil (Renard *et al.*, 2010; Bera, 2017; Benavidez *et al.*, 2018). The findings of outflows of this study for N, P, and K by soil erosion were similar to the findings of Berhane Lemma *et al*. (2017), 2.36, 0.018, and 0.32 kg ha^{-1} N, available P, and exchangeable K respectively. However, the value of this study was lower than the one estimated by (Van Beek *et al*., 2016; Melese Gezie, 2019; Mekuanint Lewoyehu *et al.*, 2020. The difference might be due to variation in rainfall, soil characteristics, slope length and steepness, soil and conservation structures, farm management practice, and cover crop factors as stated by Lulseged Tamene and Vlek (2008); Habtamu Tadele (2016); and G/Hana Girmay *et al*. (2020).

The total outflows of N from barley, tef, and wheat fields were 81.8, 21.4, and 57.6 kg N ha-1 yr-1 respectively as illustrated in (Tables 4.2 and 4.3). The highest amount of N was lost in the barley farms followed by the wheat farms. However, the lowest loss was recorded from the tef farms. The reasons for this variation could be associated with the variance in grain and straw yield, the amount of mineral fertilizer added, slope length, slope steepness, and nutrient uptake (Stoorvogel and Smaling, 1990; Kroeze et al., 2003; Tankou et al., 2013). In barley smallholder farms most of the outflows occurred via harvested grain yield and residue removal (Table 4.3). The harvested crop products (OUT1) and straw residues (OUT2) removal are mainly the major pathways of NPK losses from agricultural soils (Gebremedhin Kiros *et al*., 2014). In general, the ascending order of outflows was soil erosion > gaseous loss > leaching > residue removal > grain yield. The reasons could be linked to grain and straws had better yield. Similarly, grain yields had better N uptake (Gebremedhin Kiros *et al*., 2014; Shawl Assefa *et al*., 2021). Thus the implementation of soil and water conservation measures played an important role in minimizing nutrient loss from the watershed by soil erosion. Besides this, the rainfall effect in N loss may be low, since its value was small (Panagos *et al*., 2017; Wuepper *et al*., 2020). Therefore, the amount of N lost in this study agreed with the findings of Shimbahri Mesfin *et al*. (2020) in Raya-Azebo from the poor farmers' field 48.7 kg N ha^{-1} yr^{-1} was lost. However, it disagreed with the findings of Gebremedhin Kiros *et al*. (2014) who reported in the May-Leba catchment of northern Ethiopia the loss of N was 101 kg ha^{-1} $yr^{-1}$and Melese Gezie (2019) who reported the loss of 93.1 and 80.1 kg N ha^{-1} yr^{-1} from tef and wheat farms in the upland area of Gumara river respectively.

The outflow of phosphorous from barley, tef, and wheat farmlands were 5.02, 1.81, and 5.33 kg P ha^{-1} yr^{-1} respectively. The reason for the lower loss of P by soil erosion compared with the harvested grain yield and residue removal might be the implementation of soil and water conservation measures and the low amount of rainfall (Belay Asnake, 2016). The removal of P from tef was the lowest one compared with barley and wheat, this might be related to its smaller above-ground biomass yield. Although, the overall P outflows were low. As a result, crop yield and P contents of the watershed soil were low. The current research finding is in line with the findings of Eyasu Elias (1998); Gebremedhin Kiros *et al*. (2014). But, it contrasts with Van Beek *et al*. (2016); Melese Gezie (2019); Mekuanint Lewoyehu *et al*. (2020).

The total outflows of K from barley, tef, and wheat farms were 15.5, 6, and 8.7 kg ha^{-1} yr^{-1} respectively. According to Lefroy and Wijnhoud (2001), K removal in our finding was low for tef and moderate for barley, and wheat. This could be due to the yield of the crops, and the low amount of rainfall, the constructed stone bund, and check dams also played a role in minimizing the loss of K. The highest outflows of K were recorded by crop residue removal next to leaching. This might be due to the straw had better K content and inherent property of K being easily leached (Anderson and Hoffman, 2006; Mendes *et al*., 2016). Moreover, the overall loss of K was low compared with other studies (Table. 4.3). This might be due to low nutrient uptake by the crops as the N and P were not supplied sufficiently that resulted in low crop yield, and less loss by erosion because of the presence of conservation structures (Stoorvogel *et al*., 1993; Hillette Hailu *et al*., 2015; Berhane Lemma *et al*., 2017). The current study showed lower losses of K than the other findings (Amare H/selassie *et al*., 2005, 2006; Melese Gezie, 2019; Mekuanint Lewoyehu *et al*., 2020).

