The Effect of Rainfall Variability, Soil Erosion, Drainage Improvement, and Nutrient Management on the Vertisols in thCentral Highlands of Ethiopia

Hailu Regassa Bedane

A Dissertation Submitted to the Center for Environmental Sciences, College of Natural and Computational Sciences

Presented in Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Environmental Sciences (Environment and Natural Resource Studies)

Addis Ababa University,

Addis Ababa, Ethiopia

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Supervisors- Eyasu Elias (Professor)

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Addis Ababa,

Ethiopia, 2024

DISSERTATION APPROVAL

Addis Ababa University

College of Natural and Computational Sciences

Center for Environmental Science

This is to confirm the thesis organized by Hailu Regassa Bedane: entitled, "**The Effect of Rainfall Variability, Soil Erosion, Drainage Improvement, and Nutrient Management on the Vertisols in the Central Highlands of Ethiopia**". It is submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy (Environmental Science) that complies with the regulations of the University. It satisfies the acknowledged criteria for originality and quality.

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Poor Soils Make Poor People and Poor People Make the Soil Worse

Alfred E. Hartemink

Declaration

I, Hailu Regassa Bedane, Center for Environmental Sciences, College of Natural and Computational Sciences, Addis Ababa University, Addis Ababa, Ethiopia, hereby declare that the research work embodied in this thesis entitled " **The Effect of Rainfall Variability, Soil Erosion, Drainage Improvement, and Nutrient Management on the Vertisols in thCentral Highlands of Ethiopia** " submitted to Addis Ababa University for award of the degree of Doctor of Philosophy in Environmental Science is a bona fide record of work done by me during the period of research carried out under the supervision of Prof. Eyasu Elias and Ass. Prof Meron Tekalign, college of Natural and computational sciences, Addis Ababa University, Addis Ababa, Ethiopia. This thesis has not formed in whole or part, the basis for the award of any degree or diploma to any other University before this date.

Addis Ababa University, Ethiopia

Hailu Regassa Bedane

This dissertation has been submitted for examination with my approval as a University supervisor.

Supervisor name: Eyasu Elias (Professor)

Signature: _____________

Date: ________________

List of original papers

Regassa H, Elias E. The Impact of Rainfall Variability and Crop Production on Vertisols in the Central Highlands of. Environ Syst Res [Internet]. 2022;1–26. Available from: https://doi.org/10.1186/s40068-022-00275-3

Regassa H, Elias E. Dry matter production, nitrogen yield and estimation of nitrogen fixation of legumes on Vertisols of the Ethiopian highlands. Heliyon [Internet]. 2022;8(12):e12523. Available from: https://doi.org/10.1016/j.heliyon.2022.e12523

Regassa H, Elias E, and Meron Tekalign. The nitrogen fertilizer replacement values of incorporated legumes residue to wheat on Vertisols of the Ethiopian highlands. Heliyon, 2023: https://doi.org/10.1016/j.heliyon.2023.e22119

List of articles under review

Tthe effects of tillage practices and sowing dates on soil and water erosion and crop productivity in Vertisols of the ethiopian highlands

The time course of nitrogen mineralization of legume plant residues incorporated into Vertisols in the Ethiopian highlands, by Hailu Regassa, Eyasu Elias, and Meron Tekalign

Dedication

I dedicate this thesis to the impoverished Ethiopian farmers who persistently strive to increase food production despite the hardships they face to provide sustenance for both themselves and the Ethiopian populace.

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List of Abbreviations

BBF-	Broad bed and furrow
BBM-	Broad bed and furrow maker
RH-	Relative humidity
WS-	Wind speed
W-	Wind
MAI-	Moisture Availability index
MAX-	Max temperature
MIN-	Minimum tempratue
^{0}C-	Degree centigrade
N-	Nitrogen
P-	Phosphorus
OC-	Organic carbon
TN-	Total nitrogen
CC-	Climate change
D-	Dry
W/D-	Wet/dry
W/W-	Wet/wet
NO_3-N-	Nitrate nitrgen
NH_4NO_3 -	Ammonium nitrate
PET-	Potential evapotranspiration
DP-	Dependable rainfall
LP-	Length of the growing period
CV-	Coefficient of variation
SD-	Standard deviation
NAE-	Nitrogen agronomic efficiency
PE-	Physiological efficiency
ANR-	Agronomic nitrogen recovery

K, Mg, Ca, Al

Acknowledgment

I began this Ph.D. study at the Addis Ababa University, Center for Environmental Science, Addis Ababa, Ethiopia in 2017. The main objective of this study was to comprehensively analyze the intricate relationship between rainfall variability and its impact on runoff and soil loss. Additionally, the study aimed to determine the potential of legume biomass production, decomposition, and nitrogen (N) mineralization. Another crucial aspect of the research was to assess the transfer and fertilizer equivalent values of legume residue nitrogen to subsequent wheat crops, particularly in terms of residue incorporation into the soil and its subsequent release of nitrogen to the succeeding crops. Furthermore, the study sought to investigate N mineralization from legume residue and develop effective soil and crop management options that optimize crop growth and enhance nutrient uptake.

I would like to express my deepest gratitude and admiration for my esteemed major advisor, Professor Eyasu Elias. Working with Professor Eyasu Elias has been an extraordinary privilege, and I consider myself incredibly fortunate to have had the opportunity to collaborate with such an exceptional and amiable individual. His remarkable passion for research is truly inspiring, and it has served as a constant source of motivation for me, pushing me to explore new horizons and strive for excellence in my academic pursuits. His expertise, profound knowledge, and insightful feedback have been invaluable assets to my research endeavors. I am truly grateful to have had the opportunity to work under the guidance of Professor Eyasu Elias. his exceptional mentorship, passion for research, and genuine support have played a pivotal role in shaping my Ph.D. journey, and I am forever indebted to him for his invaluable contributions.

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The Effect of Rainfall Variability, Soil Erosion, Drainage Improvement, and Nutrient Management on the Vertisols in thCentral Highlands of Ethiopia

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Addis Ababa University,
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ABSTRACT

Vertisols, characterized by high clay content and distinct shrink-swell properties in response to changes in moisture content, are the major soil types in the central highlands of Ethiopia. On this soil, 80% of the population lives and 75% of the nation's economy relies. In traditional farming practices, soils often face management problems due to waterlogging, stickiness, and forming puddles when wet. Additionally, when the soils dry out, they form hard clods and develop deep, wide cracks throughout the soil profile. The sticky nature of the soil further complicates farming operations as it hinders tillage activities and seedbed preparation. These issues can significantly impact the planting process, leading to delays in planting activities in Vertisols due to their waterlogged and sticky nature. This can lead to reduced crop yields and overall productivity. Therefore, this study was initiated with the objectives of studying rainfall variability and its effect on runoff and soil loss, and drainage improvement and crop production. Moreover,~~,~~ legume residue decomposition and nitrogen (N) mineralization for legume residue~~,~~ and the transfer of these N to subsequent wheat crops was studied. To address the environmental as well as agricultural production challenges associated with Vertisols, such as rainfall variability, soil erosion, and reduced soil fertility, five interrelated, but separate experiments were conducted at Ginchi and Holeta Agricultural Research Centers. To study rainfall variability, rainfall data of 39 years was used. The Markov Chain with initial and conditional probability and the Gamma distribution probability models were employed. The objective was to analyze rainfall patterns, predict rainfall levels, and interpret climatic data for water resource management, agricultural planning, and cultural practices.Runoff and soil loss study was conducted using conventional plot -used runoff plots to investigate the impacts of three sowing dates and two tillage practices on runoff and soil loss. Soil fertility study was conducted using the cropping system approach of planting legumes, employing drainage systems, and studying the legumes' biomass production and N yield during the main cropping season under an improved drainage system. At maturity, the legumes were harvested. Subsequently, the biomass of these legumes was incorporated into the soil, and the decomposition. Mineralization of legume residue N were studied through in-situ field monitoring using the Raison method. Lastly, the study determined the fertilizer replacement values of mineralized N from legume residues and explored the various nitrogen use efficiencies and the transfer of legume residue to subsequent wheat crops. The results indicated that two years out of five, Ginchi experienced rainfall anomalies, showing the need for drainage improvements and adjusting cultural practices and crop planting dates. Dependable rainfall at 75% probability and moisture availability indices greater than 0.5 start spanning from the 22nd to the 39th week (May 8th to September 30th). On average, soil loss on BBF was 3.8 t ha^{-1} per year, while on a flat seedbed, it was 2.1 t ha^{-1} per year. Runoff measured for BBF was higher than the flat seed bed. Legume biomass production, incorporation into the soil, and the transfer of incorporated legume residue N demonstrated that for low-input agriculture like Ethiopia, by using legumes in cropping systems, up to 186 kg ha^{-1} N per year was accumulated. However, the full potential of N accumulated and mineralized from legume residues was not available to subsequent crop wheat. Only 30 kg ha^{-1} N in terms of urea fertilizer remained available in the soil at planting wheat in June. This indicates that a huge amount of legume residue N might be lost due to leaching, *denitrification, and immobilization. The combined effects of rainfall, runoff soil erosion, and nutrient leaching highlight the need for appropriate strategies to enhance soil conservation measures, improve drainage systems, and promote effective nutrient management practices. These measures are crucial for ensuring the long-term and sustainable utilization of Vertisols in the Ethiopian highlands.*

Keywords*: Rainfall variability, Soil erosion, Nitrogen fixation, Nitrogen balance, Residue incorporation, Fertilizer replacement value, Nitrogen transfer, Crop production, Vertisols*

CHAPTER ONE - INTRODUCTION

1.1 Background and Justification

The sustainable utilization of agricultural land holds paramount importance, particularly in regions characterized by unique soil properties, rainfed agriculture, and challenging environmental conditions. The Ethiopian Highlands, known for their extensive distribution of Vertisols, are a prime example of such a region. It is crucial to address the challenges associated with rainfall variability, soil erosion, and nutrient management in order to mitigate the potential consequences for food insecurity, ecosystem health, and the well-being of local communities (Yalew, 2020). The present study aims to shed light on this matter by investigating the impact of rainfall variability, soil erosion, drainage improvement, and nutrient management on the sustainable use of Vertisols in Ethiopian highlands. By examining the complex interactions among these factors, this research seeks to provide valuable insights that can enhance soil productivity, conserve water resources, and promote sustainable agricultural practices in the region. The findings of this study have the potential to play a significant role in influencing policy formulation and decision-making processes, thereby making a tangible contribution to the long-term viability and resilience of agricultural systems in Ethiopia's highlands.

The Ethiopian highlands face significant challenges due to unpredictable rainfall patterns and extensive land degradation, resulting in severe consequences for the region (Hurni et al., 2015). Issues like soil erosion, deforestation, land shortages, population pressure, and unsustainable land management practices pose imminent risks of environmental crises, exacerbating the already precarious situation (Nyssen et al., 2015). These challenges have resulted in notable setbacks in agriculture, impeding socio-economic progress, and perpetuating a cycle of poverty and food insecurity. Among the various soil types in the Ethiopian highlands, Vertisols stand out as a prominent soil type for agricultural production. These soils are vital for food production as they cover large areas (approximately 13 million hectares) of agricultural land (Elias et al., 2022; Asamenew et al., 1987). However, their use is threatened by various environmental factors, including rainfall variability, soil erosion, and nutrient depletion. Additionally, their management for agricultural production poses significant difficulties. Vertisols are considered problematic soils due to their physical properties, which impose limitations on crop production. One notable characteristic of Vertisols is their high clay content, which causes the soil to become waterlogged, sticky, and puddled during periods of high-intensity rainfall. Conversely, during dry periods, Vertisols become extremely hard and develop wide and deep wedge-shape cracks impeding traditional farming operations. These physical properties of Vertisols further exacerbate the challenges faced by farmers in the Ethiopian highlands, hindering their ability to cultivate crops effectively (Society, 2016 Jutzi, n.d.).

Ethiopia is a country that heavily relies on rainfed agriculture, particularly in the highlands of Ethiopia. The success and productivity of farming are closely tied to the timing, distribution, and amount of rainfall received during the rainy seasons (Yalew, 2020). The physical properties of Vertisols, such as shrink-swell behavior in response to moisture changes, present challenges to crop production and hinder the use of traditional farm implements (Makombe et al., 2007). Therefore, the potential of these soils remains underutilized due to difficulties in managing the soil during shortages or excess rainfall. To mitigate the wet conditions of Vertisols, farmers often choose to keep the land fallow and plant crops after the withdrawal of the rain. However, leaving the land fallow during the main rainy season exposes the land to high-intensity rainfall, leading to runoff and soil erosion. Consequently, planting crops later in the season, relying on residual moisture, exposes the crops to dry spells, which adversely affect crop yields when rainfall is limited. Rainfall variability, a common occurrence in the highlands of Ethiopia, poses a significant challenge to agricultural productivity and land management practices. The unpredictable nature of rainfall patterns can lead to waterlogging, prolonged dry spells, and drought conditions, affecting soil structure and nutrient availability. Vertisol soils are particularly sensitive to changes in moisture levels due to their high clay content and swelling-shrinking behavior (Kovda, 2020). The variability in rainfall can influence soil moisture dynamics in Vertisols, affecting soil structure, fertility, and crop productivity. The most profound effect of rainfall variability is linked to climate change, further exacerbating environmental challenges.

Vertisols are known to be susceptible to various forms of land degradation, including soil and water erosion, as well as nutrient losses, which have far-reaching consequences for food security, farmers' livelihoods, and environmental degradation (Adem et al., 2020; Haile et al., 2006; Muluneh, 2010; Eweg et al., 1998). These negative attributes primarily stem from the physical characteristics of Vertisols, which are further exacerbated by rainfall variability (Hurni et al., 2010). In the highlands of Ethiopia, the occurrence of intense rainfall, particularly during the extended rainy season, poses a significant risk of soil erosion. Extensive deforestation and inadequate land management practices have led to the loss of vegetation cover in many highland areas. The absence of sufficient vegetation exposes the soil to direct impact from rainfall, resulting in erosion and reduced soil fertility (Borrelli et al., 2020). Consequently, the long-term productivity of Vertisols in the highlands is severely threatened. Soil erosion not only depletes the fertile topsoil but also disrupts soil structure, diminishes water retention capacity, and hinders nutrient cycling processes. These detrimental effects further compound the challenges faced in sustainably utilizing Vertisols in the highlands of Ethiopia. Addressing soil erosion is of utmost importance to ensure the long-term viability and productivity of agricultural systems in this region (Haregeweyn et al., 2015).

Vertisols are prone to land degradation, soil and water erosion, and nutrient losses, which have significant implications for food security, farmers' livelihoods, and environmental degradation (Adem et al., 2020; Muluneh, 2010; Haile et al., 2006; Eweg et al., 1998). The physical characteristics of Vertisols, coupled with rainfall variability, are responsible for these negative attributes of the soil (Hurni et al., 2010). Intensive rainfall occurrences, particularly during the extended rainy season, have the potential to induce severe erosion of the soil. Extensive deforestation and inadequate land management practices have resulted in the loss of vegetation cover in many highland areas. Without adequate vegetation, the soil is exposed to direct impact from rainfall, leading to erosion and reduced soil fertility. Soil erosion is another critical issue that threatens the long-term productivity of Vertisols in the highlands of Ethiopia. Erosion not only depletes the fertile topsoil but also affects soil structure, water retention capacity, and nutrient cycling processes. Vertisols are prone to waterlogging and poor drainage. Therefore, to enhance productivity of Vetisols, drainage improvement is a prerequisite. Excessive water retention in the soil can hinder nutrient uptake by plants. Additionally, well-drained Vertisols are more resilient to extreme rainfall events, reducing the risk of erosion and nutrient loss. Furthermore, drainage improvement and nutrient management play vital roles in enhancing the sustainable use of Vertisols in the highlands of Ethiopia. Proper drainage systems can help mitigate waterlogging and improve soil aeration, while effective nutrient management practices can optimize soil fertility and crop productivity (Society, 2016).

The study employed the analysis of long-term rainfall data for the study area, conducted extensive field experiments and measurements, and conducted laboratory and data analysis to provide comprehensive insights into these issues. Findings from this study could inform policy decisions related to agricultural practices in Ethiopia’s highlands and contribute to more sustainable farming systems that support food security while preserving environmental health. Understanding the relationship between rainfall, drainage, soil erosion, and nutrient management on Vertisols in Ethiopia is crucial for developing sustainable agricultural practices that promote productivity while minimizing negative environmental impacts (Monsieurs et al., 2015). Properly managing these factors through innovative practices, implementing effective drainage systems, employing best practices for organic and inorganic fertilization, adopting crop rotation schemes, and utilizing climate-smart agricultural techniques can help mitigate challenges associated with Vertisol agriculture in Ethiopia while ensuring food security for its growing population.

1.2 LITERATURE REVIEW

1.2.1 The Ethiopian Highland and Rainfall Variability

The Ethiopian highlands are a vast mountainous region located in the eastern part of Africa, covering much of Ethiopia. The region is characterized by rugged mountains, deep valleys, escarpments, and high plateaus. The Ethiopian highlands consist of several mountain ranges, with elevations ranging from approximately 1,500 meters above sea level. The highlands have a diverse climate due to variations in elevation and topography. Generally, the highlands experience a temperate climate, with cooler temperatures at higher altitudes. The region receives a significant amount of rainfall, particularly during the wet season, which runs from June to September. The Ethiopian highlands are known for their rich biodiversity, different soil types and unique ecosystems. The Ethiopian highlands are an important agricultural region, with plow culture supporting various crops under rainfed agriculture (S. D. Williams et al., 2005).

1.2.2 Rainfall Variability

The Ethiopian highlands are known for their unique ecological characteristics, including significant agricultural activities that rely heavily on rainfall. Rainfall variability is a crucial aspect of the Ethiopian highlands, as the region experiences distinct wet and dry seasons (Legese et al., 2018). The highlands receive the majority of their rainfall during the wet season, which typically occurs between June and September. This rainfall is vital for agricultural activities in the region, as it supports crop growth and sustains the water supply for various purposes. However, rainfall in the Ethiopian highlands is highly variable both spatially and temporally (Seleshi & Zanke, 2004). The distribution of rainfall can vary significantly within the region, leading to areas with higher or lower rainfall amounts. This variability poses challenges for agricultural planning and management, as farmers need to adapt to these fluctuations to ensure sustainable crop production. Rainfall variability can directly impact crop yield by affecting plant growth and development (Regassa & Elias, 2022; Kyei-Mensah et al., 2019). Insufficient rainfall during critical growth stages can lead to water stress, reduced crop yield, and even crop failure. Conversely, excessive rainfall can cause waterlogging, which can also harm crop productivity. Farmers often select crops based on their adaptability to local rainfall patterns. Changes in these patterns may necessitate shifts in crop selection to ensure optimal yields. Variations in rainfall patterns require adjustments in water management practices. During dry periods, farmers may need to rely on irrigation systems or water conservation techniques to supplement insufficient rainfall. Excess rainfall may necessitate improved drainage systems to prevent waterlogging (Kassahun, 2011).

Research on rainfall variability in the Ethiopian highlands has revealed significant trends and patterns. Miheretu (2020) found that while annual rainfall has been increasing, there is a significant decrease in the short (Belg) rainfall. Seleshi (1995) and Elsanabary (2012) both established a link between Ethiopian rainfall and the El Nino-Southern Oscillation, further identifying a correlation with the Indian Ocean Dipole. Conway (2000) provided a historical perspective, noting a return to more humid conditions in the 1990s after a dry period in the 1980s. These studies collectively highlight the complex and dynamic nature of rainfall variability in the Ethiopian highlands.