Table 4. 2. Total nutrient outflows from major crops

Total outflows kg ha^{-1} yr^{-1}			
Crop type	N	P	K
Barley	81.8	6	15.5
Tef	21.4	1.8	6
Wheat	57.6	5.3	8.7

Table 4. 3. The amount of nutrient outflows from major farmlands (kg ha^{-1} yr^{-1})

	OUT1			OUT2			OUT3		OUT4	OUT5		
Crop	N	P	K	N	P	K	N	K	N	N	P	K
Barley	40.1±30	3.8±1.8	3.1±2.1	33.6±22	2.2±0.3	9.2±6.2	5.3±3.8	2.6±1.5	1.9±1.7	0.9±0.8	0.02±0.01	0.6±1
Tef	6.2±2.1	0.6±0.2	0.6±0.3	8.7±2.7	1.2±0.2	2.6±1.1	4.7±2.3	2.6±0.8	1.5±1.2	0.3±0.2	0.01±0.002	0.2±0.17
Wheat	22.5±7.7	2.4±0.7	1.3±0.5	31.3±11	2.9±0.9	4.1±1.8	1.5±0.1	2.6±1.1	1.3±0.7	1±1.4	0.03±0.01	0.74±0.9

The variabilities of standard deviation among the output and, stock of nutrients were high. In some of them, it exceeds 100% of the data as shown in the above Table 4.3. This was caused by the nature of the difference in socio-economic conditions, and farm management activities like nutrient inputs addition. The high grain and straw yield gap between farmlands was among the reasons (Van Beek *et al*., 2016).

4.3. Partial Soil Nutrient Balance

The partial nutrient balance is management-related (anthropogenic balances). It was assessed by taking the inputs of organic and mineral fertilizers, and the outputs via harvested crop yield and crop residue removal of the smallholder farms. The partial nutrient balance is the summation difference between fertilizers (organic, and inorganic) and above-ground biomass yields (grain, and straw). The partial N balance of barley, tef, and wheat were -66.1, -9.9, and -50.7 kg ha^{-1} yr^{-1} respectively (Table 4.4). Comparatively, tef's partial nutrient balance was better than barley and wheat, as a result of the outflows through grain yield, and straw was low. This may be due to low above-ground biomass yield. As a whole, the result revealed that N import into the croplands' was highly lower than export out of the soil system. Hence, as shown in (Table 4.6, and 4.7), the balance was negative. It implies that the sustainability of the farmlands was at risk (Jiri1 and Mafongoya, 2018; Theodora, 2018). Unless reversing the trend of the balance. It may be impossible to increase production, and crop cultivation at all.

Phosphorous partial balance of barley, tef and wheat were -5.9, 0.9, and -2.6 kg ha^{-1} yr^{-1} respectively, as presented in (Table 4.4), tef had positive values, even though like N the inputs were very low because of its low outflows by crop yield, and residue removals. Whereas, barley and wheat had negative balances. As a result, the outputs did not counterbalance by the inflows. P was the second most important essential plant nutrient, but farmers' could not add sufficient organic and inorganic P fertilizer sources. Consequently, the yield of crops was low (Appendix. 2) that could lead to low agricultural income and household food insecurity problem in the study area. This study finding is in line with Shimbahri Mesfin *et al*. (2020) 6.3 in Alaje and, 10.6 kg ha^{-1} in Raya-Azebo. Our study was in line with the finding of Melese Gezie (2019) who reported 11 and -1 kg ha^{-1} for tef, and wheat respectively. On the contrary, our finding differed from the findings of Amare H/Selassie *et al*. (2005) who reported 6 kg ha^{-1} yr^{-1} for Amhara National Regional State. Moreover, Amare Haileslassie's (2006) reported a barley-enset farming system with positive P while N and K revealed slightly negative balances. Generally, Phosphorus is an important agricultural input in the world, but it is limited by known phosphate reserves and geological time scales (Cordell *et al*., 2009). Hence it requires a proper management strategy.

Potassium nutrient fluxes (partial balance) of barley, tef, and wheat were -12.3, -3.2, and -5.4 kg ha^{-1} yr^{-1} respectively. The result revealed that exported K from the farms was more than the imported into the farms. This was due to the low yield of above-ground biomass. As a result, the loss of K by OUT1, and OUT2 might not cause severe K depletion in the major cereal crops farmlands. However, it needs the application of K fertilizer sources. Our finding is in agreement with Amare Haileselassie *et al*. (2005) who reported -2 kg K ha^{-1} yr^{-1} for Amhara National Regional State. But it contradicts with the national value of 7 as well as a cereal-pulse system of -87, -11, and -23 kg ha^{-1} yr^{-1} for barley, tef, and wheat respectively. Similarly, with the findings of Bogale Gelana (2014) K balance for the poor, medium, and rich were -53.98, -54.46, and -56.17 kg ha^{-1} yr^{-1} respectively.

Table 4. 4. Partial soil nutrient balance of major crop types

Cropland	IN1 + IN2			OUT1 + OUT2			Partial nutrient balance		
	N	P	K	N	P	K	N	P	K
Barley	7.7	0	0	73.7	5.9	12.3	-66	-5.9	-12.3
Tef	5.1	2.6	0	14.9	1.7	3.2	-9.8	0.9	-3.2
Wheat	3.1	2.7	0	53.8	5.3	5.4	-50.7	-2.6	-5.4

The partial balance of P and K had no statistically significant effect at ($P \leq 0.05$) on the major croplands as presented (Table 4.5). While N had a statistically significant effect among the farmlands (Table 4.5). Tef had a better N partial balance, this might be due to its low yield. Soil nutrient balance values variation within the croplands were due to the variation of farm management and related factors (Amare Haileselassie, 2005; Amare Haileselassie *et al*., 2006; Abebayhu Aticho *et al*., 2011).

Table 4. 5. Comparison of N, P, and K full and partial balance among farmlands

Nutrient	N	P	K
Crop	Partial balance	Partial balance	Partial balance
Barley	-66^{B}	-5.9	-12.3
Tef	-9.87^{A}	0.9	-3.2
Wheat	-50.68^{B}	-2.6	-5.4
LSD (0.05)	-23.5	NS	NS
CV	29.6	24.9	26.99

4.4. Implication of Nutrient Balances for Sustainable Agriculture

In this study, the partial balance of N, P, and K was negative for barley, tef, and wheat farmlands, except P balance for tef fields. The negative balances indicate that there have been declining trends of soil fertility and higher mining of nutrients. This is the major implication of land degradation. As a result, the agricultural production and household incomes were low in the study area. Finally, these problems may cause water pollution and other socio-economic problems. This has been a major concern for sustaining agricultural production. Therefore, the negative nutrient balance in this study implies that the overall sustainability of prediction in the watershed is under question. It needs further studies related to different land management scenarios. Integrated soil fertility management is essential to reverse this problem (Workineh Ejigu *et al*., 2021).

4.5. Nutrient Stock of the Study Farms

Total N, available P, and available K stock for the upper 0.2m depth of the watershed values were low as illustrated in Table 4.9. The stock of N for barley, tef, and wheat farms were 1295 ± 481.1, 1510 ± 600, and 1240 ± 181 kg ha^{-1}, respectively. Available P stock for barley, tef, and wheat farms were 63 ± 81, 18.7 ± 4.3, and 27.5 ± 11 kg ha^{-1} respectively. Whereas, the stock of available K on barley, tef, and wheat farms was 1092.7 ± 122, 1059.4 ± 169.4, and 1090.6 ± 168.5 kg ha^{-1} respectively. The result revealed that the stocks were varied among croplands. The differences were related to bulk densities and nutrient content variation (Abebayhu Aticho and Eyasu Elias, 2011). The stock of N, P, and K had no direct relationship with the current available amount. Because it will be available to the plants gradually in the coming 5-10 years (Sanchez and Palm, 1996). The objective of nutrient stock improvement was not to maximize their concentration on soil but to maintain the required optimum amount for sustaining agricultural production. In the tropics and sub-tropics food production usually relies on available soil nutrient stocks (Sheldrick *et al.*, 2002). The result indicated that inappropriate soil fertility as well as, land management activities were not effective in maintaining soil nutrient stocks (Belay Tegene, 1998; Eyasu Elias, 2002). Removal of crop residue for animal feed, low addition of compost, farmyard manure, and mineral fertilizers cause land degradation (Amare H/Selassie *et al.*, 2005; Workneh Bedada, 2015). Soil fertility management practices should be modified continuously in space and time since it is not static (Boesen and Hansen, 2001).