1.2.3 Vertisols of the Ethiopian Highlands

Vertisols, which are deep, black, cracking clay soils, hold significant agricultural importance in many parts of the world. The global coverage of these soils is estimated to be around 308 million hectares, with 90% of them found exclusively in tropical and sub-tropical regions (Coulombe et al., 1996; USDA-SCS, 1994). In Africa, Ethiopia ranks third in the acreage of Vertisols, following Sudan and Chad. An estimated 12.6 million hectares of these soils, or approximately 7.6 million hectares, are located in the highlands situated above 1500 meters above sea level (Society, 2016). The soils are widespread on medium- to higher-elevation plateaus, and the slope ranges between 2 and 8%. The ecology of these plateaus is characterized by high annual rainfall (more than 900 mm) and moderate temperatures, which lead to relatively low evaporation, particularly during the growing period. Agriculture is a vital economic activity in the highlands of Ethiopia. Due to its diverse topography and climate variations, different agricultural practices are observed across the region. The Ethiopian highland Vertisol areas are generally characterized by smallholder, mixed cereal-livestock farming systems with a marked subsistence character.

Heavy clay soils (Vertisols appear to be more prone to waterlogging stress than light soils (McDonald & Gardner, 1987). Waterlogging is a soil condition whereby excess water in the root zone inhibits gas exchange with the atmosphere above the soil surface (Setter & Belford, 1990). In the central highlands of Ethiopia, the duration and severity of waterlogging stress are highly pronounced on Vertisols. Waterlogging of soils can be temporary, intermittent, or continuous ponding of excess surface water on agricultural fields. There are several reasons for the formation of waterlogged conditions, but to mention a few: the rising of the water table (Gardner and Flood, 1993) and high rainfall areas characterized by flat and bottomland topography and with high clay soils (Musgrave & Ding, 1998). One-third of all cropland in Ethiopia is made up of heavy, cracking clay soils. This may have helped the tef (Eragrostis tef (Zucc.) Trotter) crop become popular in the past because it can handle a lot of water. As most of the field crops are prone to waterlogging, the various traditional drainage systems were not able to drain the excess moisture from the farm field. The relatively high productivity potential of Ethiopian highland Vertisols is not fully utilized in traditional drainage systems. Therefore, it was necessary to bridge the yield gap (actual and potential) through research intervention.

1.2.4 Rainfall, Soil Erosion, and Environmental Degradation

The Ethiopian highlands face severe soil erosion and environmental degradation due to a combination of factors, including erosive rains, steep slopes, and human activities such as deforestation, overgrazing, and unsustainable agricultural practices (Nyssen, 2015; Bishaw, 2005; Hurni, 2010). Efforts to address these issues have been made through soil and water conservation measures, afforestation and conservation programs, and sustainable land management practices (Nyssen, 2015; Bishaw, 2005; Hurni, 2010). However, the success of these efforts has been limited, and further interventions are needed to address the underlying causes of soil erosion and environmental degradation in the highlands of Ethiopia (Shiferaw, 1999).

Rainfall variability can contribute to land degradation through erosion processes. Intense rainfall events following prolonged dry periods can cause soil erosion due to reduced vegetation cover and weakened soil structure. Variability in rainfall can have an impact on soil health and quality. Intense rainfall events, particularly after dry spells, can increase soil erosion rates (Singh et al., 2014). The lack of vegetation cover during droughts makes the soil more susceptible to erosion when heavy rain occurs. Eroded soil can lead to reduced fertility, loss of topsoil, and decreased agricultural productivity. Variations in rainfall patterns directly affect soil moisture content.

Drought conditions result in lower soil moisture levels, leading to water stress for plants and reduced nutrient availability. Conversely, heavy rainfall can saturate the soil, increasing the risk of waterlogging and the leaching of nutrients. Rainfall variability affects nutrient cycling processes in the soil. Dry periods can slow down decomposition rates, resulting in reduced nutrient availability for plants. On the other hand, heavy rainfall can leach nutrients from the soil, leading to nutrient imbalances and potential losses. Adequate and consistent rainfall is crucial for maintaining good soil structure. Dry spells followed by heavy rain can cause soil compaction and crusting, reducing infiltration rates and increasing surface runoff. This can lead to decreased water-holding capacity and increased vulnerability to erosion.

1.3 Nutrient Management on Vertisols

Vertisols present specific constraints to nutrient management in agriculture. The high cation exchange capacity of Vertisol properties helps retain nutrients and also results in low nutrient availability for plant uptake. The clay particles can tightly bind nutrients such as phosphorus, potassium, and micronutrients, making them less accessible to plants. Despite their ability to retain water, Vertisols can also experience the leaching of nutrients due to heavy rainfall or excessive irrigation. The rapid movement of water through the soil can carry away dissolved nutrients, leading to nutrient loss and polluting the environment (van Beek et al., 2016). Vertisols may exhibit imbalances in nutrient levels, particularly in terms of macronutrients like nitrogen, phosphorus, and potassium. These imbalances can affect crop growth and yield and may require targeted nutrient management strategies to address deficiencies or excesses. Vertisols are prone to erosion, particularly during heavy rainfall events. Erosion can remove the nutrient-rich topsoil layer, depleting the soil of essential nutrients and reducing its fertility (Henao & Baanante, 2006).

To improve soil fertility in Vertisols, it is essential to manage water effectively and address any issues related to compaction and poor drainage. Additionally, adding organic matter through compost or manure can enhance soil fertility by improving soil structure and nutrient availability. In Vertisols, residue incorporation can be beneficial for enhancing soil fertility by increasing organic matter levels and promoting microbial activity.

1.4 Past Research Experiences on Vertisols

Research work on Vertisols in Ethiopia started in the late 1960s and early 1970s. The research was mainly focused on drainage improvement, fertilizer trials, and testing agronomic practices on the station and farmers' fields. There is strong evidence from both on-station and on-farm tests that better surface drainage is the key to unlocking the huge amount of productive potential of high-response highland Vertisols (Jutzi, n.d.). To ameliorate the waterlogging problem on Vertisols, research has developed an animal-drawn implement, the broad bed and furrow maker (BBM), by attaching curved metal sheets to both sides of the local plow (*Maresha*), which is constructed by modifying the local plow "*Maresha.*". The BBM creates 80-cm-wide raised seedbeds separated by a 40-cm-wide furrow, commonly referred to as the broad bed and furrow (Astatke & Kelemu, 1987). This technology facilitates the early sowing of crops, thereby utilizing a longer growing period, resulting in higher crop yields. The BBM technology, coupled with improved seed, fertilizer, weeding, and early sowing, had proven to increase the yield of most field crops.

Vertisols, characterized by their high content of expanding clay minerals, exhibit unique properties that necessitate site-specific research. Vertisols are found in different agroecologies, showing differences in agroclimatology, soil (clay content), moisture regime, topography, and slope. Vertisols are typically dark in color and have variable organic matter content (ranging from 1% to 6%). The specific characteristics of Vertisols vary due to environmental conditions**.** Understanding their behavior requires detailed investigations at the site scale. Climate influences weathering processes, affecting the duration and intensity of dry-wet cycles critical for their shrink-swell behavior. While topography and vegetation do not impact regional distribution, they significantly affect soil moisture regimes, hydrology, water availability, leaching potential, soil depth, and mineralogy. Vertisols remain a fascinating subject for further research and exploration.

This PhD study tried to investigate rainfall variability and soil-related problems in Vertisols and identify management options for sustainable use of soil resources in the central highlands of Ethiopia. The study looked at how changes in rainfall affect soil and water erosion, nutrient loss, and integrated soil fertility management. To fix soil fertility problems, legume planting, residue incorporation, and N mineralization were used. The sustainable use of Vertisols is crucial because the soil is underutilized, but food insecurity and poverty are major problems for the ever-increasing human population in the country.

1.3 Statement of the Problem

Vertisols are a type of soils characterized by high clay content and present significant challenges and constraints to agricultural productivity, land management, and the environment. The sustainable use of Vertisols are threatened by multiple interconnected challenges, including rainfall variability, soil erosion, inadequate drainage infrastructure, and suboptimal nutrient management practices. These factors can lead to soil degradation, nutrient loss, reduced crop yields, and environmental degradation (Aleminew & Alemayehu, 2020). The unique properties of Vertisols, such as high shrink-swell behavior and low internal drainage, contribute to several problems that need to be addressed (Kovda.n.d.). The variability in rainfall on Vertisols significantly influences drainage, erosion, nutrient management, cultivation practices, and crop production. Rainfall variability, such as insufficient or uneven rainfall distribution, can lead to moisture stress, while excessive rainfall can result in waterlogging. Vertisols show high volume changes with moisture fluctuations, exhibiting shrink-swell properties. When wet, the soil swells and becomes sticky, and when dry, clods and wedge-shape wide cracks form. The shrink-swell properties of Vertisols can lead to soil structure degradation, nutrient leaching, and imbalance, and create difficulties in seedbed preparation and crop establishment (Jutzi et al., 1988). The high clay content of Vertisols reduces aggregate stability, making the soil susceptible to surface runoff, water erosion, and wind erosion. This erosion can lead to the loss of topsoil, decreased soil fertility, and reduced land productivity (Meng et al., 2021). In addition to the shrink-swell behavior and cracking, tillage operations in Vertisols are often challenging.

Previous research conducted on the Vertisols of the Ethiopian highlands primarily concentrated on enhancing drainage systems, overlooking the analysis of rainfall probability using long-term weather variables, specifically rainfall (Regassa & Elias, 2022b). Predicting rainfall patterns and estimating the expected amount can assist smallholder farmers in anticipating the start, end, quantity, and distribution of rainfall, enabling more sustainable crop production practices. Concerning rainfall variability, runoff, and soil study was conducted using conventional field-based small runoff plots. Because Vertisols are prone to erosion during excess rainfall. For increased crop production, legume biomass production and their N accumulation, decomposition, and N mineralization of legume residues, and the N transfer and fertilizer replacement values of legume residue N to subsequent crop wheat were investigated. Integrated soil fertility management is critically important for low input and output agriculture in Ethiopia. The use of organic fertilizer in combination with inorganic fertilizer can help smallholder farmers to decrease the inorganic fertilizer requirement of crops. The use of improved drainage systems on Vertisols has been a technology accepted in high-rainfall areas of the Ethiopian highlands (Haile et al., 2022). However, drainage improvement and soil and water erosion were not properly quantified concerning slope and land configuration. Therefore, there is an urgent need to comprehensively understand the impacts of rainfall variability, soil erosion, drainage improvement, and nutrient management on Vertisols to develop effective strategies for the sustainable utilization of these soils. This study aims to investigate the complex relationships and interactions between these factors and their combined effects on soil health, agricultural productivity, and the long-term sustainability of Vertisols in the highlands of Ethiopia.

Understanding the patterns of rainfall variability, its causes, and its effects on Vertisols is crucial for developing effective strategies to mitigate its adverse effects (Regassa & Elias, 2022b). This may include the adoption of water management techniques, soil conservation measures, and the use of drought-resistant crop varieties. Furthermore, addressing the challenges posed by variability in rainfall on Vertisols in Ethiopia requires interdisciplinary approaches that integrate knowledge from fields such as agronomy, hydrology, climatology, and soil science. Collaborative efforts between researchers, government agencies, non-governmental organizations, and local communities are essential for developing sustainable solutions to this pressing issue. The problem of variability in rainfall on Vertisols in Ethiopia is a complex and multifaceted issue that requires comprehensive understanding and targeted interventions to ensure the resilience and productivity of agricultural systems in the face of changing climatic conditions and rainfall variability.

2.1 Research Questions and Hypothesis

The research question of this study is entitled "The Effect of Rainfall Variability, Soil Erosion, Drainage Improvement, and Nutrient Management on the Vertisols of the Ethiopian Highlands". It focused on understanding the comprehensive influence of various factors, including rainfall variability, soil and water erosion, drainage improvement, and nutrient management, on Vertisols in the Ethiopian Highlands. The study aims to investigate the interplay between these factors and their collective impact on the sustainable utilization of Vertisols in the highland region.

The following research questions provided a starting point for investigating the impacts and interactions of rainfall variability, drainage improvement, soil erosion, and nutrient management on the sustainable use of Vertisols in the highlands of Ethiopia.

- How does rainfall variability affect crop production in the highlands of Ethiopia?
- What are the main drivers and rates of soil erosion on Vertisols in the study area, and how does rainfall variability influence erosion processes and sediment transport?
- How do drainage systems and sowing dates affect runoff and soil loss under variable rainfall on Vertisols?
- How does nutrient management, including fertilization practices and organic amendments, impact soil fertility, nutrient availability, and crop yields on Vertisols in the study area, considering the challenges posed by rainfall variability?
- How organic matter decomposition and nitrogen mineralization are affected by rainfall variability?

1.4 Brief Description of the Methodologies and Objectives

The Ph.D. dissertation follows the "article-compilation-based" format according to the guidelines set by Addis Ababa University in 2022. The Ph.D. The candidate has published three manuscripts in international peer-reviewed journals and submitted two more for review. All published and pending papers are included in this Ph.D. dissertation from chapters 2 to 6, with specific methodologies placed in their respective chapters. The methodology described in this subsection of the dissertation is a general one.

The Ph.D. research study was conducted at Holeta and Ginchi research centers, located in the central highlands of Ethiopia and representing mid-highlands areas of Ethiopia in terms of agroecology and limited ssoil type. Due to limited financial resources, proximity, and laboratory and technical support, the research was conducted in these two locations. Both locations are found in the central highlands of Ethiopia, west of Addis Ababa, in West Showa Zone of the Oromia region, Ethiopia. Geographically, Holetta is located at 9° 02' 12" N and 38° 29' 00" E, at an elevation of 2400 meters above sea level, while Ginchi is located at 9°01’54" N to 9°04’03" N latitude and 38°09’10" E to 38°10’40" E, at an elevation of 2200 m.a.s.l.

The locations have two rainy seasons: the long and short rainy seasons. The short rainy season in these highland locations is not significant for crop production. Crop-livestock integrated farming system dominate the farming system. The soils at both study sites are typically dark black clay soils (Vertisols). An excess or shortage of rainfall can disrupt the water balance necessary for crop growth and development. Excessive rainfall may lead to waterlogging, erosion, or nutrient leaching, negatively impacting the agricultural sector. Vertisols are known as problematic soils for management due to waterlogging related to their physical properties. Soil erosion is prevalent, hindering nutrient availability for crops and polluting the environment due to irregular rainfall patterns and soil-related problems that pose significant obstacles to agricultural productivity and environmental sustainability.

The research methodology conducted is specific to each manuscript. The rainfall variability study used the initial and conditional probability of the Markov Chain Model. The purpose of a Markov chain model in rainfall studies is to analyze and predict the patterns and behavior of rainfall over time. By using historical data on rainfall events, a Markov chain model can help researchers understand the transition probabilities between different states of rainfall (e.g., dry, light rain, heavy rain) and forecast future rainfall patterns. This model is useful for studying the dynamics of rainfall, assessing water resources, and making informed decisions related to water management and agricultural planning. For this purpose, 39 years of daily rainfall data of Ginchi was used. The gamma distribution model is commonly used in rainfall studies to represent the distribution of rainfall intensity or duration. In the context of rainfall, the gamma distribution can help researchers model and analyze the variability of rainfall events over time. By fitting observed rainfall data to a gamma distribution, researchers can estimate parameters such as shape and scale to describe the characteristics of rainfall patterns accurately. This model is valuable for statistical analysis, hydrological modeling, and risk assessment in various water-related applications. To conduct a water balance study involving rainfall, soil moisture, and evapotranspiration, we typically followed these steps. The water balance equation typically states: Precipitation = Evapotranspiration + Runoff + Change in Soil Moisture. We analyzed the water balance to assess water availability, potential water stress, and hydrological processes in the study area. The results helped to understand the relationship between rainfall, soil moisture, and evapotranspiration in the ecosystem.

1.5 Objectives

1.5.1 General Objective

The general objective of this study is to investigate the impacts of rainfall variability, soil erosion, drainage improvement, and nutrient management on the use of Vertisols in the Highlands of Ethiopia.

1.5.2 Specific Objective

- To examine the pattern of rainfall distribution, estimate expected rainfall amounts at various probability levels and determine the start and end of the crop-growing period and interpret rainfall data for agricultural planning and operations as well as the timing of cultural practices involving Ginchi Vertisol.
- To quantify soil and water erosion generated from sowing dates and tillage practices on Vertisols at Ginchi.
- To assess the dry biomass and nitrogen yield of legumes under drained Vertisol conditions with two levels of P application during the long rainy season.
- To assess the decomposition of incorporated legume residues and nitrogen mineralization in a time course.
- To evaluate the N fertilizer replacement values of incorporated legume residues and the N transfer of legume residue N to subsequent wheat crop in vulnerable agroecosystems facing challenging conditions.

1.6 Significance of the Study

The study holds great significance in several aspects. Firstly, the study focuses on Vertisols, a specific type of soil found in the Ethiopian Highlands. Understanding the impacts of various factors on the sustainable use of Vertisols is crucial for food security and environmental sustainability. Vertisols are known for their high clay content, which makes them prone to waterlogging during the rainy season and extreme cracking during droughts. Studying the effects of rainfall variability, soil erosion, drainage improvement, and nutrient management on Vertisols, the study contributes to a broader understanding of sustainable land management in this specific region. Secondly, the study addresses the issue of rainfall variability, a pressing concern in the Ethiopian Highlands. Climate change has resulted in increased unpredictability and irregularity in rainfall patterns, leading to challenges in agriculture, food security, and water management. By analyzing the impacts of rainfall variability on Vertisols, the research provides insights into how farmers and policymakers can adapt their practices to minimize the negative consequences and ensure the sustainable utilization of the land.

Furthermore, soil erosion is a significant environmental issue, not only in the Ethiopian Highlands but also globally. This dissertation explores the relationship between soil erosion and the sustainable use of Vertisols. By identifying the factors contributing to erosion and evaluating the effectiveness of different erosion control measures, the study offers practical recommendations for managing soil erosion in Vertisols. This knowledge can contribute to the development of sustainable land management strategies that mitigate the loss of fertile topsoil, improve agricultural productivity, and preserve the ecological integrity of the Ethiopian Highlands.

Maintaining the productivity of Vertisols is essential for sustaining food security in the area, as the economy of Ethiopia heavily relies on agriculture. It is possible to create methods to increase agricultural output and preserve food security by having a better understanding of the effects of rainfall variability, drainage improvement, and soil erosion. Factors such as fluctuating rainfall can cause soil erosion, resulting in the loss of fertile topsoil and negative impacts on the ecosystem. Examining the connection between soil erosion and the deterioration of characteristics of Vertisols may help with the development of techniques for conserving soil and reducing erosion, both of which will promote environmental sustainability. Vertisols, due to their high clay content, are more prone to waterlogging, which stunts crop development and reduces agricultural productivity. For sustainable water management and better agricultural results, evaluating how well drainage improvement measures reduce waterlogging and increase soil quality is essential. Because of their high clay concentration, Vertisols are more likely to experience waterlogging, which hinders crop growth and lowers agricultural production. One important effect of climate change is rainfall variability, which affects agricultural systems and needs to be handled for resilience and adaptation. Comprehending the correlation between fluctuations in rainfall and soil erosion in Vertisol ecosystems would facilitate the creation of climate-smart agriculture methodologies and tactics.

1.7 Scope and Limitations of the Study

The Ph.D. study titled " **The Effect of Rainfall Variability, Soil Erosion, Drainage Improvement, and Nutrient Management on the Vertisols in the Central Highlands of Ethiopia**" aimed to comprehensively analyze and evaluate the multitude of factors that influence the sustainable use of Vertisols in the Ethiopian Highlands. The study delved into the examination and analysis of these factors, thereby expanding the understanding of their influence on the management and long-term viability of Vertisols in the region. The study aims to investigate the impacts of rainfall variability, soil erosion, drainage improvement, and nutrient management on Vertisols, with the ultimate goal of indicating sustainable land management strategies. Specifically, the study examines the effects of rainfall variability on Vertisols and how this variability influences soil moisture, runoff and soil loss, and agricultural productivity.