Soil nutrient stocks were affected by farming systems, and soil depth in spatial, and vertical distribution (Getaneh Gebeyehu and Teshome Soromessa, 2018). Application of combined organic and inorganic fertilizers for a long time improved soil nutrient contents of total N, P, K, Ca, and Mg in the upper 0.1 m depth (Workneh Bedada, 2015). The current study had lower stock compared to Amare Haileselassie's (2006) who reported 5510, 1200, and 30800 kg ha^{-1} of N, P, and K stock respectively in tef-based cereal-pulse systems, and compared to Getaneh Gebeyehu and Teshome Soromessa (2018) who reported N stock value of 2890 kg ha^{-1} for rain feed and 3180 kg ha^{-1} for irrigation 0 - 0.15 m depth. This might be related to poor soil fertility management practices of our study area (G/Hana Girmay *et al*., 2020). Low inputs additions, severe land degradation, and lack of crop residue retention reduce the stock (Gebeyanesh Zerssa *et al*., 2021).

The stocks of N, P, and K had no statistically significant difference ($P \leq 0.05$) among the farmlands (Table 10). However, the farmlands barley, tef, and wheat had a significant effect on nutrient stocks. The stock of N > K > P in all field sites. The results revealed that the amount of N, P, and K throughout the watershed were similar, but there was an amount difference between the N, P, and K amounts.

Table 4. 6. The nutrient stock within farmlands (0.2 m soil depth)

Stock (kg ha^{-1})				Stock (kg ha^{-1})			
Crop	N	P	K	Nutrient	wheat	tef	Barley
Tef	1510	18.79	1059.4	N	1240.8^{A}	1510^{A}	1295.3^{A}
wheat	1240.8	27.5	1090.6	P	27.5^{C}	18.79^{C}	63^{B}
Barley	1295.3	63	1092.7	K	1090.6^{B}	1059.4^{B}	1092.7^{A}
LSD (0.05)	NS	NS	NS	LSD 5%	128.45	239	205
CV	28.37	32.5	14.88	CV	24.76	29.74	35.29

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The habit of using locally available nutrient sources was underprivileged. Thus inflow addition for N, and P were below the recommended level. The total inflows of N were 15.08, 12.47, and 10.52 kg ha^{-1} yr^{-1} for barley, tef, and wheat respectively. The overall P addition for barley, tef, and wheat were 0.66, 3.24, and 3.39 kg ha^{-1} yr^{-1} respectively. The total added K amount was similar for barley, tef, and wheat with 2.65 kg ha^{-1} yr^{-1}. The nutrients outflows were higher than the inflows. The overall N export from barely, tef, and wheat farmlands were 81.8, 21.4, and 57.6 kg ha^{-1} yr^{-1} respectively. The total P depletion from barley, tef and wheat was 6.02, 1.81, and 5.33 kg ha^{-1} yr^{-1} respectively. Moreover, 15.5, 6, and 8.7 kg ha^{-1} yr^{-1} K were depleted from barley, tef, and wheat croplands respectively.

The partial balance of N, P and K was negative in all farmlands of barley, tef, and wheat, except tef P balance. As a result of, the imbalance between imports, and exports amounts. The result implies that the diminutions of soil nutrients were more severe in the smallholder farms. Which leads to the sustainability of the agricultural production system, and farms are at risk. Because of this, the agricultural production was low, as well as, there were food insecurity and malnutrition problems in the study area. The stocks of NPK were low because of inadequate input additions. The Stock of N was 1295, 1510, and 1240 kg ha^{-1} in barley, tef, and wheat farmlands respectively. Likewise, K stock of barley, tef, and wheat croplands was almost similar values 1092.7, 1059.4, and 1090.6 kg ha^{-1} respectively. Whereas, P stock was 63, 18.7, and 27.5 kg ha^{-1} from barley, tef, and wheat farms. The stock value of N, P and K was insignificant among the farmlands. Nitrogen stock better than potassium and phosphorous values. In general, the study showed a negative nutrient balance with low total nutrient stocks.