Additionally, the study investigates the role of drainage improvement in managing waterlogging issues in Vertisols. It examined different drainage techniques and their impacts on soil moisture, runoff, soil loss, and overall land productivity. Furthermore, the study explores the effects of nutrient management on Vertisol fertility and productivity, considering organic and inorganic nutrient applications to enhance soil nutrient levels and crop yields. The study encompasses a range of research methodologies, including field experiments and laboratory work. It also involved reviewing existing literature, conducting statistical analysis, and using models to assess addressed in the objectives section.

The research aims to contribute to the development of sustainable land management strategies and provide practical recommendations for farmers, policymakers, and land managers to enhance the productivity and long-term viability of Vertisols in the region. The voluminous soil data collected and analyzed were not without problems. Some of the parameters collected required high-tech laboratory equipment, which was not available at the Holeta Soil and Plant Nutrition Laboratory. Despite the limitations and the one-year delay caused by the COVID-19 pandemic, this study has made substantial contributions to advancing the existing knowledge base on various aspects. The study has significantly contributed to important areas such as rainfall variability, drainage channel requirements, N mineralization, transfer mechanisms, and the fertilizer replacement values of legume residue N in subsequent wheat crops. These findings enhance our understanding of these factors and their impact on agricultural productivity.

1.8 Conceptual Frameworks

This study attempts to investigate the extent of rainfall variability, runoff, soil loss, legume biomass production applying drainage systems, legume residue decomposition and nitrogen mineralization, and the transfer of nitrogen mineralized from legume residues to subsequent wheat crops. Several studies have explored the relationship between natural resources, rainfall, runoff, soil loss, drainage improvement, and nutrient management with a focus on sustainable management of Vertisols. The papers emphasized the need for interventions based on erosion severity predictions by different factors such as rainfall, slope, topograpgy and in preventing soil erosion and improving ecological environments. Bukoma (2022) underscores the importance of continuous assessment of soil erosion, in various agroecologies, and recommends the development of soil conservation and management strategies. The study collectively underscore the significance of understanding and managing the relationships between natural resources, rainfall, runoff, and soil loss for sustainable development (Miheretu et al., 2018).

A rainfall variability study was conducted using historical rainfall data for Ginchi (39 years), using the first-order Markov chain model, the initial and conditional probabilities, and the incomplete gamma model were utilized to assess the start, end, and the length of the growing season and expected amounts of rainfall. Potential evapotranspiration and the moisture availability index were utilized to determine the optimum soil moisture for plant growth and development (Anache et al., 2017). Rainfall variability significantly affects runoff, sediment, and nutrient loss, with higher intensity leading to greater loss. The relationship between rainfall, runoff, and soil loss is a critical aspect of understanding erosion processes in various environments. Rainfall energy plays a significant role in initiating soil erosion by impacting the soil surface and causing detachment and transport of soil particles. The kinetic energy of raindrops, influenced by factors such as drop size, intensity, and frequency, determines the erosive potential of rainfall. When rainwater hits the ground, it can lead to surface runoff, which can further contribute to soil erosion by carrying sediment away. Rainfall amount received during the study period was measured using rain Gauge. Collection devices or sediment and runoff samplers were installed at the plot outlet to collect runoff water and sediment from the drainage furrows established while constructing the BBF. These data were collected over the wet season considering rainfall events causing runoff and soil loss. The appropriate models and statistical software were used to interpret the runoff and soil loss data.

Vertisols are soils prone to waterlogging during high-intensity rainfall. Drainage improvement is a prerequisite for successful crop production on Vertisols. The BBM system was introduced to drain the excess water from the farmland (Astatke et al., 2002). After the construction of the BBF, vetch and clover were planted with and without phosphorus application. At maturity, the dry biomass of these legumes was estimated, the N concentration of these legumes was measured using the Kedijal method for N concentration, and the N yield of legumes was determined by converting N concentration into a hectare base. Legume cover crops play a critical role in nitrogen fixation and mineralization. They help in improving nitrogen uptake by subsequent crops by transferring more fertilizer nitrogen to the soil, enhancing soil fertility and crop productivity. Effective drainage systems can help manage runoff, reduce soil erosion, and improve soil quality. Proper drainage plays a key role in sustainable cropping systems by mitigating the negative impacts of excess water on agricultural lands.

Legume biomass production and decomposition significantly influence the transfer of nitrogen to subsequent crops. The rate of nitrogen mineralization from legume crop residues varies depending on the type of residue, with alfalfa stover decomposing more rapidly than maize stover (Paré, 2004). This mineralization is further influenced by the presence of living roots, which enhances the process (Paré, 2004). The decomposition of legume residues, particularly the shoot residue, serves as a source of nitrogen for subsequent crops (Talgre, 2017). Managing legume residues can also manipulate their nitrogen mineralization dynamics, potentially maximizing the nitrogen supplied to subsequent crops (Reeves, 2018). The shoot residue decomposition serves as a source of nitrogen for the subsequent crop. With the efficient utilization of symbiotically fixed N by legumes in green manure, it is possible to achieve higher yields of subsequent crops. The interrelationships of the variables, rainfall variability, drainage improvement, runoff and soil loss, and nutrient management are shown in Figure 1.1. The conceptual framework variables were interconnected where necessary showing the relationships between them.

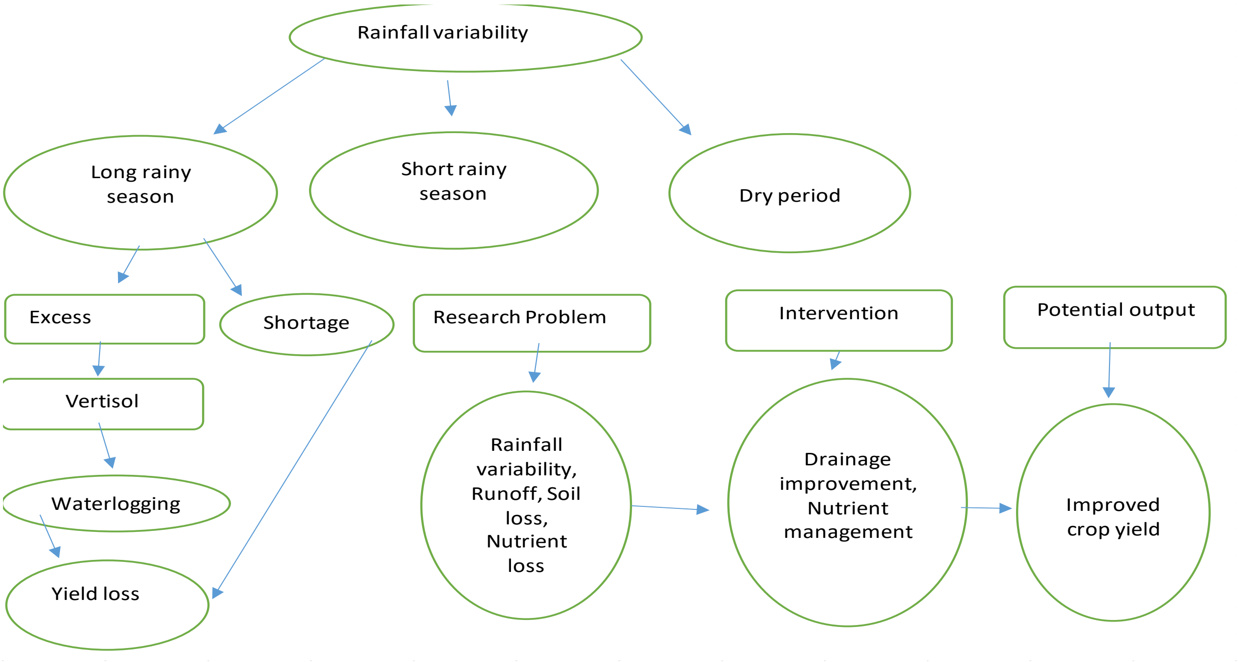

Figure 1.1 Schematic representation of conceptual framework

1.9 Organization of the Dissertation

The introduction part (Chapter 1) of this thesis analyzed the rainfall variability, occurrence, distribution, and its impact on Vertisol farming was discussed. Crop production constraints and the major social, economic, and environmental problems related to Vertisols in the central highlands of Ethiopia were also addressed. Statement of the problem in relation to rainfall variability, soil and water erosion, crop management, and the need for drainage improvement was assessed. The general methodology of the study, objectives, significance of the study, limitations, and structure of the dissertation were included in this part of the thesis. Chapter Two is a published manuscript in Springer. Under the title " The Impacts of Rainfall Variability and Crop Production on Vertisols in the Central Highlands of Ethiopia" thoroughly discussed the impact of rainfall variability on Vertisols using The Markov Chain Model. Chapter Three discussed the dry biomass production of legumes, N contribution, and N-fixation capacity of legumes under drained Vertisol conditions. The manuscript was published in Elsevier. Chapter Four is a follow-up experiment of Chapter Three in which the legume residues were incorporated into the soil to find out the fertilizer replacement values of these legumes. The study was also published in Elsevier under the title "The Nitrogen Fertilizer Replacement Values of Incorporated Legumes Residue to Wheat on Vertisols of the Ethiopian Highlands. Chapter Five, under the manuscript entitled "N mineralization, Mineralization of incorporated legume residues on Vertisols of the Ethiopian highlands was submitted to a journal and is under review. Chapter Six, a manuscript under the title "Rainfall variability, tillage practices, and soil and water erosion on Vertisols of the Ethiopian highlands is under preparation to send for the potential journal. Finally, Chapter Seven discusses all these pieces of research together under the title "General Discussion/Conclusions and Recommendations" and makes a synthesis and their policy implications. This chapter describes some of the important lessons learned from the study and suggests some important actions to be taken by different stakeholders so that the burdens of rainfall variability and Vertisol management problems could be resolved and environmentally friendly technologies developed to improve the livelihoods of small-holder farmers.

Chapter Two-The Impact of Rainfall Variability on Crop Production in Vertisols of the Central Highlands of Ethiopia

Abstract

Understanding the yearly, seasonal, monthly, and weekly rainfall variability is crucial for improved agricultural practice in Ethiopia, where agriculture depends on rainfall. In particular, knowledge of rainfall onset, withdrawal, amount, distribution, and the length of the crop growing period would protect farmers from crop damage due to climatic anomalies. This study collected and described thirty-nine years of rainfall data using the Markov chain model. Based on the rainfall probability levels at different threshold values, the length of the dry and wet spells and the length of the growing period were determined.

Results: The study shows dependable rainfall at a 75% probability level commences in June. The chance of receiving greater than 10 mm at a 50% probability level starts in week 10 (5 March–11 March), with much discontinuity up to week 21st (21 May–27 May). The dependable weekly rainfall begins the week of 22 May (28th May-3rd June) with a probability of greater than 20 mm. The study revealed that the short rainy season rainfall (February to May) is unreliable for growing crops at Ghinchi as opposed to other highland areas of Ethiopia. The major crop growing season is therefore confined to periods of the long rainy season (weeks 22nd to 39th, or 28th May-30th September). The water balance for the study area indicates that the moisture availability index is greater than 0.5, and potential evapotranspiration is lower than precipitation during these months.

Conclusions: Rainfall variability could create a problem on crop production in the rain-fed agricultural production system in the highlands of Ethiopia. Physical properties of the soil coupled with the unfavorable soil-rainfall relationship limit increased crop production on Vertisols. Improving the drainage system and capturing rainfall variability in agronomic-relevant terms is essential. Improving the physical limitations of the soil, adapting to rainfall variability, and practicing improved agronomic practices may help farmers to overcome the production problem. This study provides critical information on rainfall variability for Vertisol management and crop production. However, to overcome the problem, technological support is needed from researchers and policymakers.

***Keywords*:** Probability, Markov chain model, threshold, Vertisol

2.1 Introduction

Ethiopia is endowed with substantial water resources (Melesse et al., 2013). However, the agricultural sector is entirely rainfall-dependent, and smallholder farmers plow their land under climate change and rainfall variability using traditional technologies of low input and low output agricultural production practices (Baye, 2017; Menale et al., 2011; Segele & Lamb, 2005). Farmers’ weak socioeconomic status, limited access to agricultural technologies, and limited options for diversifying crop production constrained the use of the country’s water resources (Yigezu Wendimu, 2021). Therefore, the traditional rain-fed agricultural production system is subsistence-oriented, and smallholder farmers suffer from food shortages due to rainfall variability and recurrent droughts (Lewis, 2017; Awulachew & Ayana, 2011). Land degradation, soil and water erosion, and soil fertility depletion are widespread on the Vertisols of the Ethiopian highlands, causing nutrient losses and reducing soil productivity (Elias et al., 2022; Kharchenko, 2011; Dubale, 2001; Tekalign Mamo, 1988).

Ethiopian agriculture is susceptible to frequent draughts, usually related to the deficiency in total annual and seasonal rainfall amounts, affecting farmers' livelihoods (Mera, 2018). Climate change, rainfall variability, and soil determine the food security situation of a given area. From the perspective of rainfall variability, agricultural crop production depends on soil moisture availability, rainfall amount, onset, cessation, and length of the growing period. Rainfall variability impacts the soil's water availability to crops, causing reduced crop production. In particular, annual and seasonal rainfall information is important to overcome the social and economic problems for farmers who entirely depend on rainfall. Farmers usually rely on prior knowledge of weather conditions when planning farm activities. However, in a changing climate, it may be difficult for them to capture the variability of rainfall and accordingly plan agricultural management practices. A research-supported study of climate change and rainfall variability may help traditional farmers plan agricultural crop management options and develop adaptation and mitigation mechanisms. The sustainability of any agricultural production system depends on prior knowledge of climate change, rainfall variability, and soil properties (Pulwarty et al., 2007). The function of soil and proper ecosystem services determine the optimal relationship between soil and water, minerals, organic matter, and organisms. Excessive precipitation increases soil moisture and thereby enhances waterlogging, surface runoff, and erosion (Tian et al., 2021; Sehler et al., 2019; Pimentel et al., 2007), while less rainfall in a dry environment leads to reduced organic matter and nutrient availability (Jeong et al., 2018; Dairaku et al., 2004).

Changes in precipitation affect vegetation, which has an impact on the soil organic matter cycle and changes in soil properties (Bansal et al., 2014).

Vertisols are one of the major soil types covering a large portion of the Ethiopian highlands (Elias et al., 2022; Srivastava et al., 1989) and suffering from excess or shortage of rainfall, which makes land preparation difficult for sowing and for the implementation of agronomic practices (Manik et al., 2019; Tekalign et al., 1993; Tekalign Mamo, 1988). These soils are moderately fertile, but rainfall variability, their physical characteristics, and unsustainable land management practices limit the ability to exploit the full potential and produce sufficient food. The dominant clay minerals exhibit distinct characteristics of swelling and shrinking properties with changes in soil moisture. During wet conditions, the soil becomes sticky and plastic, and in dry conditions, it becomes hard, and wide cracks develop down through the soil profile, restricting the use of traditional farm implements to plow and prepare the land for sowing crops. The soils have a narrow moisture range between drought stress and excess moisture (Elias, 2019; Tekalign et al., 1993). When rainfall is heavy, waterlogging creates unfavorable soil and water relationships, restricting the use of traditional farm implements. Vertisols are usually regarded as problematic soils that severely restrict cultivation due to climate change and soil physical characteristics that need attention for sustainable crop production (Patil et al., 2016; Erkossa et al., 2004).

Crop production on Vertisols at Ghinchi is predominantly rain-fed. The major crops grown are wheat and teff, which have different responses to waterlogging conditions. Wheat is sensitive to waterlogging conditions, while teff can better tolerate waterlogging. As a result, the decision to plant either of the two crops in kiremt is based on indigenous knowledge and the farmer's previous experience with local farming practices in relation to seasonal rainfall scarcity, adequacy, or excess. The net potential effect of rainfall is always based on its patterns, which dictate surplus or deficit crop production, leading to food self-sufficiency or food insecurity, respectively. The Vertisol farmers of the study area usually grow crops on residual moisture just after the withdrawal of the main rainy season in September to avoid waterlogging. This practice allows the soil to be bare without any crop cover and makes the soil vulnerable to soil and water erosion. The crops planted on residual moisture sometimes suffer from thermal drought and dry spells.

The study area's agro-climatic characteristics must be understood in order to achieve food self-sufficiency and reduce climatic risk. For rain-fed dependent agriculture like Ethiopia, knowledge of rainfall features in agronomic terms is essential. It is not always possible to determine which agricultural technologies are profitable to develop and which farming methods are sustainable in the face of climate change. In the past, research was frequently focused on finding solutions to technical issues; today, it also aims to establish research objectives and the best technologies to meet the needs of the farming community today and in the future related to climate change. These top goals include studying the likelihood of rain, forecasting, and adapting the results to the needs of farmers. Climate variability and its interconnections have a greater and greater impact on agricultural production. Rainfall variability may affect farmers and the environment in many ways, most importantly by reducing crop production and aggravating poverty. Understanding how climate change and rainfall variability impact agricultural productivity and food security may encourage farmers to implement local adaptations and reduce their susceptibility. Given that climate change is unavoidable and intensifying, farmers need assistance from weather forecasting and prediction. Farmers that have a pressing need for food can adapt to local conditions and reduce weather anomalies. Farmers may find it easier to adjust to local conditions and cultivate acceptable crops if the interpretation and forecasting of weather aspects are strengthened in terms of their agronomic significance.

Therefore, crop production (onset, withdrawal, duration, seasonal totals, and dry and wet spells) provides a better understanding of rainfall variability (Manik et al., 2019), which is a crucial criterion for strategic agricultural development planning (Journal et al., 2009; Virmani et al., 1982). For this purpose, the long-term rainfall data of the Ghinchi area was interpreted using the Markov chain model (Appendix A). Therefore, the objectives of this study were (i) to examine the pattern of rainfall distribution, (ii) to estimate expected rainfall amounts at various probability levels, (iii) to determine the start and end of the crop-growing period using a Markov chain model of the first order, and (iv) to interpret climatic data for agricultural planning and operations as well as the timing of cultural practices involving Ghinchi Vertisol.

2.2 Methodology

2.2.1 Description of the study area

Rainfall (R) data for 39 years (1982–2020) was collected from the First Class Weather Station at Ghinchi Agricultural Research Sub-Centre and the National Meteorological Agency at Addis Ababa, Ethiopia. Ginchi is located 75 km west of Addis Ababa, in the Oromia region of Ethiopia, with geographical coordinates of 09^0 00’03" N, 38^0 00’30" E, and an elevation of 2200 m a.s.l. (Figure 2.1). The study area has flat to undulating topography and is dominated by dark black, high clay soils (Vertisols).