5.2. Recommendations

To improve the agricultural production capacity of smallholder farms, and feed the ever-increasing human population:

- Soil fertility enhancement should be in place.
- The sustainability, and boost of the agricultural production system could be achieved through the addition and management of nutrients into the farming systems.
- Reversing the imbalance between inflows, and outflows nutrient flows needs the application of nutrient sources like crop residue retention.
- Soil fertility should be corrected by adding organic and inorganic fertilizers.
- More extension services on the addition of organic and synthetic fertilizers shall be in place.
- It is very unlikely to increase the productivity of crops with small N and P fertilizers.
- Orienting farmers about proper nutrient management implementation is also essential.
- Further studies on integrated soil fertility management activities should be practiced to recover the agricultural productivity of the farms.

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APPENDIX

Appendix 1.Questioner for interview and group discussion

1. *What were the major cropping systems in the Agew Mariam watershed?*

2. What were the major dominant crop types in this catchment?

3. Did you use mineral fertilizers to increase crop productivity? A. Yes B. No

4. If your answer to question 3 were yes, which fertilizer did you use?

A. NPS B. NPSZnB C. NPSB D. Urea E. All F. A & E G. B&D

5. How much mineral fertilizers did you add to increase crop yield?

6. Did you use organic fertilizer to increase crop productivity? A. Yes B. No

7. If your answer to question 6 were yes, which fertilizer you added?

A. Compost B. Farmyard manure C. Ash D. All

8. How much organic fertilizers did you add to increase crop productivity?

9. Did you remove crop residues from your farmland? A. Yes B. No

10. If your answer for question 9 is yes, how much did you remove?

A. 86-100% B. 70-85% C. 50- 69% D. < 50%

11. How many kilograms did you harvest from the major dominant crop types?

12. was there practice of crop rotation? A. Yes B. No

13. If your answer for question 12 was yes, which sequence did you practice?

A. From cereal to pulse B. From cereal to cereal C. Shifting cultivation

Appendix Table 1. Summary of grain and straw yield

Site	Crop	GY kg ha^{-1}	SY kg ha^{-1}	Area (ha)	N kg ha^{-1}	P_2O_5 kg ha^{-1}	P kg ha^{-1}
1	Barley	923.08	1476.93	0.13	0	0	0
2	Barley	1750.00	2800	0.2	23	0	0
3	Barley	3561.71	5698.74	0.07	0	0	0
4	Tef	483.33	1533	0.12	0	0	0
5	Tef	400	1210	0.1	0	0	0
6	Tef	720	2174.8	0.05	8.65	17.25	7.59
7	Tef	294.12	588.24	0.17	0	0	0
8	Tef	600	1902.5	0.08	0	0	0
9	Tef	900	20600	0.05	20.76	41.4	18.216
10	Tef	375	1625	0.04	0	0	0
11	Tef	400	1262.22	0.09	0	0	0
12	Tef	707.69	2214.62	0.13	21.23	0	0
13	Tef	625	1613	0.04	0	0	0
14	Wheat	816.67	1843.2	0.12	0	0	0
15	Wheat	716.67	1615.47	0.06	0	0	0
16	Wheat	857.14	1915	0.07	0	0	0
17	Wheat	800	1739	0.15	9.23	18.4	8.1
18	Wheat	900	2013	0.14	0	0	0
19	Wheat	800	1726	0.1	0	0	0
20	Wheat	1000	2186.96	0.05	10.38	20.7	9.11
21	Wheat	1153.85	2657.31	0.13	0	0	0
22	Wheat	1666.67	3726.81	0.03	11.53	23	10.12
23	Wheat	1500	3416	0.02	0	0	0