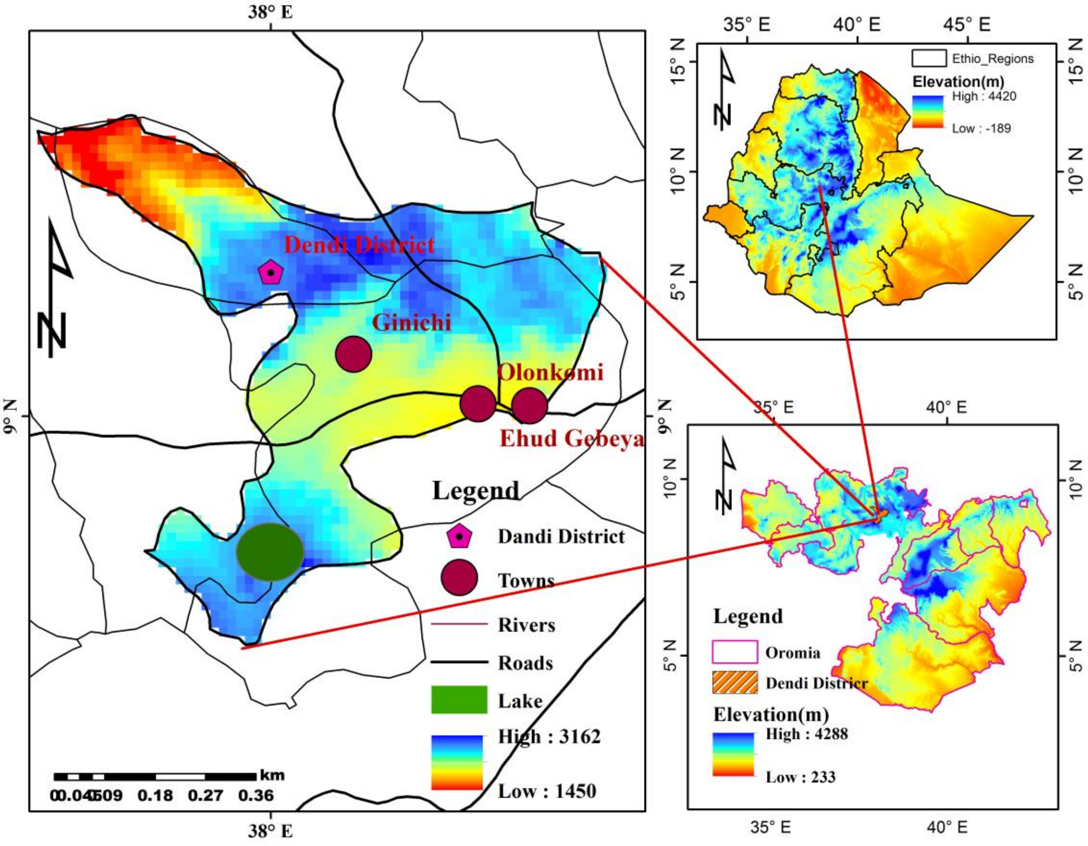

Figure 2. 1 Geographical location and study area map of Ginchi

In Ethiopia, according to the traditional classification, seasons are divided into three based on rainfall amount and distribution. The seasons are known locally as *Kiremt*, which represents the long or primary rainy season, which runs from June to September, and *Belg*, which represents the short or minor rainy season, which runs from February to May. October through January is the driest season and is named *Bega* (Diro et al., 2011).

2.2.2 Data management and methods used

The Ghinchi agricultural research sub-center's first-class meteorological station and the Ethiopian national meteorological agency provided the daily rainfall data from 1982 to 2020. The mean, standard deviation, and coefficient of variation of annual, seasonal, monthly, and weekly rainfall were computed using the data received. A five-year moving average analysis was used to estimate annual rainfall trends. Using historical rainfall data, the first-order Markov chain model, the initial and conditional probabilities, and the incomplete gamma model were utilized to assess the likelihood and expected amounts of rainfall (Liu et al., 2009; Mugalavai et al., 2008; Jail et al., 2005; Ochola & Kerkides, 2003).

Several researchers have used the incomplete gamma distribution technique to compute the monthly rainfall amount at 10, 25, 50, 75, and 90% probability levels using long-term daily rainfall data gathered using standard meteorological weeks (SMW). The SMWs are widely used in agroclimatological studies (Sabarish et al., 2017; Goyal et al., 2015; Mandal et al., 2015; Mohita Anand & Jai Bhagwan, 2010). In a year, 52 weeks are assigned, and in leap years, the 52nd week will have 8 days. The Markov Chain Probability Model (Appendix A) was used for weekly rainfall of > 10, > 20, > 30, > 40, and > 50 mm based on the quantity of precipitation received in each week. The model can estimate the likelihood of future rainfall probability and variability at tolerable threshold levels. The conditional probability level study focused on a rainy week after a wet week, a wet week following a dry week, and the beginning probability of rain this week being wet (Table 2; Appendix C). A threshold level of between 10 and 20 mm f rain in a week was chosen for agricultural management activities. The anticipated rainfall amounts were calculated using incomplete gamma distributions using different probability levels (Jale et al., 2019; Virmani et al., 1982).

The monthly probabilities at 10, 25, 50, 75, and 90% confidence levels were calculated using an incomplete Gamma distribution. Reliable rainfall is defined as the quantity of precipitation received with a probability of 75% for a Gamma distribution by Hargreaves (1975). The 50% and 75% likelihood levels serve as the threshold values to indicate rainfall during the growing season. The 75% likelihood level is normally used to establish the start and end of the growing season’s rainfall. PET is the loss of water by transpiring plants and evaporating water from the earth that is influenced by temperature, humidity, sunlight, and the wind.

The end of the growing season was determined by rainfall below 10 mm at a 50 % probability level (Gramow and Henery, 1972). A value of R/PET >0.75 was also chosen because it represents an optimum range of plant growth. The start of sowing rains is considered to be the week that comes just before the start of the available effective rainy period. Generally, this is the amount of rain needed to moist the topsoil layer and allow seed germination. It is specified by R/PET >0.50, in addition to a continuous humid period later. The length of the growing season was then estimated using the calculated start and end dates. The other climatic factors were omitted from the analyses because they are frequently tropical, consistent, and predictable.

As Zotarelli et al. (2014) described, Penman’s model was used to estimate the weekly and monthly PET values. The ratio of assured rainfall at 50 and 75% probability levels to PET on a monthly and weekly basis is known as the moisture availability index (MAI), and an MAI of greater than 0.5 was deemed adequate for growing crops (Hargreaves 1975). Based on the determined start and withdrawal of rainfall dates, the length of the growing season was then estimated. If there is a greater than 50% chance of obtaining 20 mm of precipitation per week and the following week is rainy or wet, the growing season begins (Reddy, 1983). Therefore, planting would be possible in the first week following February if there was a 50% chance of receiving at least 20 mm of rain in back-to-back days without a 10-day dry period (Journal et al., 2009; Abeyasekera et al., 1983).

2.3 Result and discussion

2.3.1 Annual rainfall statistics

The recent trend in climate change and rainfall variability affects crop production in developing nations like Ethiopia, where rain-fed agriculture dominates the farming system (Alemayehu et al., 2020a; Alemayehu et al., 2020b; Dereje Ayalew, 2012). In particular, the sub-African region is greatly affected by climate change due to various socio-economic situations and a lack of low adaptation and mitigation capacity (Kotir, 2011). Ethiopia has a wide range of agroecologies, from higher (>4550 m.a.s.l.) to 125 m below sea level. Rainfall and temperature vary greatly depending on altitude and topography (Reda et al., 2015).

The annual, the long-term mean, and the five-year moving average rainfall are shown in Figure 2.2. The mean annual rainfall of Ghinchi was 1099 mm. The yearly rainfall varied from 813 mm in 2002 to 1456 mm in 1988, showing high variability between the years. The mean annual rainfall for the 39 years was 1099.6 mm. The total annual rainfall observed over the 39 years showed that 16 years (41.7%) had more rainfall than the long term mean; while 23 years (58.3%) recorded more rain than the annual average. The long-term annual rainfall has decreased in amount since 2000. In effect, for the 39 years (1982–2020), the total average rainfall amount is declining yearly by an average of 351 and 267.2 mm for the long and short rainy seasons, respectively. The Magnitude of the rainfall in the study area decline at the rate of -4.51 mm/year. Negative anomalies were common in two to three years. Since 2000, the annual total rainfall has been far lower than the long-term mean. The rainfall in 1985 and 1986 was significantly below the long-term mean and was the drought year in Ethiopian history (Mera, 2018) . The coefficient of variation and annual standard deviation was 78.3 and 85.3%, respectively. The results of the coefficient of variations depicted in Table 2 show the dry and the short rainy season rainfall are more variable than the kiremt season rainfall. The study agrees with past studies conducted elsewhere in Ethiopia (Alemayehu et al., 2020b; Seleshi & Zanke, 2004). Mekasha et al., (2014) also concluded that rainfall variability and inconsistency are prevalent over the Ethiopian highlands.

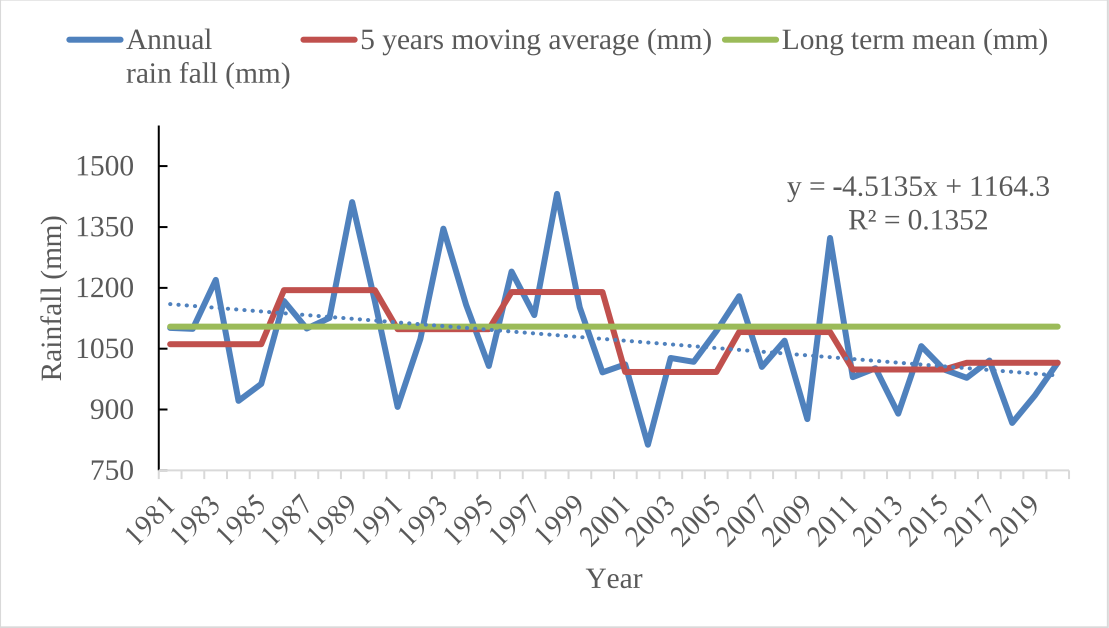

Figure 2. 2 Annual, long-term mean, and five-year moving average rainfall

The five-years moving average shows that six of the eight years had rainfall below the long-term average (75%). Only two of the five-years moving averages rainfall had above the long-term mean. In particular, since 2000, the continuous decline in yearly rainfall below the long-term average indicates the need to find alternative management options and farming strategies considering rainfall variability and soil conditions.

2.3.2 Seasonal rainfall variability

The rainfall of Ghinchi is characterized by a bio-modal rainfall pattern of two rainy seasons, namely the long and short rainy seasons, and a dry season. The long rainy season, known locally as *Kiremt* (July to September), accounts for approximately 699.9 mm (64%) of the annual rainfall, while the short rainy season (February to May), known locally as *Belg*, accounts for approximately 28% of the annual rainfall. The dry season, known locally as *Bega* (October to January), provides 90.8 mm of rainfall, or 8% of the annual total (Figure 2 3). The bega rainfall has no agronomic importance, as it is not adequate for crop production during this time. Except for the bega season, the long-term seasonal rainfall showed an upward tendency throughout the 39-year period. The rainfall exhibits a slightly decreasing tendency during the *Belg* (little rainy) season and a negative trend during the bega season. The yearly rainfall pattern shows dry and wet years, altering one after the other.

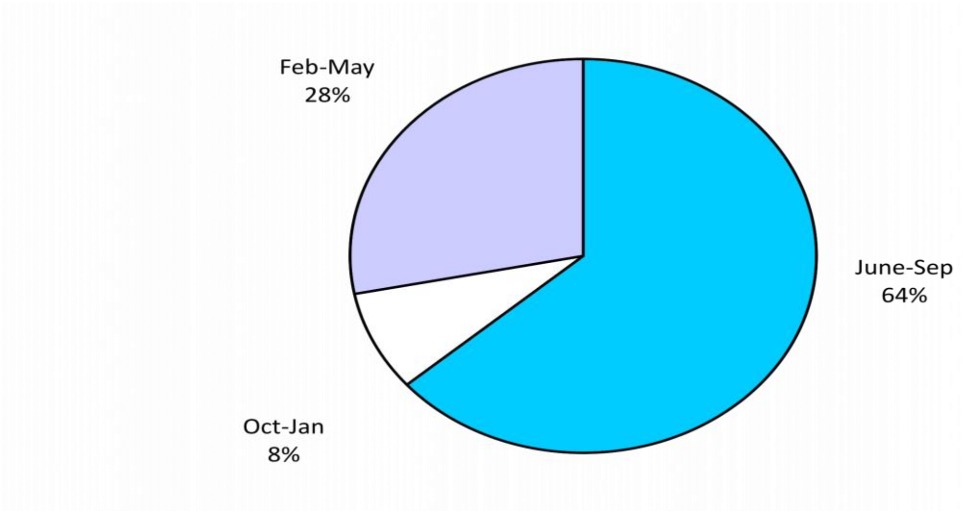

Figure 2.3 Long-term mean seasonal rainfall for the three seasons at Ginchi

The amount and distribution of seasonal rainfall are more crucial for rain-fed agriculture than the annual amount. The length of the growing season for crop production depends on the timely onset and cessation of rain in a particular area (Robinson et al., 2013). As a result, decisions regarding crop production depend on the seasonal variation in rainfall amount and distribution, which supplies the soil with the water required for plant growth. Reduced yields could result from the seasonal rain's unpredictability, start, and cessation (Torres et al., 2019). Thus, to plan and make decisions in rain-fed farming systems, it is crucial to understand the features of seasonal rainfall concerning the growing season (Guido et al., 2020).

The rainfall pattern, amount, and distribution of the rainfall greatly vary between the three seasons. Farmers in the Ghinchi area expect rainfall during the long rainy season starting in June. Sometimes, rainfall comes early or late, making traditional farming difficult (Society, 2016). Vertisol sowing always needs precautions. As soon as the rain starts and the soil gets friable, planting is normally done on Vertisols. Once the soil is saturated, the land becomes sticky and plastic; when dry, Vertisol forms hard clods, making farm operations difficult (Society, 2016). Sometimes, in years of above-average rainfall in the short rainy season, the long rainy season tends to be lower, and vice versa. Obtaining the optimal soil moisture range becomes difficult as the climate and rainfall variability change.

The rainfall pattern, amount, and distribution greatly vary between the three seasons. Farmers in the Ghinchi area expect rainfall during the long rainy season starting in June. Delay in onset or early withdrawal has a profound effect, making traditional farming difficult (Society, 2016). Vertisol farming is sensitive to excess or shortage of rainfall because, in both extremes, planting would be impossible. The area's short rainy season rainfall is variable and unreliable across years and seasons. Crop production during the short rainy season is constrained by inadequacy or a limited duration of rain. High and erratic rain during the long rainy season brings waterlogging to the farmlands. To overcome the waterlogging problem, farmers have traditional ways of draining the excess water from their farmlands. These practices include ridge and furrow, opening drainage furrows at different spacing along slopes, and sowing crops on residual moisture after the cessation of the long rainy season in September. Sowing crops on residual moisture results in crop failure due to dry spells in December or November. If the land is fallow during the long rainy season, it is exposed to erosion, causing land degradation and soil fertility depletion.

Traditional farming practices cannot fully drain the water from the farmlands. Therefore, the research has developed the broad bed and furrow maker (BBM), an implement that constructs the broad bed and furrow (BBF) capable of draining the excess water from the farmland. The BBM is a curved metal sheet attached to two unmodified traditional plows, usually oxen-drawn. Metal wings scoop the soil towards the center between the two plows (Astatke, Jabbar, et al., 2002). The BBM builds raised beds 80 cm wide and alternates them with furrows 40 cm wide and 15 cm deep. The implement needs friable soil to make the necessary bed and drainage furrows. Crop production losses are inevitable if an intense and heavy shower comes at the onset of rain because of the soil puddles, and it becomes difficult for local oxen to pull the soil and make the bed. Continuous rainfall for a longer period prohibits the use of farm implements on Vertisols. As a result, most farmers leave their farmland fallow during the rainy season and sow pulse crops on residual moisture after September.

2.3.3 Monthly rainfall statistics and seasonal variability

Monthly rainfall variability is very high for Ginichi. The long-term mean monthly rainfall ranged from the lowest of 9.9 mm in December to the highest of 242.1 mm in August. The long rainy season months have high amounts of rain, with the highest rainfall amounts received in July and August. The monthly rainfall’s standard deviation ranged from 16.3 to 67.4, the lowest for the dry seasons. The coefficient of variation (CV) was between 21.5 and 206.7%, the highest being for the drier months. The coefficient of variation (CV) shows how the individual data points vary about the mean value. A higher CV indicates higher temporal variability, and vice versa. The long rainy season’s rainfall has a lower coefficient of variance. The monthly average standard deviation and CV were 78.3 and 85.3%, respectively. The lowest standard deviation was observed for the dry season, while an almost similar standard deviation was observed for the long and short rainy seasons. The highest coefficient of variation was observed for the short rainy and dry periods, while the long rainy seasons had a lower coefficient of variation (Table 2 1). Statistical parameters for monthly rainfall analysis for Ghinchi (database 1981-2020). This study confirmed that the result is in agreement with the findings of previous studies conducted in the highlands of Ethiopia (Dereje Ayalew, 2012; Asfaw et al., 2018). Variability in seasonal and interannual rainfall affects the livelihood of rainfall-dependent smallholder farmers (Adamseged et al., 2019).

Table 2.1 Summary of monthly rainfall statistics (data base 1981-2020)

Months	Mean rainfall (mm)	Standard deviation	CV (%)	Maximum rainfall l(mm)	Minimum rainfall (mm)	Range (mm)
Jan	24.3	24.4	120.2	98.9	0.0	98.9
Feb	41.8	41.7	113.4	194.9	0.0	194.9
Mar	76.5	67.4	91.8	188.5	0.0	188.5
Apr	94.9	50.4	56.7	240.5	12.3	228.2
May	95.7	49.8	55.5	179.7	4.7	175.3
Jun	157.2	46.1	31.3	253.2	62.2	191.2
Jul	173.9	50.4	21.5	403.3	158.8	244.5
Aug	242.1	49.1	21.9	330.1	149.9	180.2
Sep	126.7	44.1	33.2	208.1	48.0	160.1
Oct	37.1	37.7	104.8	157.6	0.5	157.1
Nov	19.5	21.9	162.2	83.6	0.0	83.6
Dec	9.9	16.3	206.7	68.3	0.0	68.3
Annual	1099.6	78.3	85.3	2406.6	436.4	1970.2

2.3.3.1 Monthly rainfall and PET relationships

The study area's long-term rainfall and PET data of 2000–2020 were summed up to find the mean annual rainfall and PET, as illustrated in Figure 2 4. According to the data, nearly eight months of the year had higher PET than rainfall. These months are divided into the short rainy season and the dry season (October-May). Higher PET values create a negative water balance, resulting in soil dryness and necessitating irrigation for crop production (Cui & Zornberg, 2008). During the short rainy season, in some highlands, the rainfall is inadequate to grow short- and long-duration crops. However, particularly in the Ghinchi area, rainfall in the rainy season is insufficient to plant crops. The short rainy season rain is important for farmers to prepare their land before the long rainy season rain commences.

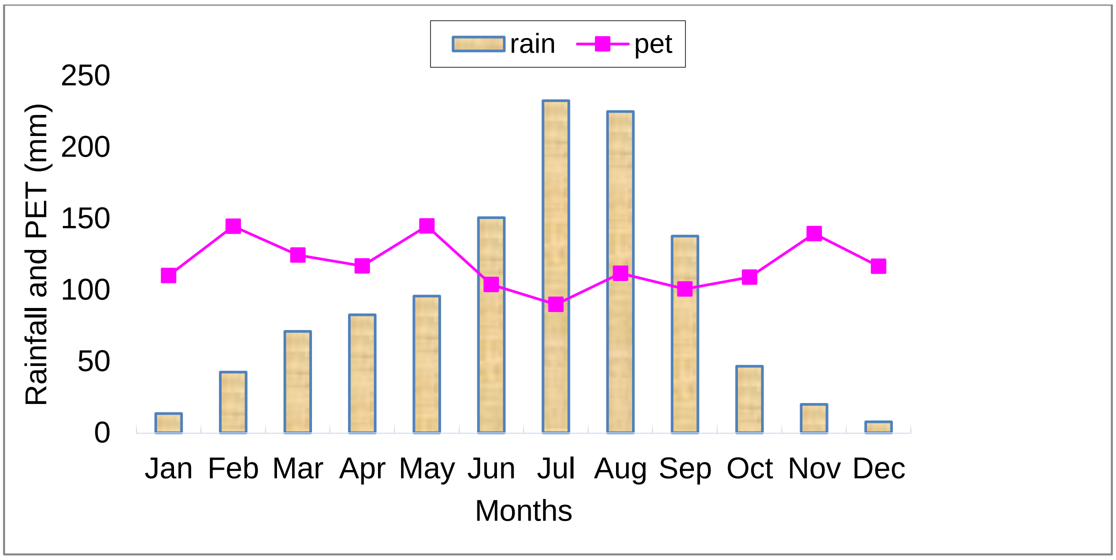

Figure 2. 4 Monthly rainfall and PET for Ghinchi (database 1981-2020)

The long rainy season (July–September) has rainfall above the PET; therefore, the water requirement of crops can be met. During this period, excess soil moisture may be expected, causing waterlogging, flooding, and soil and water erosion.

2.3.4 Weekly rainfall and PET relationships

Weekly and monthly rainfall data were used to evaluate the 39-year rainfall trend. The first standard week for this study is January 1 to January 7. Every standard week following this consists of 7 days, ending on December 30. The mean weekly rainfall for the last 39 years was 82.3 mm. Thirty-one weeks (60%) had rainfall below the weekly average of 82.3 mm, while the remaining twenty-one weeks (41%) had rainfall above the mean. The maximum mean weekly rainfall of less than 20 mm per week was observed for weeks 2, 3, 4, 8, and the weeks from the 43rd to the 52nd (Figure 5). These weeks are confined to the dry seasons. The rainfall that commences during the dry season may cause problems with crops that are ready to be harvested or threshed because these activities are done during the dry season immediately after the withdrawal of the long rains. On the other hand, the October rainfall may have positive and negative effects. Crops that grow on residual moisture favor the dry season rain, while crops planted during the long rainy season are ready to be harvested or threshed and cause discomfort. This shows the complexity of the farming system on Vertisols. During the long rainy season, rainfall above 100 mm is expected in a week, with the highest being 231.7 mm in August. The weekly standard deviation was 69, and the average CV of the rainy season was above 100%. A lower CV was recorded for weekly rainfall during the short rainy and dry seasons (Figure 2 5). The high CV of the long rainy season is explained by the high variability of rainfall between years.

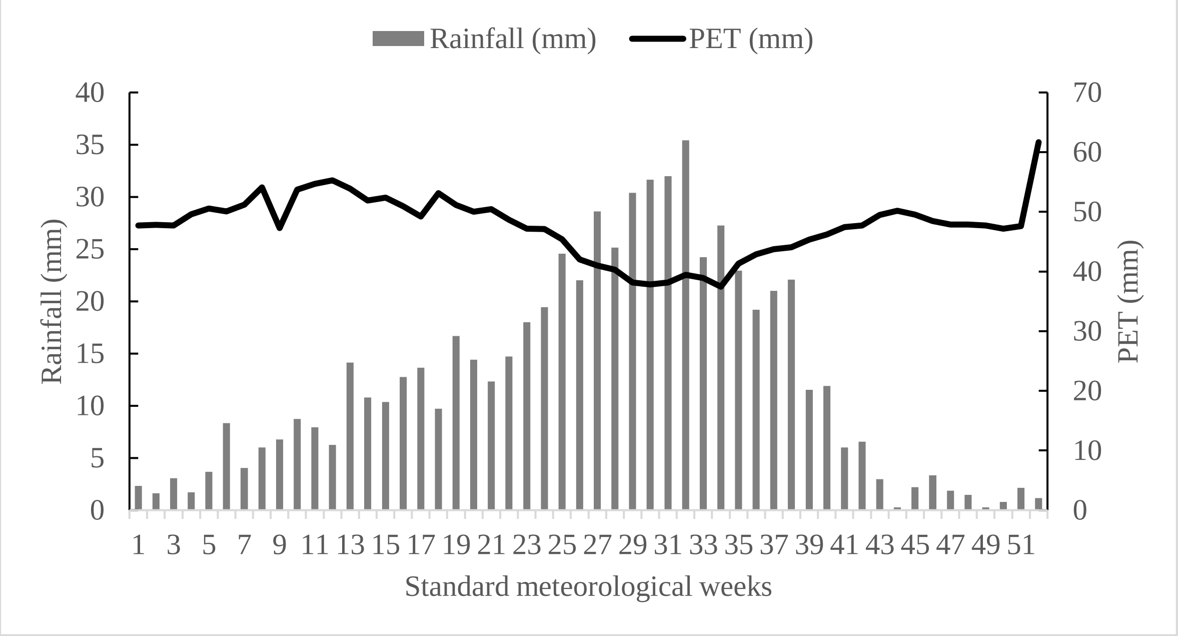

Figure 2.5 Expected weekly rainfall distribution and PET for Ghinchi (database 1981-2020)

A trend in weekly rainfall distribution and PET is shown in Figure 5. Weekly rainfall was higher than the PET during the weeks from 22nd (28 May-03 June) to 39th (24 September-30 September. The maximum weekly rainfall was recorded during the 22nd to 38th (May 28 to September 23) weeks, with an average of 163.8 mm (68%). The weeks belong to the long rainy season and crop planting period. Overall, the mean weekly rainfall for the dry period was 16.8 mm (6%), while in the short rainy season, it was 61.5 mm (24%). The mean weekly rainfall distribution during the three seasons shows that the dry and short rainy periods' rainfall was below PET, while the long rainy season had rainfall higher than PET. Four months of water surplus (June–September) and eight months of water deficit (October–May) were identified. The management of water resources, rain-fed agriculture, food security, and the fight against poverty are all seriously threatened by the spatial and temporal variability in rainfall amount and evapotranspiration brought on by global climate change, particularly in developing nations. Among many other aspects of the water balance, evapotranspiration is taken into account when determining water surplus and deficit. These two factors are consequently necessary for crop growth. The weekly rainfall data showed that the water deficit in the study area is roughly eight months, as indicated by the PET values being higher than the rainfall (Figure 5). The consequence is that food security will be challenged (Ashaolu & Iroye, 2018)

2.3.5 Monthly and weekly rainfall amounts at a given probability level

The monthly minimum rainfall quantities expected at five probability levels (10, 25, 50, 75, and 90%) are shown in Table 2 2. The data shows that, at a 75% probability level, rainfall of more than 20 mm during the short rains can be expected in March and extends up to May but never exceeds 38 mm. During the short rainy season, the rainfall is far from the 50% value, which explains the high variability influenced by a few high values. The short rainy season rainfall is not sufficient to grow crops but is adequate for pre-sowing land preparation and other agricultural activities before the onset of the long rainy season. In June, a sharp increase in rainfall amount is expected (116 mm), which is an increase of 88 mm more rainfall than in May (42.3%). The probability of the monthly gamma distribution at a 75% probability level ranged between 107 and 201 mm, with the highest value in July (201 mm). The mean difference and 50% values in the long rainy season are similar, and the data represents a normal distribution. The abrupt increase during this period causes waterlogging on the soil, making planting difficult. Therefore, the soil requires drainage improvement.

Table 2.2 Monthly Incomplete Gamma distribution at different probability levels

	Precipitation (mm) for the probabilities				
Month	90	75	50	25	10
Jan	1	3	9	20	35
Feb	2	8	25	60	110
Mar	16	12	59	99	147
Apr	18	36	67	114	171
May	18	38	75	133	204
Jun	84	116	151	187	219
Jul	171	201	233	266	296
Aug	152	187	225	264	299
Sep	86	107	134	165	197
Oct	5	14	33	66	110
Nov	0	2	10	28	56
Dec	0	1	5	12	22

A comparison of the long-term mean monthly rainfall and the monthly expected rainfall amount at five probability levels shows different values (Tables 1 and 2). Rainfall with a 75% probability is more reliable (Hargreaves H.G. 1975) for agricultural crop management planning than the monthly mean rainfall amount. Dependable rainfall has lower values and is less skewed compared to the annual average.

2.3.6 Weekly rainfall and initial and conditional probabilities

The Markov Chain Probability Model has been extensively used in agriculture to determine dry and wet spells, the onset and cessation of rainfall events, and to develop agricultural management operations. The Markov chain model was used to compute the long-term (39) year rainfall data using the initial probability level of receiving a certain amount of rainfall during a given week, i.e., [P(W)], the conditional probability level that predicts the likelihood of rain next week if we had rain this week [P(W/W)], and the likelihood of rain next week if this week is dry [P(W/D)]. The weekly precipitation was examined for probabilities by receiving a specific amount of rainfall, such as 10, 20, 30, 40, and 50 mm. The probabilities of receiving a specific amount of precipitation in a week (Table 2 3) can be used as a threshold level for various crops, cultivars, or soil types with various water-holding capacities. This information helps determine what crops should be grown and what agricultural practices would be employed.

Therefore, dependable rainfall at a 75% probability level on a weekly basis is more important (Hargreaves 1975; Stern et al., 1982), and careful consideration of the target environment and crop selection should be prioritized. For most field crops, at least >20 mm of rainfall at a 75% probability level in a week could serve as a reasonable threshold. In this study, consecutive weeks with assured rainfall exceeding 20 mm occurred between the 22nd and 38th weeks. Hence, planting crops can be done during this period without the risk of a moisture deficit. The optimum period for planting crops for Ghinchi is around mid- to late-June. The temperature, humidity, and rainfall for June and July are conducive to rapid growth. Nevertheless, the period covering late July through August experiences a high intensity of rainfall, more cloud cover, and more saturated soil, which aggravates the problem of waterlogging. When rainfall is in excess, improved drainage systems and water harvesting structures are recommended to supplement crops grown on residual moisture with irrigation water if a dry spell may occurs.

The W/W probability indicates continuity in rainfall and suggests those weeks are favorable for crop production. At a 50% probability level, the chances of receiving more than 10 mm in a week begin around week 10, although they are inconsistent until week 21st, while increasing the threshold limits the probabilities closer to the true value. Effective rainfall of more than 20 mm/week, at a 50% probability level, starts on the 22nd week and extends to week 38 (16–22

September). At the 50-mm/week threshold limit, they are confined to weeks 29–32 (15–21 July to 5–11 August) only, indicating that there are high chances of heavy rains and a risk of soil erosion in these weeks, as well as waterlogging. In dry periods between October and January (weeks 40–52 and 1-4), the probability of getting at least 10 mm/week decreases, and the variability is very high. Particularly, weeks 45 and 46 had some rain at the 10-mm threshold level, which may indicate the harvest and threshing of crops. Considering 20 mm or more of rain in a week without discontinuity at a 50% probability level is sufficient for tillage and planting crops (Reddy, 1983; Virmani et al., 1982). The period corresponds to weeks 22nd to 37th (June to mid-September), which indicates the length of the growing period.

Table 2.3 Initial and conditional probability (%) rainfall at Ghinchi (database 1981-2020)

SMW	>10 mm			>20 mm			>30 mm			>40 mm			>50 mm			mean
	w	w/w	w/d	w	w/w	w/d	w	w/w	w/d	w	w/w	w/d	w	w/w	w/d	
22	75	73	67	55	82	56	45	56	45	20	50	25	15	67	24	26.1
23	70	100	0	70	71	67	50	70	20	30	50	21	30	50	21	29.2
24	90	100	0	70	86	100	45	67	64	30	50	43	30	33	21	36.9
25	100	100	0	90	83	100	65	85	43	45	56	45	25	40	33	39.1
26	100	100	0	85	76	100	70	79	50	50	70	60	35	71	38	41.4
27	100	100	0	80	88	75	70	71	83	65	38	71	50	30	30	53.2
28	100	100	0	85	94	100	75	93	100	50	70	90	30	67	57	43.1
29	100	100	0	95	95	100	95	95	100	80	63	100	60	50	75	54.1
30	100	100	0	95	95	100	95	89	100	70	71	50	60	58	50	58.6
31	100	100	0	95	100	100	90	94	100	65	77	57	55	82	44	53.8
32	100	95	0	100	95	0	95	79	0	70	57	33	65	46	29	62.4
33	95	100	100	95	95	100	75	73	100	50	70	60	40	63	42	46.7
34	100	100	0	95	79	0	80	63	50	65	54	43	50	50	20	49.7
35	100	95	0	75	87	80	60	42	63	50	30	20	35	0	23	40.6
36	95	89	100	85	71	67	50	60	50	25	20	40	15	0	12	34.2
37	90	89	100	70	64	67	55	45	44	35	29	31	10	50	28	33.5
38	90	61	100	65	46	43	45	33	27	30	17	7	30	0	7	36.8
39	65	62	29	45	44	27	30	33	21	10	0	22	5	0	21	20.6

2.3.7 Dependable rainfall

Rainfall is the most important climatic component since it has a detrimental effect on crop productivity. Cropping patterns in different ecological zones vary depending on rainfall quantity, occurrence, variance, and reliability. In rainfall-dependent developing countries, climate change and variability cause crop failure and food insecurity. Therefore, a rainfall probability study for a specific location becomes essential because agricultural production is highly affected by climate change and rainfall variability (Gitz et al., 2016; Chijioke et al., 2011). Since there is some there is always some variability in space and time, it is important to have a probability estimate using various models. Crop production can be sustained only under good soil conditions and conducive climatic conditions. Proper soil management, harnessing climatic risks, and improved agricultural technologies such as crop selection and irrigation practices have become prerequisites for planning agricultural activities and increasing crop productivity. Rainfall prediction is essential to protect farmers from negative weather anomalies.

2.3.8 Monthly dependable rainfall and MAI

Monthly rainfall has more variability than dependable rainfall and estimates less rainfall for crops, while dependable rainfall (DP gives reasonable estimates in line with global climatic changes. Dependable rainfall with a 75–80% probability of occurrence suffices for crop production (Hargreaves, G. H. 1975). Estimating dependable rainfall through long-term study and analysis of long-term climatic data helps plan the water management for a specific area and crop type. If the probability of occurrence is above or below the threshold levels, agricultural crop management decisions will be made, such as irrigation or draining the excess water. For excessive rainfall, drainage improvement can overcome the problem, while during dry periods, the water requirement of crops will never be met.

The 50 and 75% probability levels are the periods of weeks in which the chances of getting dependable rainfall of more than 20 mm/week are adequate. The months coincide with the farmer’s planting date for the long rainy season. The length of the growing season depends on the onset of the rain; therefore, in this study, the length of the growing season varied between 70 and 133 days for the short and long rainy seasons, respectively. The weeks of the 25th to the 32nd had 100% guaranteed rainfall, with a high risk of erosion and waterlogging. The rainfall parameters, such as onset, withdrawal, amount, cessation of distribution, and the probability of receiving dependable rainfall in a month or week, will depend on the management options and type of crops to be planted. For the Ghinchi area, the amount and distribution of annual rainfall and the growing season’s length are closely related. The dependable rainfall and PET relationship (Figure 2 6) also shows that PET drops below the mean annual rainfall during the long rainy season, while vice-versa during the short and dry seasons of the year.

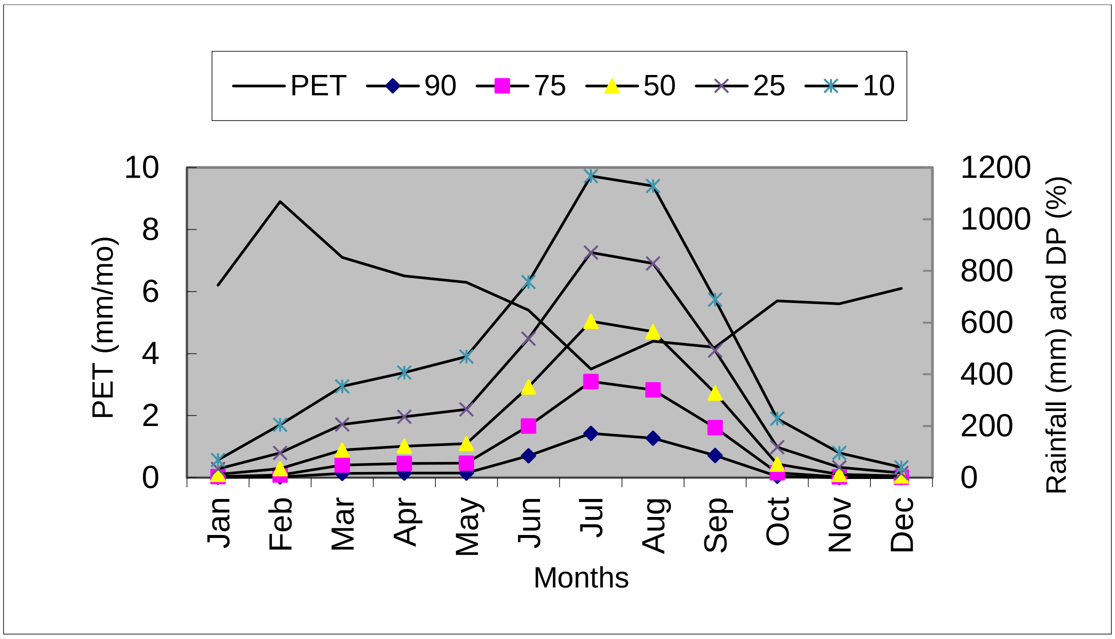

Figure 2. 6 Monthly expected rainfall amounts and PET at 90, 75, 50, 25, and 10% probability levels

The 75% probability level indicates that dependable monthly rainfall begins in June, while at a 50% probability level it begins around May. The monthly PET reveals a positive water balance from June to September. Rainfall throughout the remaining months is below PET; thus, short-duration crops can probably be cultivated with the help of additional irrigation. Considering the 50% probability level, precaution should be taken that the lower the probability level, the higher the threshold values, but dependability matters. The relationship between rainfall, PET, and MAI is shown in Figure 2 7. According to these data, at a 75% probability level, rainfall exceeds PET from July to September, while at a 50% probability level, it covers May and September. The weekly and monthly rainfall probability levels indicate that a moisture availability index (MAI) of more than 0.75 starts in June. Sowing of wet-season crops occurs in June, while pulse crops grow on residual soil moisture after September. The relationship between rainfall and PET shows that PET is lower than rainfall starting from week 22 to week 38. The positive water balance during this period allows long-duration crops to grow because the weekly rainfall is dependable. The MAI is at a 75% probability level, implying that more than 20 mm of rain is likely.