Appendix Table 2.Sampling sites physical properties

Site	Crop land	Area (ha)	Slope (%)	Slope length (m)	BD (gm^{-3})	Textural class	Structural class
1	barley	0.13	7	18	1.63	sandy loam	medium blocky
2	barley	0.2	58	26	1.24	loam	thick granular
3	barley	0.07	2	39.5	1.26	loam	medium granular
4	teff	0.12	7	25	1.88	sandy loam	coarse granular
5	teff	0.1	6	15	1.5	sandy clay loam	coarse blocky
6	teff	0.05	10	12	1.44	loam	coarse blocky
7	teff	0.17	21	15	1.38	clay loam	coarse granular
8	teff	0.08	15	12.5	1.47	loam	fine granular
9	teff	0.05	5	14	1.64	clay loam	thick granular
10	teff	0.04	16	13.5	1.38	clay loam	coarse granular
11	teff	0.09	7	15.1	1.49	loam	coarse blocky
12	teff	0.13	7.5	42	1.47	sandy loam	coarse granular
13	teff	0.04	6	12	1.45	sandy loam	coarse blocky
14	wheat	0.12	16	22.5	1.6	sandy loam	fine granular
15	wheat	0.06	30	20	1.38	sandy clay loam	medium granular
16	wheat	0.07	15	18.8	1.5	clay loam	coarse granular
17	wheat	0.15	19	22.5	1.32	clay	thick granular
18	wheat	0.14	19	24	1.75	clay loam	thick granular
19	wheat	0.1	6	25	1.26	clay loam	coarse granular
20	wheat	0.05	3	9.25	1.53	clay	fine blocky
21	wheat	0.13	32	8	1.46	clay loam	medium granular
22	wheat	0.03	6	11	1.48	clay loam	thick granular
23	wheat	0.02	50	12	1.54	clay loam	fine granular

Appendix Table 3. The geographic location of sampling sites

Site	Geographic location		
	X: coordinate	Y: coordinate	Altitude (m, a, s, l)
1	12^0 32’ 05.8” N	$038^0$55’58.7’’ E	2137
2	12^0 31’ 59.4” N	$038^0$55’47.4’’ E	2210
3	12^0 32’ 24.8” N	$038^0$55’48.3’’ E	2282
4	12^0 32’ 05.8” N	$038^0$56’06.7’’ E	2126
5	12^0 32’ 06.2” N	$038^0$55’58’’ E	2141
6	12^0 32’ 09.3” N	$038^0$56’04’’ E	2123
7	12^0 32’ 06.1” N	$038^0$55’44.5’’ E	2278
8	12^0 32’ 10.8” N	$038^0$55’53.3’’ E	2160
9	12^0 32’ 23.1” N	$038^0$55’31.7’’ E	2277
10	12^0 32’ 12” N	$038^0$55’43.5’’ E	2228
11	12^0 32’ 11.9” N	$038^0$55’34.3’’ E	2272
12	12^0 32’ 30” N	$038^0$55’25.2’’ E	2304
13	12^0 32’ 10.1” N	$038^0$55’33.7’’ E	2283
14	12^0 32’ 13.7” N	$038^0$56’10.2’’ E	2115
15	12^0 32’ 17.0” N	$038^0$56’04.8’’ E	2156
16	12^0 31’ 50.0” N	$038^0$55’44’’ E	2285
17	12^0 32’ 29.2” N	$038^0$55’26.8’’ E	2297
18	12^0 32’ 25.9” N	$038^0$55’30.3’’ E	2288
19	12^0 32’ 23.6” N	$038^0$55’33.7’’ E	2278
20	12^0 32’ 14.9” N	$038^0$55’24.8’’ E	2277
21	12^0 32’ 12.3” N	$038^0$55’40.5’’ E	2239
22	12^0 32’ 26.8” N	$038^0$55’37.9’’ E	2280
23	12^0 31’ 52.3” N	$038^0$55’54.6’’ E	2207

Appendix Table 4. Summary of nutrient balances studies in Ethiopia compared to our finding research

Reference	Cropping system	Nutrient balance kg ha^{-1} yr^{-1}		
		N	P	K
This study	barley	-66.7	-5.4	-2.5
This study	tef	-8.9	+1.4	-2.6
This study	wheat	-47.1	-1.9	-4.8
Abebayhu Aticho *et al*. (2011)	Enset-coffee system	+3	+5	n.d
Assefa Abegaze *et al*. (2003)	Low potential Tigray	-65	-6	-34
Assefa Abegaze *et al*. (2005)	Mixed farming	-92	-6	-34
Van beek *et al*.(2016)	Mixed farming	-24	+9	-7
Eyasu Elias (2002)	National average	-92	+5	-49
Amare H/Selassie *et al*. (2006)	Cereal central Ethiopia	-50	-4	-64
Amare H/Selassie *et al*. (2006)	Enset	+68	+7	-23
Amare H/Selassie *et al*. (2006)	Cereal western Ethiopia	-46	+3	-7.5
Amare H/Selassie *et al*. (2007)	Mixed farming	-28	+27	-47
Melese gezie (2019)	tef	-61.4	+11	-26.7
Melese gezie (2019)	wheat	-20.9	-0.7	-37.87
Mekuanint Lewoyehu *et al*. (2020)	Treated watershed	-97.37	-23.66	-124.75
Mekuanint Lewoyehu *et al*. (2020)	Untreated watershed	-120.81	-20.62	-130.26
Stoorvogel and Smaling (1993)	National level	-47	-7	-32
Shimbahri Mesfin *et al*. (2020)	Mixed farming in Alaje	-26.2	+ 6.7	+ 2.9
Shimbahri Mesfin *et al*. (2020)	Mixed farming in Raya	-17.9	+ 3.9	-5.2

Appendix Table 5. Grain and straw yield nutrients content analysis result

Amhara Design & Supervision Works Enterprise
Laboratory Service
Soil Chemistry & Water Quality Section

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Teff & Wheat analysis of Laboratory Report
Client :Tilahun Esubalew (BDU)

Sr. No.	Lab. No.	Client Code	N	P	K
			%	ppm	
1	0148/21	Teff grain 01	1.14	2432.09	987.48
2	0149/21	Teff grain 02	1.31	2623.21	1127.14
3	0150/21	Teff grain 03	1.08	1743.27	1055.97
4	0151/21	Teff grain 04	1.10	2483.30	922.11
5	0152/21	Teff grain 05	0.98	1792.39	826.98
6	0153/21	Teff grain 06	1.09	2613.28	1015.14
7	0153/21	Teff grain 07	1.08	2556.50	908.83
8	0154/21	Teff grain 08	1.16	3116.30	808.13
9	0155/21	Teff grain 09	1.18	3305.95	1498.15
10	0155/21	Teff grain 10	1.20	2259.05	905.7
11	0156/21	Teff grain 11	0.94	2142.09	1531.6
12	0157/21	Teff Straw 01	0.60	1401.85	1742.5
13	0158/21	Teff Straw 02	0.71	1592.85	1589.48
14	0159/21	Teff Straw 03	0.54	1017.21	1418.19
15	0160/21	Teff Straw 04	0.56	1452.93	1672.35
16	0161/21	Teff Straw 05	0.44	1062.02	1375.09
17	0162/21	Teff Straw 06	0.58	1582.91	1663.25
18	0163/21	Teff Straw 07	0.57	1526.13	1456.94
19	0164/21	Teff Straw 08	0.49	2085.93	1356.24
20	0165/21	Teff Straw 09	0.52	2297.58	2246.26
21	0166/21	Teff Straw 10	0.45	1728.68	1509.11
22	0167/21	Wheat grain 01	2.11	5685.34	1013.20
23	0168/21	Wheat grain 02	2.19	4976.34	984.62
24	0169/21	Wheat grain 03	2.03	6496.39	896.4
25	0170/21	Wheat grain 04	2.36	5236.42	1106.9
26	0171/21	Wheat grain 05	2.29	4628.62	1376.7
27	0172/21	Wheat grain 06	2.23	5349.51	1268.1
28	0173/21	Wheat grain 07	2.05	4982.73	1589.3
29	0173/21	Wheat grain 08	2.08	5852.53	1168.5
30	0174/21	Wheat grain 09	2.31	5042.18	1319.5
31	0175/21	Wheat grain 10	2.29	4995.284	1249.7
32	0176/21	Wheat Straw 01	1.37	3045.72	1253.6
33	0177/21	Wheat Straw 02	1.23	2480.18	1783.65
34	0178/21	Wheat Straw 03	1.21	3180.21	1521.65
35	0179/21	Wheat Straw 04	1.49	2805.25	1614.9
36	0179/21	Wheat Straw 05	1.47	3015.33	1693.80
37	0180/21	Wheat Straw 06	1.42	2865.81	1873.4
38	0181/21	Wheat Straw 07	1.28	2835.39	1928.4
39	0182/21	Wheat Straw 08	1.26	3135.285	1757.9
40	0183/21	Wheat Straw 09	1.41	2701.17	1974.02
41	0184/21	Wheat Straw 10	1.48	2676.045	2017.31

Parameter	N	P	K
Unit	%	PPm	PPM
Barley grain 1	2.05	4628	1394.1
Barley grain 2	1.64	4341.2	1474.84
Barley grain 3	2.11	3461.4	1501.21
Barley straw1	1.04	2142.1	2729.6
Barley straw2	0.98	1043.1	2760.4
Barley straw3	1.02	1204.3	2835.2