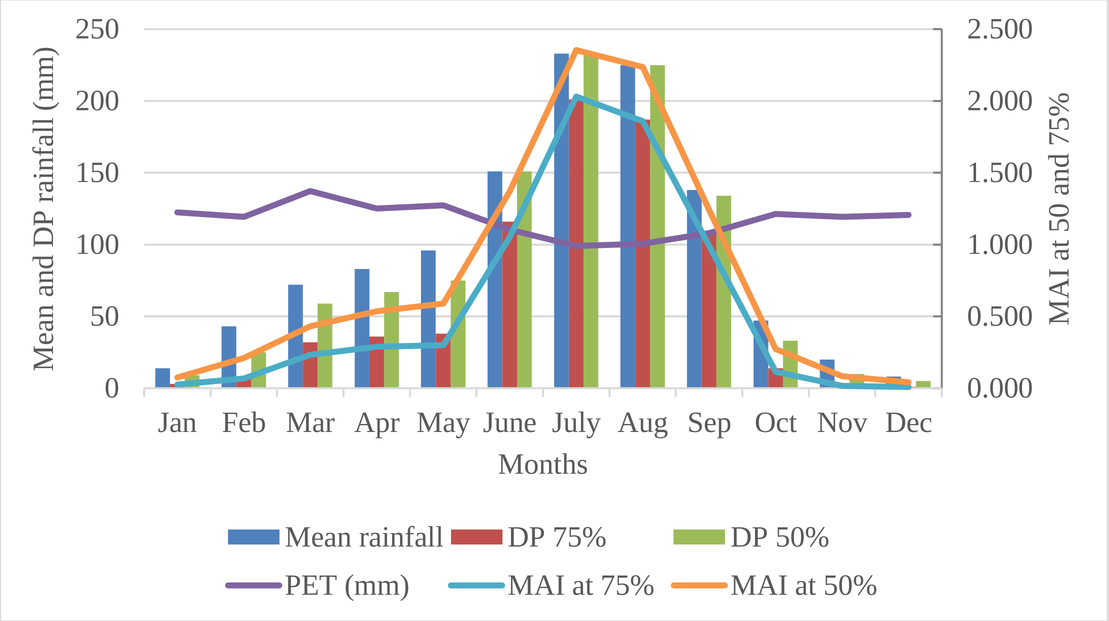

Figure 2. 7 Average monthly and dependable rainfall, PET, and MAI at 50 and 75% probability level

2.3.9 Weekly dependable rainfall and MAI

Understanding the relationship between rainfall and PET, as well as MAI calculated as the 75% dependable rainfall ratio to PET, is critical for agricultural planning and irrigation needs. Figure 2 8 illustrates the weekly average and dependable rainfall at a 75% probability level, including MAI and PE for Ghinichi. Rainfall above PET (R/PET) is expected in this month. Sometimes, due to the intermittent and patchy nature of the rain, it is unpredictable to establish the exact sowing week and cessation of the rainfall. Rainfall above PET (R/PET) is the amount of rain that falls during the four months that are the main crop-growing periods. Sometimes, due to the intermittent and patchy nature of the rain, it is unpredictable from year to year to determine the beginning and cessation of the rain weekly. PET is lower than rainfall, and crop growth requirements can be maintained during these months. A MAI value of 0.33 is the threshold value to demarcate dry and moderately wet periods (Hargreaves et al., 1985). This value is significant at a 75% probability level and even higher at MAI value up to the 38th week. Waterlogging and runoff occur during the rainy season when rainfall exceeds 75% of the annual average.

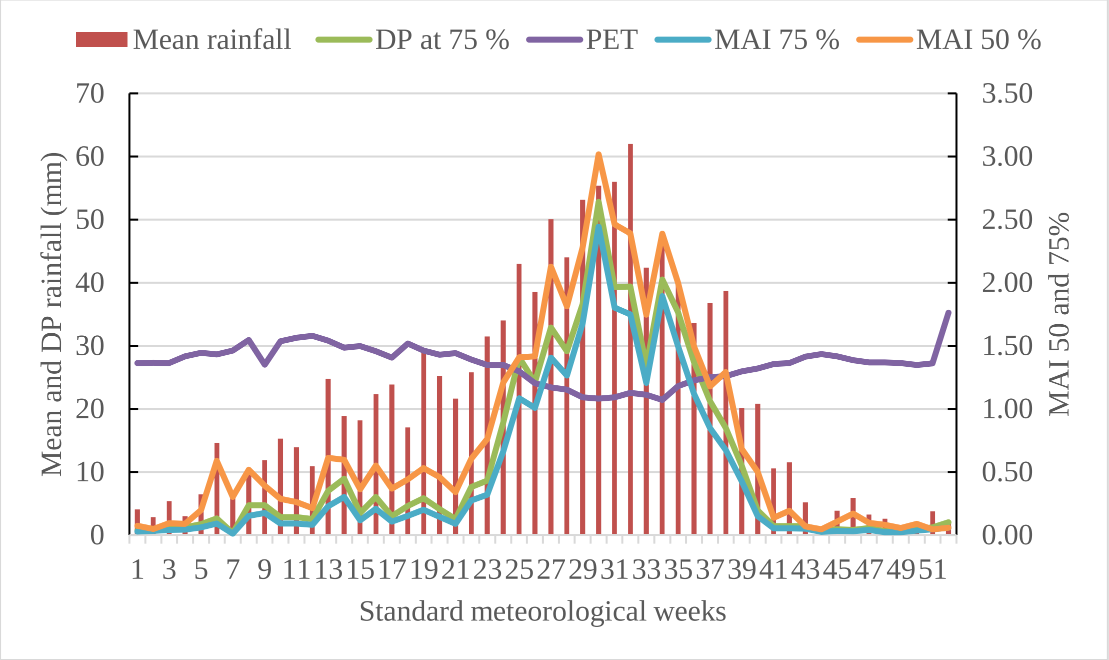

Figure 2. 8 Average weekly dependable rainfall, PET, and MAI at 75% probability level

The MAI of Ghinchi is more than 1.33 from the 21st to the 38th week, indicating no water shortage for agricultural activities during this period. However, the rest of the months are always short of moisture.

2.3.10 The effective rainfall

An effective measure of the water balance is the computed ratio of 75% dependable rainfall and PET, defined as MAI. The long rainy season in Ghinchi begins in June and lasts until September. During these months, approximately 64% of the annual budget is received. A water requirement calculation at 50% probability can be used to check the ranking of the Gamma distribution (Hargreaves et al., 1985). Table 2 compares the mean (50% probability) and dependable (75% probability) assured rainfall for the long rainy season at Ghinchi. The 75% probable rainfall values are less than the mean rainfall and can be used for computations. The ratio of assured rainfall to PET, calculated weekly, gives a better understanding of water availability to plants because a month is a long period (Hargreaves H.G. 1975). Weekly rainfall at a 75% probability level and an MAI greater than 0.5 were considered optimal for plant growth in this study area. The dependable rainfall at a 50 and 75% probability level exceeds PET, starting in weeks 23 and 25 and ending in weeks 38 and 36, respectively, showing a positive water balance. The rest of the weeks had a negative water balance, meaning PET was greater than the dependable weekly rainfall. Thus, on average, for 16 weeks a year, the climatic water balance is positive, while for 35 weeks, the climatic water balance is negative. The mean annual rainfall of the study area is

1099 mm, while the mean annual PET is 1412 mm, indicating that the annual water deficit is 313 mm. According to Hargreaves (1975), the value of MA1 > 0.34 could be considered the lower value for dry land crops. The MA1 values exceed the lower threshold value of 0.34 in all the rainy months of Ghinchi, and the data for the length of the rainy seasons show that there are 133 days in Ghinchi (19th to 38th weeks), which is 280 days. During the 1st to 17th weeks and the 40th to 52nd weeks, MA1 values are below the lower threshold value. The MAI exceeds 0.5 falls from June to September (22nd–40th weeks), which indicates a crop growing period. However, MA1 during the 40th and 41st weeks was low. In some years, the October MAI falls short of the total water requirement for crops grown on residual moisture. MA1 at a 50% probability level falls between the 25th and 35th weeks, which is more than 1.00, indicates excess water, and requires an improved drainage system. The high water availability in this period would be sufficient to meet the moisture requirements of the crops in the latter part of the season. The construction of water harvesting structures that help crops grow to full maturity during dry spells is advantageous in years of unusually low precipitation.

Every month, the ratio of R/PET was below 1.00 from January to May and then dropped below the same threshold value of 1.00 from October to December. From June to September, adequate rainfall was received, whereas July and August received >1.33 signals that the soil is saturated due to excessive rainfall, and draining the excess water from farmland is critical (FAO, 2009; Hargreaves, 1971).

2.3.11 The rainy days

Continued rainfall data is crucial to assessing the probability of dry and wet spells. It can be made possible by examining and summarizing some of the long-term climatic records of a study area. This information for calculating the probability of any specified combination of "wet" and "dry" days may be required to make long-term management decisions. The study confirmed that the amount of rain per rainy day and the number of rainy days increased from June to September and then declined. As evidenced in Table 4, the wet day count in July and August is more than 250 days and starts to decrease from September on. The wet day count above 100 started in March, reached 265 days, and then declined. The dry day count of more than 100 days started in September, reached 300 days in December, and then declined steadily. The lowest dry day counts below 100 days were for June, July, and August.

Dry counts were lower between February and May. The wet day count following a dry day count was higher for the short rainy season, while the values were lower for the main rainy season. The wet/wet day count was higher starting in May and extending up to September. The mean minimum rainfall amount was 0.25 mm for the dry periods. The mean maximum rainfall was 38.9 mm. The highest maximum rainfall recorded was in August, which was 74.9 mm. The other weather parameters shown in Table 2 4 are not clearly different between months.

Table 2.4 Statistics of mean weather elements for the period 1981-2020

Variables	units	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
W	Number	34	62	103	118	125	213	270	265	184	56	19	10
D	Number	276	220	207	182	185	87	40	45	116	254	281	300
W/D	Number	22	30	49	52	42	48	34	36	51	25	10	9
W/W	Number	12	32	54	66	83	165	236	229	133	31	9	1
Rainfall	Min.	0.25	0.25	0.25	0.3	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	Max.	10.2	20.5	57.8	29.4	28.8	39.8	54.6	75.9	48.8	48.7	32.8	19.6
Tmax (^{0}C)	Min.	18.8	18.8	21.2	15	18	18.5	16.1	17.1	18.2	18.3	19.6	21.9
	Max.	29.1	32.1	32.7	34.6	30.5	31.8	25.4	25.7	25.8	26.7	27	26.9
Tmin (^{0}C)	Min.	1.3	1.6	3.1	2.8	3.2	1.9	4.8	3.6	3.5	2.4	1.3	1.9
	Max.	13.4	14.1	15.6	16.2	15.2	13.7	16.9	17.6	14.3	15.3	11.9	12.1
SR (w/m^2)	Min.	23.8	23.5	17.6	2.3	15.3	10.6	1.8	6.1	16	10.2	23.3	23.6
	Max.	25.4	27.2	28.3	28.3	28.1	27.4	27.2	27.9	27.9	27.4	25.7	24.3
Max. RH	Min.	7.8	7.7	11.8	9.3	15.5	13.3	23.2	25.9	21.2	7.9	10.4	7.7
	Max.	55.7	60	62.1	86.7	64.2	70.9	88.3	79	63.6	77.9	56.2	48.5
WS (m/sec)	Min.	3	3	3	3	3	3	3	3	3	3	3	3
	Max.	3	3	3	3	3	3	3	3	3	3	3	3

W-wet days count; D-dry dys count;W/W- wet days count following wet days count; W/D-wet days count following dry day count; R- rainfall; T min-Minimum temperature; T max-maximum temperature; SR-solar radiation; RH-relative humidity; WS-wind speed

2.3.12 Length of the growing period

At Ghinchi, the number of rainy days and the amount of rain per rainy day increased from June to August and then declined. June and August are the most assuredly rainy months, as is evident from the average duration between the rainy days (Table 4). The probability of receiving dependable rainfall of 20 mm is 50% in the 22nd week and extends up to the 38th week. The week coincides with the farmers' planting time during the long rainy season. For the short rainy season, the probability of receiving at least 10 mm of rainfall at a 50% probability starts around week 16, with some discontinuity in the preceding weeks. However, the chance of getting rainfall above 20 mm/week at a 50% probability for a short rainy season coincides with the long rainy season. As the length of the season mainly depends on the starting date, the effective length of the rainy season was found to vary between 120 days at a 90% probability level and 210 days at a 75% probability level (Table 2 5). Therefore, depending on the onset and withdrawal of rainfall, a decision will be made on the type of crop to be grown. However, dependable rainfall at a 75% probability level and a threshold level of greater than 20 mm with a conditional probability of [P(W/W)] are critical when considering the length of the growing period. In this connection, the growing season is about 17 weeks (119 days). The different threshold limits give different values for the growing season, which depend on the type of crop to be grown, the water requirement of crops, and soil suitability.

Table 2. 5 Probability (%) of receiving rainfall at different threshold levels in a week

Rainfall per week (mm)	Probability (50%) and above in a week			Length of the growing season	
	P(W)	P(W/W)	P(W/D)	*Total No. of weeks	No. of days
>10	13-40	21-38	21-38	27	189
>20	22-38	20-37	22-37	17	119
>30	25-37	21-36	26-36	15	105
>40	26-35	22-34	26-33	12	84
>50	29-34	28-34	28-30	7	49

* Length of the growing period based on >20 mm threshold level (PW/W)

Other climatic elements

There is no major difference in weather parameters recorded for the last ten years (Table 4). The maximum and minimum temperature ranges have relatively few variations, with a small standard deviation. The average yearly relative humidity varied between 50 and 84. Approximately 12 and 38 MJ/m2/day of solar radiation per month were measured. This study did not include weather parameters because they are consistent and predictable in all years.

2.3.13 Crop production on Vertisols

A large variety of crops are grown in the area under various agricultural systems, allowing for much flexibility. The traditional farming practice depends on the onset of rain to grow crops. However, growing crops does not consider the water requirements, the potential yield, or the soil capability to grow crops. To assess the potential use of seasonal forecasts, the types of decisions and the factors, including the climate, that affect them need to be documented. An assessment was made to characterize some of the decisions made by farmers to improve their livelihoods. The various farming practices on Vertisols specific to this area include planting long-duration crops such as maize and sorghum if the rains come during March or April (the short rainy season). The crops will grow with short and long rains. Otherwise, the land is left fallow for grazing livestock. However, the land allocation decisions for each crop depend on various factors, which vary each year, including other resources such as labor and land preparation. Most crops are planted during the long rainy season with minimal input and no irrigation facilities if weather anomalies occur. If the rain delays during the long rainy season, teff can be planted in late June.

Teff requires much labor throughout the planting, harvesting, and threshing processes. Teff also prefers waterlogged soil conditions and needs a fine seedbed preparation. The agro-climatic data analysis may indicate possible options for diversifying crops on these soils. The performance of different combinations of cropping systems under different rainfall distributions can be tested. Together with the seasonal rainfall forecasts, the probabilities can help to develop the various scenarios available to the farmers, whatever level of risk they choose. Some decisions that can be made affect land preparation, crop and variety choice, fertilizer application rate, soil and water conservation measures, and disease and pest control practices. To maximize crop production, improved management of Vertisols such as double cropping, water harvesting, and improved agronomic practices are crucial.

2.3.14 Potential Yield and Crop Production Constraints

Vertisols are soils with high potential for crop production, but their physical characteristics limit their use and full potential. In the highlands, the major farming practice is sowing crops on residual moisture to alleviate the waterlogging problem. Using only part of the growing season may lead to low crop yields and considerable erosion hazards because fields are left without vegetative cover for much of the time. Today, most farmers use the broad bed and furrow drainage system to overcome the waterlogging problem and plant crops early in the season. However, the yield of crops grown on these soils is still much lower compared to other developing countries. To analyze the rainfall-soil-yield relationships, 20 years of rainfall and wheat yield data were taken, and regression analyses were performed (data not shown).

However, it turned out that the relationship between crop production and total annual or growing season rainfall was so weak that it could not adequately convey the effects of rainfall variability on crop productivity. Rainfall throughout the growing season, particularly rainfall in June, July, August, and September, has little link with crop productivity. The linear model approach’s key flaws were that it could not distinguish between negative and positive effects while also recognizing a wider range of years with normal or around normal yield levels. However, in certain years, negative yield anomalies signified rainfall’s negative impacts, just as in other years, positive anomalies signified positive impacts. On Vertisols, negative impacts of the climate are more likely to result from excess rainfall and a poor drainage system during the crop-growing period. For wheat, positive climate impacts were recorded in 1993, 1995, and 1997. In the other year, crop yield anomalies did not attain the levels at which they could be considered impacts. This is not sufficient for forecasting crop yields or the impacts of climate. In the Ethiopian highlands, crop-livestock integration is very strong. Therefore, the impact severely affects the whole system.

2.4 Conclusion and recommendations

Vertisols are considered one of the major soil types in the highlands of Ethiopia. Rainfall variability greatly affects crop production and the environment through waterlogging and soil and water erosion. The rain-fed subsistence agriculture in the Ethiopian highlands is a victim of climate change and rainfall variability, resulting in food insecurity. Past rainfall probability studies showed that climate change is evident; the question is how to translate the results to farmers' needs so that farmers can adapt to the existing climatic conditions. Understanding rainfall variability helps farmers develop resilience and mitigation capacity. Agricultural production relies mainly on rainfall onset, cessation, intensity, amount, and distribution. As a result, it would be crucial to build development plans and programs, forecasts and early warning systems, and integrated adaptation strategies that consider local conditions. The present study tried to identify the onset, withdrawal, and length of the growing season for the Ghinchi area from the long-term rainfall data analysis. Dependable rainfall at a 75% probability level starts in June and extends until September. The planting time for main-season cropping may range from the last week of May to mid-June. The short rainy season is unreliable for planting crops due to its low amount and high variability. Double cropping can be exercised in years of optimal rain because Vertisols have a naturally high waterlogging capacity. Sowing wheat in June using an improved drainage system, followed by growing pulse crops in October, as opposed to traditional practice, is advantageous. Building a water harvesting structure is another promising venture for Vertisols to combat dry spells. Our findings show that the chances of receiving more than 50% of the predicted rainfall at a >20 mm (P(W/W)) threshold level begin on the 20th (14–20 May) and end on the 36th (3–9 September). Based on this calculation, the length of the growing period becomes four months, with 116, 201, 187, and 107 mm for June, July, August, and September, respectively. Forecasting the likely onset and cessation of precipitation on Vertisols helps farmers prepare their land, plant crops, and harvest on time before the soil becomes saturated or dries out, making farm operations difficult under the traditional farming system. During years of excess rain, improving the drainage system and constructing water harvesting structures become useful so that farmers can supplement their land if an early withdrawal of rainfall occurs at any time of the year.

Rainfall variability also affects the envirionment through soil and water erosion and land degradation. Early planting of crops accompanied with drainage improvement on vertisols can minimize soil erosion. The copping sytem study showed that growing legumes followed by wheat crop can minimize the use of sysnthetic fertilizer at least by 50%. Mineralization of legume residue N can contribute the N accumulation in the soil which can be taken by the following crops. For poor resource farmers a one year legume growing can improve the soil structure and fertility.

2.5 Limitations of the Methodology and the needs for Future Research

A lack of reliable rainfall data from nearby stations hampered comparative analysis. The untapped potential of crop production on Vertisols is constrained by climate variability. Therefore, future research has to consider field-based studies on soil-water relationships, crops, and soil management for sustainable crop production. The variability of rainfall was the primary focus of this study. The rainfall-yield relationship was not conducted because this study was time-bound.