Name of Chemist Abel. A
Date
Sign

Checked by
Date
Sign

Approved by
Date
Sign

Appendix Table 6. Soil laboratory analysis result

Site	Crop type	BD(gcm^{-3})	% OC	% OM	% TN	Avi. P (PPM)	%Sand	%Clay	%Silt	Textural class
1	Barley	1.63	0.44	0.77	0.05	6.19	54	16	30	Sandy loam
2	Barley	1.24	0.78	1.34	0.03	4.99	42	24	34	loam
3	Barley	1.26	2.16	3.73	0.06	62.06	34	24	42	loam
4	Tef	1.88	0.45	0.78	0.03	7.48	70	10	20	Sandy loam
5	Tef	1.5	0.44	0.77	0.03	5.19	56	20	24	Sandy clay loam
6	Tef	1.44	0.63	1.08	0.05	5.19	50	20	30	loam
7	Tef	1.38	0.70	1.21	0.04	5.55	42	28	30	Clay loam
8	Tef	1.47	0.46	0.79	0.04	5.79	48	22	30	loam
9	Tef	1.64	1.11	1.91	0.09	5.73	29	30	41	Clay loam
10	Tef	1.38	1.39	2.40	0.07	6.64	30	36	34	Clay loam
11	Tef	1.49	0.81	1.40	0.04	5.99	42	26	32	loam
12	Tef	1.47	0.78	1.34	0.05	8.37	44	28	28	Sandy clay loam
13	Tef	1.45	0.83	1.43	0.04	5.99	52	18	30	Sandy loam
14	Wheat	1.6	0.59	1.01	0.04	15.61	70	10	20	Sandy loam
15	Wheat	1.38	1.40	2.41	0.06	12.80	52	20	28	sandy clay loam
16	Wheat	1.5	0.67	1.16	0.04	5.23	36	34	30	Clay loam
17	Wheat	1.32	0.90	1.55	0.04	6.68	28	46	26	clay
18	Wheat	1.75	1.05	1.81	0.04	7.72	30	38	32	Clay loam
19	Wheat	1.26	1.15	1.98	0.04	16.26	22	36	42	Clay loam
20	Wheat	1.53	0.79	1.37	0.04	7.72	26	46	28	clay
21	Wheat	1.46	1.76	3.04	0.04	7.32	28	34	38	Clay loam
22	Wheat	1.48	0.83	1.43	0.04	5.99	34	28	38	Clay loam
23	Wheat	1.54	1.43	2.46	0.04	6.03	24	38	38	Clay loam

Appendix Table 7. Categories of annual nutrient depletions (kg ha^{-1}) in sub-Saharan Africa

Nutrient level	N	P	K
Average	22	2.5	15
Low	<10	<1.7	<8.3
Moderate	10 - 20	1.7 - 3.5	8.3 – 16.6
High	20 - 40	3.5 - 6.6	16.6 – 33.2
Very high	>40	>6.6	> 33.2

Source: (Lefroy & Wijnhoud, 2001)

Appendix figure 1. Collecting of tef samples using 1m X 1m quadrant

Appendix figure 2. Collecting of barley samples using 1m X 1m quadrant

Appendix figure 2. Taking soil samples using auger *and* identifying soil structural class

Appendix Figure 3. Measuring soil weight using sensitive balance and drying

BIOGRAPHICAL SKETCH

Tilahun Esubalew was born in Burie Woreda, West Gojjam administration zone of Amhara National Regional State, Ethiopia in 1989. He followed his primary educations at Sertekze and Horoseka primary full-cycle school. The secondary and preparatory school was completed at Burie Shikudad secondary and preparatory school. He received his BSC degree in Soil Resource and Watershed Management from Mekelle University in July 2011. Then he was employed in the Burie Woreda Land Administration and Environmental Protection office from 2012 –2014 served as an expert on soil and water conservation, from 2015 –2016 worked as an environmental impact assessment expert. Since June 2016 still, he is an employer of Sekota Dryland Agricultural Research Center as Assistant soil fertility researcher 1. Then, in October 2019 he has joined Bahir Dar University, College of Agriculture and Environmental Sciences, Department of Natural Resources Management in a regular program as a candidate for a Master of Science degree in Soil Science.