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A Probabilities of Dry/Wet Spells Based on the Markov Chain Model

Initial probability:

PD = FD/n (1)

PW = FW/n (2)

Conditional Probabilities:

PDD= FDD/FD (3)

PWW= FWW/FW (4)

PWD = 1− PDD (5)

PDW = 1− PWW (6)

Consecutive dry and wet week probabilities:

2D = PDw1. PDDw2 (7)

2W = PWw1. PWWw2 (8)

3D = PDw1. PDDw2. PDDw3 (9)

3W = PWw1. PWWw2 PWWw3 (10)

Where

PD - Probability of the week being dry, FD - Probability of the week being wet, FD - Number of dry weeks, FW - Number of wet weeks, n - Number of years of data , PDD - Probability (conditional) of a dry week preceded by a dry week, PWW - Probability (conditional) of a wet, PWD - Probability (conditional) of a wet week preceded by a dry week, PDW - Probability (conditional) of a dry week preceded by a wet week, FDD - Number of dry weeks preceded by another dry week, FWW - Number of wet weeks preceded by another wet week, 2D - Probability of 2 consecutive dry weeks starting with the week, 2W - Probability of 2 consecutive wet weeks starting with the week, 3D - Probability of 3 consecutive dry weeks starting with the week, 3W - Probability of 3 consecutive wet weeks starting with the week, PDw1 - Probability of the week being dry (first week), PDDw2 - Probability of the second week being dry, given the preceding week dry, PDDw3 - Probability of the third week being dry, given the preceding week dry, PWw1 - Probability of the week being wet (first week), PWWw 2 - Probability of the second week being wet, given the preceding week wet, PWWw 3 - Probability of the third week being wet, given the preceding week wet.

Appendix 2 B **Standard Meteorological weeks**

SMW	Dates	SMW	Dates
1	1 Jan-7 Jan	27	2 June-8 July
2	8 Jan-14 Jan	28	9 July-15 July
3	15 Jan-21 Jan	29	16 July-22 July
4	22 Jan-28 Jan	30	23 July-29 July
5	29 Jan-4 Feb	31	30 July-5 Aug
6	5 Feb-11 Feb	32	6 Aug-12 Aug
7	12 Feb-18-Feb	33	13 Aug-19 Aug
8	19 Feb-25-Feb	34	20 Aug- 26 Aug
9*	26 Feb-4 Mar	35	27 Aug- 2 Sep
10	5 Mar-11 Mar	36	3 Sep- 9 Sep
11	12 Mar-18 Mar	37	10 Sep-16 Sep
12	19 Mar-25 Mar	38	17 Sep- 23 Sep
13	26 Mar- 1 Mar	39	24 Sep-30 Sep
14	2 April- 8 April	40	1 Oct-7 Oct
15	9 Apr-15 Apr	41	8 Oct-14 Oct
16	16 Apr- 22 Apr	42	15 Oct-21 Oct
17	23 Apr- 29 Apr	43	22 Oct- 28 Oct
18	30 Apr- 6 May	44	29 Oct - 4 Nov
19	7 May-13 May	45	5 Nov-11 Nov
20	14 May-20 May	46	12 Nov-18 Nov
21	21 May-27 May	47	19 Nov-25 Nov
22	28 May -3 June	48	26 Nov-2 Dec
23	4 June-10 June	49	3 Dec-9 Dec
24	11 June-17June	50	10 Dec-16 Dec
25	18 June-24 June	51	17 Dec- 23 Dec
26	25 June-1 July	52**	24 Dec-31 Dec

*Week No. 9 will have 8 days during the leap year

** week no 52 will always have 8 days

Appendix 2 C Initial and conditional probabilities (%) of rainfall

Station: Ghinchi (1126.0 mm) DATA BASE : 1981-2020

STD WEEK	>10 mm			>20 mm			>30 mm			>40 mm			>50 mm			MEAN (mm)
	W	W/W	W/D	W	W/W	W/D	W	W/W	W/D	W	W/W	W/D	W	W/W	W/D	
1	10	0	11	10	0	6	5	0	0	5	0	0	0	0	0	4.0
2	10	0	11	5	0	0	0	0	0	0	0	0	0	0	0	2.8
3	10	50	6	0	0	0	0	0	0	0	0	0	0	0	0	2.5
4	10	0	22	0	0	10	0	0	10	0	0	5	0	0	0	3.0
5	20	50	25	10	50	17	10	50	17	5	100	11	0	0	15	6.4
6	30	50	14	20	25	13	20	0	6	15	0	6	15	0	0	14.6
7	25	40	33	15	33	12	5	0	16	5	0	5	0	0	5	7.1
8	35	57	31	15	67	18	15	33	6	5	0	5	5	0	5	10.5
9	40	63	50	25	40	33	10	50	6	5	100	5	5	100	5	12.9
10	55	45	33	35	29	23	10	50	17	10	50	11	10	0	6	16.6
11	40	63	33	25	60	7	20	0	6	15	0	0	5	0	0	13.7
12	45	44	64	20	50	50	5	0	32	0	0	20	0	0	20	9.9
13	55	55	67	50	40	40	30	33	21	20	0	19	20	0	19	25.3
14	60	58	0	40	50	8	25	40	20	15	0	18	15	0	12	20.7
15	35	100	54	25	100	40	25	80	33	15	33	24	10	0	11	15.2
16	70	79	33	55	36	33	45	22	27	25	20	20	10	0	6	25.3
17	65	62	29	35	71	31	25	40	27	20	50	19	5	0	16	18.0
18	50	70	60	45	56	36	30	50	29	25	40	27	15	0	24	20.8
19	65	62	14	45	22	27	35	14	23	30	17	21	20	0	25	25.0
20	45	44	36	25	60	33	20	25	19	20	25	19	20	0	13	18.4
21	40	100	58	40	75	42	20	75	38	20	25	19	10	0	17	19.0
22	75	73	60	55	82	56	45	56	45	20	50	25	15	67	24	26.1
23	70	100	67	70	71	67	50	70	20	30	50	21	30	50	21	29.2
24	90	100	100	70	86	100	45	67	64	30	50	43	30	33	21	36.9
25	100	100	0	90	83	100	65	85	43	45	56	45	25	40	33	39.1
26	100	100	0	85	76	100	70	79	50	50	70	60	35	71	38	41.4
27	100	100	0	80	88	75	70	71	83	65	38	71	50	30	30	53.2
28	100	100	0	85	94	100	75	93	100	50	70	90	30	67	57	43.1
29	100	100	0	95	95	100	95	95	100	80	63	100	60	50	75	54.1
30	100	100	0	95	95	100	95	89	100	70	71	50	60	58	50	58.6
31	100	100	0	95	100	100	90	94	100	65	77	57	55	82	44	53.8
32	100	95	0	100	95	0	95	79	0	70	57	33	65	46	29	62.4
33	95	100	100	95	95	100	75	73	100	50	70	60	40	63	42	46.7
34	100	100	0	95	79	0	80	63	50	65	54	43	50	50	20	49.7
35	100	95	0	75	87	80	60	42	63	50	30	20	35	0	23	40.6
36	95	89	100	85	71	67	50	60	50	25	20	40	15	0	12	34.2
37	90	89	100	70	64	67	55	45	44	35	29	31	10	50	28	33.5
38	90	61	100	65	46	43	45	33	27	30	17	7	30	0	7	36.8
39	65	62	29	45	44	27	30	33	21	10	0	22	5	0	21	20.6
40	50	40	0	35	43	0	25	20	0	20	25	0	20	25	0	21.9
41	20	50	44	15	33	18	5	100	16	5	0	11	5	0	0	8.0
42	45	33	9	20	25	6	20	25	0	10	0	0	0	0	0	12.1
43	20	0	0	10	0	0	5	0	0	0	0	0	0	0	0	4.5
44	0	0	20	0	0	15	0	0	5	0	0	0	0	0	0	.3
45	20	50	6	15	33	6	5	0	11	0	0	5	0	0	5	5.3
46	15	0	6	10	0	6	10	0	6	5	0	5	5	0	5	9.0
47	5	0	5	5	0	5	5	0	5	5	0	5	5	0	0	3.1
48	5	0	0	5	0	0	5	0	0	5	0	0	0	0	0	2.5
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.5
50	0	0	10	0	0	5	0	0	5	0	0	5	0	0	5	1.5
51	10	50	6	5	0	5	5	0	0	5	0	0	5	0	0	3.6
52	10	50	0	5	100	0	0	0	5	0	0	5	0	0	0	2.0

Chapter Three- The Impact of Tillage and Sowing Dates on Runoff, Soil Loss, and Wheat Yield in Vertisols of Ethiopian Highlands

3.1 Abstract

Soil erosion is a critical environmental issue, and understanding its causes and impacts is essential for sustainable land management. The highlands of Ethiopia have vast areas of underutilized Vertisols due to unfavorable climatic conditions, unique soil characteristics, and unsustainable land use practices. Despite their potential for productivity, Vertisols face social and technical challenges that hinder their improvement. Enhancing the productivity of Vertisols is crucial for achieving food self-sufficiency and reducing poverty. This study aimed to investigate the impact of tillage practices and sowing dates on runoff and soil loss on Vertisols. Results showed that tillage practices and early sowing significantly increased wheat yields by 51% compared to traditional flat seedbed planting. However, the improved drainage system increased runoff and soil compared to the traditional flat seedbed planting system. The increase in crop production came at the cost of improving the drainage system, which simultaneously increased runoff and soil loss. Unprotected runoff and soil loss are socially, economically, and environmentally unacceptable from a natural resource conservation point of view. Considering the implications of these findings, further research is necessary to explore methods that minimize runoff and soil loss while simultaneously enhancing crop productivity.

Keywords: Drainage, Vertisol, flat seed bed, erosion, runoff

3.2 Introduction

Numerous studies have reported that soil erosion is a global concern affecting human livelihoods in terms of social, economic, and environmental sustainability (Borrelli et al., 2020; García-Ruiz et al., 2015). Soil erosion is a major concern in many African countries due to a combination of factors, including climate change, rainfall variability, and poor agricultural land management practices, which contribute to soil erosion and subsequent land degradation, ultimately leading to food insecurity and poverty. Soil is crucial for world food security, as 95% of the world's population relies on it (Hartemink, 2007). In Sub-Saharan Africa (SSA), approximately 25% of the land area equivalent to 350 million hectares is degraded (Vlek et al., 2010). Among the SSA countries, Ethiopia is the most affected country by erosion (Fenta et al., 2021), even though the severity and extent vary from region to region depending on rainfall, farming practices, topographic features, and landscape (Nyssen et al., 2015; Hurni et al., 2010). Erosion depletes soil nutrients and reduces the productivity of the soil by affecting biodiversity and ecosystem services (Lal, 2014; Pimentel & Burgess, 2013). The United Nations Sustainable Development Goal (SDG) 2 emphasizes the need to eradicate hunger, achieve food security, improve nutrition, and promote sustainable agriculture by 2030 (Braun et al., 2020). To accomplish these crucial goals, it is imperative to implement soil management techniques that boos agricultural production and widely adopt agroecological practices strategically.

Vertisols are a type of soil that is characterized by their vertic properties, meaning they have a high concentration of expansive clays that can shrink and swell with changes in moisture content. These soils are widely distributed in the highlands of Ethiopia covering approximately 7.6 million hectares of land and are known for their ability to retain water and nutrients. However, they are also prone to erosion, especially during periods of heavy rainfall. When wet, waterlogging, sticky, and swelling nature of the soil restricts land preparation and cultivation more difficult. During dry periods, Vertisols form hard clods, and deep wide cracks open down throughout the profile. The cracking allows water to flow down and lateral causing soil erosion, that causes social economic, and negative environmental consequences (Kovda, 2020). Soil erosion and soil nutrient depletion have determinantal factors on food security and economic development (Pimentel, 2006; Hurni et al., 2015). During the extended rainy season from June to September, crops grown on Vertisols may encounter waterlogging and nutrient depletion, causing land degradation, and resulting in reduced agricultural productivity and food insecurity (Bekele, 2019; Hurni et al., 2010). Consequently, farmers leave vast areas of Vertisols bare during the main rainy season, relying on residual soil moisture to plant short-duration crops. This practice of leaving the land bare without vegetative cover and planting late-season crops on stored residual soil moisture catalyzes soil erosion.

Several studies have demonstrated that soil erosion is a major biophysical problem in Ethiopia (Yesuf & Mekonnen, 2005). In response, the Ethiopian government, NGOs, and local communities have implemented measures such as soil and water conservation, afforestation programs, and sustainable land management practices (Land & Project, 2014). However, in Ethiopia, investing in soil conservation practices is always a challenge due to socio-economic constraints (Feyisa, 2020; Mekonen et al., 2013). In particular, ensuring food self-sufficiency and addressing food security remain significant challenges on the widely distributed Vertisols of the Ethiopian highlands. These soils are left uncultivated during the extended rainy season due to waterlogging and unfavorable soil-water relationships. Vertisol farmers in Ethiopia face challenges from rainfall variability because the untimely and early onset of progressive rainfall disturbs the traditional sowing dates practiced by farmers. The traditional sowing dates and land preparation practices have been disturbed due to rainfall variability. Rainfall variability associated with soil erosion is harming agricultural output and causes water bodies to become sedimented. Reducing the environmental impact of erosion and maintaining soil health are two benefits of addressing erosion through appropriate land management techniques. Due to rainfall variability, nowadays farmers have a problem determining the sowing dates of crops. The improved drainage system, using the broad bed and furrow has resulted in varying results, concerning drainage improvements and related runoff and soil erosion (Lebay et al., 2021; Erkossa et al., 2005).

It is believed that Vertisols found in different areas have their specificity in terms of clay content, topography, and agroclimatic conditions that influence the unique behavior exhibited by Vertisols found in different agroecological settings. Considering this specificity of Vertisols found in different agroecology, this study is initiated for Ginchi are of the highland region to quantify soil and water erosion resulting from BBF and flat seed bed preparation combined with three planting dates. The overarching goal is to assess the impact of rainfall variability on Vertisols in the Ethiopian highlands and evaluate the extent of soil and water erosion from these practices.

3.3 Materials and methods

3.3.1 Study site description

The study was conducted near the Ginchi Agricultural Research Sub-Center, which spans from 9°01’54" N to 9°04’03" N latitude and 38°09’10" E to 38°10’40" E longitude. The altitude of the center is 2200 meters above sea level. The center is situated in the Dendi district of the West Showa zone within the Oromia region, approximately 75 kilometers west of Addis Ababa, Ethiopia (Figure 3.1). A composite soil sample was collected from five spots in the experimental field for physical and chemical characterization. Soil samples were collected from 0–20 and 20–40 cm depths, following a zigzag pattern, before establishing the experiment. The soil exhibited a pH of 5.6 (according to the methodology described by Breitenbeck & Bremner (1984[Ma1][Ma2]), a total nitrogen content of 0.07% [Ma3](according to Bremner & Mulvaney, 1982[Ma4]), available phosphorus of 9.5 P mg kg^{-1} (Bray, 1945; Boem et al., 2011), and organic carbon of 0.85% (according to Emmert, 1938[Ma5][Ma6]). The soil is classified as black clay soil (Vertisol) (Ababa, 1993), with a clay content of 65%. The rainfall pattern at the study site is bimodal, with the short rainy season lasting from February to May and the long rainy season extending from June to September. The cropping season in the Ethiopian highlands is during the long rainy season.

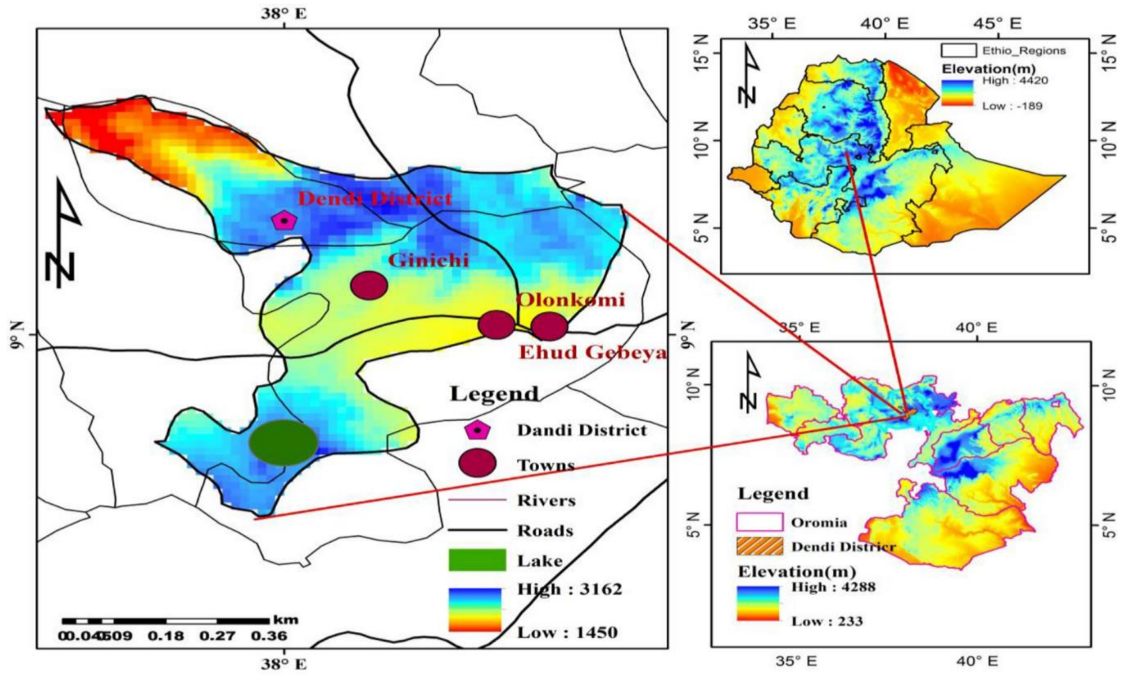

Figure 3. 1 Geographical location and study area map of Ginchi

3.3.2 Experimental design and treatments

The runoff and soil loss experiment was initiated in 2020 and spanned for three years. The experiment was designed using a randomized complete block design (RCBD) with split plot arrangements, replicated three times. The experimental setup consisted of three different sowing dates (mid-June, mid-July, and end of August[Ma7][Ma8]) as the main plot and two drainage improvement treatments (flat seed bed and broad bed and furrow (BBF)) as the sub-plot treatments. The BBF tillage practice involved the use of a broad bed and furrow maker (BBM) (Astatke et al., 2004; Astatke et al., 2002; Ababa, 1993, Figure 3.2). We selected the wheat variety HAR 1685 and planted it at a seed rate of 185 kg ha^{-1} as the test crop for this experiment. The wheat crop received a nitrogen fertilizer application of 60 kg ha^{-1} as urea, along with a phosphorus fertilizer at 26 kg ha^{-1} in the form of Triple superphosphate (TSP). The plot size for the experiments was 10 m x 3.2 m and had a main slope of 1.5% running along the length of the plot. Earth banks surrounded the plot, except for the downstream end. Surface runoff and sediment load from both the flat seed bed and the BBF plots were directed into a plastic tank container with a volume of 0.2 m^3, which was installed at the downstream side of each plot.

Figure 3. 2 The modified broad bed and furrow makers (BBM) used for this experiment

3.3.3 Methods of data analysis

Runoff and soil loss were measured using the conventional (standard) runoff and erosion plots as described by Morgan (Ayoubi & Alizadeh, 2006). A plastic tank with a capacity of 200 liters was installed downstream of each plot and covered with a plastic sheet to prevent rainfall from entering the tank. Runoff and eroded sediments were channeled into the collecting tanks from flat seed beds and BBF plots. The experimental plots were precisely delineated, measuring 10 m by 3.2 m with a slope of 1.5%. This allowed for the systematic application of different planting dates and tillage practices. To ensure reliable results, the entire experiment was replicated three times, minimizing potential biases. The runoff was quantified and sampled in 1000-mL flasks after each rainfall event. The runoff and sediments were thoroughly mixed, and five sub-samples of(Ayoubi & Alizadeh, 2006) the 1000 mL were taken to determine soil loss after oven drying at 105°C for 24 hours. The average of these sub-samples was subjected to statistical analysis. Following standard practice, the height of water in each tank was measured, sediment flux was sampled, and sediment and soil losses were calculated for each plot.

Additionally, rainfall was measured using a recording gauge during runoff sampling. The soil loss for each plot was calculated by multiplying the average sediment concentration by the runoff volume. After each rainfall event, the sediment load was allowed to settle, and then the quantity of the runoff was measured. The average of the five sub-samples was used to conduct the necessary statistical analysis. After each occurrence of precipitation, the quantity of water runoff was assessed following the process of sediment settling. For each rainfall event, runoff volume and sediment loss from the plots were calculated. Rainfall was measured at each rainfall event that caused runoff with a rainfall gauge installed 200 meters away. At 500 meters away from the experimental plots, a first-class meteorological station was installed. The rainfall collected was measured after each rainfall event. After measurement was taken, the collection plastic tank was emptied into the nearby pond constructed for storage of the water and later use for supplemental irrigation in case of dry spell occurrence for crops planted on stored residual moisture following the harvest of the main season crop (Figure 3.3). The main plots of wheat were harvested at ground level upon reaching maturity from a 20 m^2 area of the experimental field between December 8 and 13 each year. Subsamples were taken to determine fresh weight, dry weight, and nitrogen concentration. Approximately 200 grams of each subsample were oven-dried at 70°C for 24 hours to determine the moisture content of wheat per hectare.

Figure 3.3 Water harvesting pond to collect runoff from drainage furrows

3.3.4 Statistical Analysis

An analysis of variance (ANOVA) using Statistics 10.2 (http://statistix.software.informer.com/) software was used to examine tillage practices and sowing dates effects on runoff and soil loss. We set up the studies using a split plot in a randomized complete block design with three replications to test whether the differences in runoff and soil loss were induced by treatments were statistically significant. An estimate of the least significant difference (Tukey LSD) between treatments was obtained. Statistical differences were considered significant at the $p \leq 0.05$ level.

3.4 Results and discussion

3.4.1 Annual and seasonal rainfall patterns and variability

The annual average rainfall of the study area during the last 10 years indicated that the variability is very high, ranging from 876.7 in 2022 to 1431.5 in 2011, with a standard deviation of 160.1 (Figure 3 4). A study conducted on the rainfall variability in the highlands of Ethiopia also demonstrated that rainfall variability is considerably high (Seneshaw Getahun, 2015).

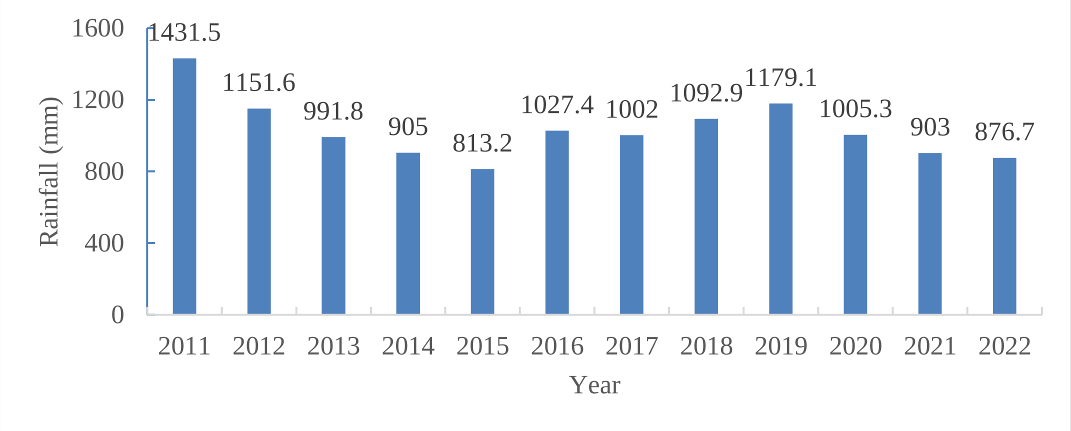

Figure 3.4 Annual rainfall for the study area during the last 12 years

3.4.2 Seasonal rainfall distribution

Figure 3.5 illustrates the monthly rainfall patterns during the cropping season (June to September) over three consecutive years: 2020, 2021, and 2022. The graph reveals considerable variability in rainfall distribution for these four months. Notably, the total seasonal rainfall for June to September was 654.6 mm, 509.1 mm, and 755.3 mm in 2020, 2021, and 2022, respectively. In June, the rainfall decreased from 228.8 mm in 2020 to 143 mm in 2021 and then declined to 125 mm in 2022. Although June experienced the highest rainfall in 2020, July and August reached peak rainfall in 2022, with 254.4 mm and 280.3 mm, respectively. September displayed variability, with 83.3 mm in 2020, a decrease to 48.5 mm in 2021, and an increase to 96.4 mm in 2022. These months significantly influence crop productivity and food security in Ethiopia, as they contribute approximately 75% of the annual rainfall (Wakjira et al., 2021; Manatsa et al., 2008).

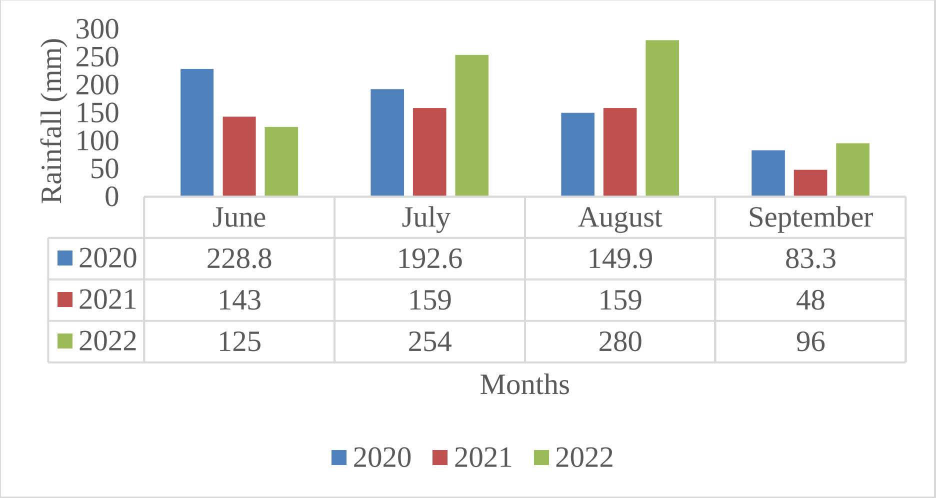

Figure 3.5 Seasonal rainfall for the study period (2020-2022)

3.4.3 Tillage Practices and sowing date effect on wheat grain yield

Vertisol drainage improvement

Increased rainfall amounts cause waterlogging in poorly drained soils as Vertisols. If farmers effectively manage Vertisols, the soils possess significant potential for crop production. To enhance and sustain crop production in Vertisols, it is essential to implement suitable land-shaping practices and effective water management techniques. This can help to optimize water use efficiency, reduce soil erosion, and improve soil health, ultimately leading to better crop yields and sustained agricultural productivity. In general, Vertisols are difficult to work with when wet due to their sticky nature and waterlogging characteristics, and when dry, the soil has a hard consistency. The workability of the soil is often restricted to short periods of optimal soil moisture conditions. This limitation is attributed to the low hydraulic conductivity of Vertisols, which hinders substantial water movement after the soil has become saturated and reached field capacity (Singh et al., 2022; Society, 2016). Flooding can be a major problem in areas with higher rainfall. Particularly, planting crops in June becomes extremely challenging in the absence of proper drainage systems to prevent waterlogging (Kovda, 2020). Farmers have attempted several traditional farming practices to drain excess water from farmland, but none of them have fully resolved the problem. One of the traditional farming practices exercised by farmers is to keep the land bare during the primary rainy season and, subsequently, plant crops using stored soil moisture once the long rains have ceased. However, this approach exacerbates soil erosion and poses a risk of a dry spell for crops planted on residual moisture, as they may experience insufficient soil moisture, which can also contribute to lower crop yields. Therefore, it becomes crucial to improve drainage systems and implement early sowing practices to establish favorable soil-water relationships that promote optimal crop growth and development (Lebay et al., 2021; Ababa, 1993). It is important to note that sowing crops early in the season without implementing proper drainage measures significantly reduces crop yields and may even result in complete crop failure. Additionally, the late sowing of crops using BBF techniques is also challenging since the construction of BBF necessitates the presence of friable soil conditions to facilitate bed formation.

Planting crops on Vertisols

Typically, in the highlands of Ethiopia, planting takes place during the main rainy season, which lasts from June to September. However, traditional farming practices involve planting pulse crops in Vertisols after the main rainy season, often after September. The waterlogging situation and the physical properties of wet Vertisols during the primary rainy season impose limitations on crop planting. Furthermore, land preparation for planting crops on Vertisols is hindered by the distinct characteristics of these soils when dry, including the formation of hard clods and deep, wide cracks throughout the soil profile. These characteristics cause traditional farming practices and can adversely affect crop production. Several research findings have indicated that implementing an improved drainage system alongside appropriate agronomic practices enables crops to grow during the main rainy season in June (Ababa, 1993). Due to the wide cropping calendar, our investigation focused on determining the optimal sowing dates and tillage practices for crops planted on Vertisols.

Late-planted wheat using BBF land management practices significantly reduces grain yields. This is primarily due to the impracticability of mid-July planting, as the soil becomes excessively plastic and sticky, making it challenging to work with traditional farm implements and construct the BBF drainage system. Similarly, planting late in the season, after the cessation of the main rainy season after September causes difficulty in preparing the bed uniformly. Planting crops at the beginning of the cropping season without implementing drainage improvements is simply unfeasible due to the risk of waterlogging. In contrast, adhering to traditional farming practices that involve planting crops after the cessation of heavy rain, sometimes after September, can lead to relatively better crop yields. This approach takes advantage of the stored soil moisture, which proves beneficial compared to the potential total failure of planting crops during periods of intensive rainfall and in the middle of the rainy season. To maximize crop production on Vertisols, it is of paramount importance to focus on two key strategies: improving the drainage system and implementing early sowing practices. By addressing drainage issues, farmers can optimize the soil-water relationship, enhance aeration, and make soil nutrients more readily available for the thriving of crops (Ondrasek et al., 2014). Understanding and effectively managing Vertisols are crucial for promoting sustainable agriculture, particularly in regions where rainfall patterns and rainfed agriculture significantly influence crop production. Therefore, it becomes imperative to address drainage challenges as part of a comprehensive approach to ensure optimal conditions for crop growth and maximize agricultural productivity (Sigunga et al., 2002).

Sowing dates, drainage improvement, and wheat grain yield

Table 3.1 displays the mean wheat yields for sowing dates and tillage practices, revealing distinct differences in yields among the treatments. Under traditional farming practices, the end of August planting wheat resulted in the highest mean wheat yield of 1623.2 kg ha^{-1}, followed by mid-June with 1218.6 kg ha^{-1} and mid-July with 893.5 kg ha^{-1} for flat seedbed preparation. In contrast, the BBF practice yielded the highest mean wheat yield of 2550.4 kg ha^{-1} with the mid-June sowing date, followed by mid-July with 1937.4 kg ha^{-1}, and the lowest yield was observed with the end of August sowing at 1243.1 kg ha^{-1}. These results indicate that both tillage practices and sowing dates associated with soil moisture level have a significant impact on wheat yields. The choice of tillage practice and optimal sowing date has a significant impact on overall productivity. Notably, the grand mean of wheat yield across all combinations was 1257.1 kg ha^{-1} for the flat seedbed system and 1910.3 kg ha^{-1} for the BBF system. The results show that the BBF practice consistently yielded higher wheat grain yields compared to the flat seedbed practice across all sowing dates. To determine the statistical significance of these differences, a significance level of $P<0.05$, corresponding to a 95% confidence interval, was used. The statistical analysis revealed highly significant differences in yields among the tillage practices and sowing dates. The standard deviation (SD) for wheat yield in the flat seedbed system is 316.3 kg ha^{-1}, and for the BBF system, it is 563.9 kg ha^{-1}. The coefficient of variation (CV), which measures relative variability, is 25.2% for the flat seedbed and 29.5% for the BBF system. The P-values indicate that the observed differences in wheat yield among the various combinations of tillage practices and sowing dates are highly significant ($P<0.001$).

Table 3.1 Pooled ANOVA results of wheat grain yield over the three years

Source	DF	SS	MS	F	P
Rep	2	351757	175879		
Sowing date	2	3374425	1687212	187.4	0.0001
Error rep*SD	4	36012.5	9003		
Tillage	1	6164580	6164580	254.42	0.0000
SD*D	2	6195002	3097501	127.84	0.0000
Error	42	1017638	24229		
Total	53	1.71E+07			

**Rep-Replication, SD-sowing date, D-drainage*

ANOVA results show average wheat grain yield data from three years revealed significant main effects of sowing dates, drainage practices, and their interactions (Table 3.2). The analysis was performed using Statistics 10X software, with a sample size of 30 observations per treatment. The results showed that sowing dates had a significant main effect on wheat yield, with an F-value of 187.40 and a p-value of 0.001. Similarly, the drainage improvement factor demonstrated a highly significant main effect on wheat yield, with an F-value of 254.42 and a p-value of 0.0000. Additionally, the interaction between sowing dates and drainage improvement exhibited a significant main effect on wheat yield. The coefficient of variation (CV) for replication and sowing dates (rep*SD) was calculated as 5.93%, indicating the variability between replicated measurements. The CV for error was determined to be 9.73%, reflecting the variability within each treatment group. These results provide valuable insights into the factors that affect wheat grain yield and can inform future research and agricultural practices.

Table 3. 2 The effect of tillage practices and sowing dates on wheat grain yield on Vertisols

Sowing dates	Wheat grain yield (kg ha^{-1})	
	Tillage practices	
	Flat seedbed	BBF
Mid-June	1218.6b	2550.4a
Mid-July	893.5c	1937.4b
End of August	1623.2a	1243.1c
SD	316.3	563.9
CV (%)	25.2	29.5
Grand mean	1257.1	1910.3
P	0.0001	0.0001

The results in all seasons and over the years revealed that delaying sowing dates from mid-June to mid-July and the end of September caused a significant reduction in wheat grain yield compared to drainage improvement and early sowing. However, the traditional farming practice of late planting has some yield increments compared to early sowing without drainage improvement. The results highlight the importance of drainage improvement for successful crop production, particularly emphasizing on early planting of crops. Overall, these findings lead to the conclusion that a lack of drainage improvement significantly reduces wheat grain yield. Previous studies have demonstrated that implementing improved drainage systems, utilizing early sowing dates, and employing effective agronomic practices can greatly enhance wheat productivity on Vertisols. Late-season employment of BBF can reduce crop yields due to soil turnover and moisture loss, although Vertisols' high water-holding capacity benefits late planting with stored soil moisture. Combining early planting with drainage improvement allows for double cropping, where the initial crop can be harvested early to facilitate a second crop to grow on stored soil moisture. However, late-planted crops may suffer a shortage of available water in the soil if the previous season was short of sufficient rainfall. In this case, the Vertisol technology should be accompanied by a water-harvesting structure. The harvested water can be used for supplemental irrigation of the second crop if a dry spell occurs for the second crop planted after the harvest of the first crop.

Rainfall and soil erosion

The distribution, amount, and intensity of rainfall as well as consecutive rainy days play a crucial role in runoff and soil erosion (Mohamadi & Kavian, 2015; Wang et al., 2018; Ziadat & Taimeh, 2013). When intense rainfall occurs over a short period, it can cause soil detachment and erosion. In the Ethiopian highlands, high-intensity rainfall during the main cropping season (June to September) is the primary driver of runoff and soil loss on Vertisols (Dagnew et al., 2015). To investigate the impact of rainfall on soil erosion, we conducted a three-year monitoring period (2020-2022) using rainfall data from a nearby meteorological station in Ginchi. The total annual rainfall for the three years experimental period (2020-2022) was 1005.3, 980.1, and 1254.5 mm, respectively. During these periods, the mean seasonal rainfall for *kiremt* were 753.4, 509.2, and 940.3 mm, respectively (Table 3.3). We measured 18, 12, and 21 erosive rainfall events for BBF and 16, 9, and 17 for flat seedbed tillage practices in 2020, 2021, and 2022. Notably, a significant concentration of these erosive events occurred in July and August across all three years, as these months receive the highest monthly precipitation. The highest number of erosive events was observed in 2022, which aligns with the highest seasonal rainfall (Table 3.3). Flat seed beds showed the least number of erosive days. The lower number of erosive days on flat seedbeds might be due to less soil disturbance during planting, while on BBF, several passes are essential before bed formation and planting.

Seasonal rainfall, runoff, and soil loss

The seasonal rainfall and associated runoff and soil loss for the three-year study period are presented in Table 3.3. Under the same amount of precipitation, the tillage practices exhibited varying responses to runoff and soil loss. In all three years, BBF tillage practices induced higher runoff and soil loss compared to the flat seedbed. Pooled over the three years, soil loss on BBF was 3.8 t ha^{-1}, while on flat seedbed it was 2.1 t ha^{-1}. In 2021, seasonal rainfall decreased to 509.2 mm. However, the runoff was higher in BBF (210 mm) than in a flat seedbed (105 mm). Finally, in 2022, the highest seasonal rainfall occurred at 940.3 mm. BBF had the highest runoff (315 mm), while flat seedbed had a lower runoff (237 mm). BBF construction requires land shaping which have raised beds that have increased runoff and soil loss compared to a flat seed bed. The BBF tillage practice was designed to improve the surface drainage system on Vertisols (Abyie et al., 2002) so that excess rainfall from the bed drains to the furrow, but induces more runoff and soil loss. The findings are in line with that of Erkossa (2004), who also found that BBF induced more runoff than flat seed due to raised beds. A study conducted by Bakker et al., (2005) on Australian Vertisols showed that the raised beds constructed to improve drainage produced more runoff than the control plots. Another major reason is typically the soil's physical characteristics, having highly expanding clay minerals when moistened swells and when dry shrinks (Jean Pierre et al., 2019; Society, 2016).

3.4.4 Rainfall, runoff, and soil loss relationship

The distribution, amount, and intensity of rainfall as well as consecutive rainy days play a crucial role in runoff and soil erosion When intense rainfall occurs over a short period of time, it can cause soil detachment and erosion. In the Ethiopian highlands, high-intensity rainfall during the main cropping season from June to September is the primary driver of runoff and soil loss on Vertisols (Dagnew et al., 2015). To investigate the impact of rainfall on soil erosion, we conducted a three-year monitoring period (2020-2022) using data from a nearby meteorological station in Ginchi. We measured 18, 12, and 21 erosive rainfall events for BBF and 16, 9, and 17 for flat seedbed tillage practices in 2020, 2021, and 2022. Notably, a significant concentration of these erosive events occurred in July and August across all three years, as these months receive the highest monthly precipitation. The highest number of erosive events was observed in 2022, which aligns with the highest seasonal rainfall (Table 3 3).

Table 3.3 presents data of seasonal rainfall, runoff and soil loss. Under the same amount of precipitation, the tillage practices exhibited varying responses to runoff and soil loss. In all three years, BBF tillage practices induced higher runoff and soil loss compared to the flat seedbed. Despite the equal rainfall for both tillage practices, BBF resulted in higher runoff (279 mm) compared to a flat seedbed (212 mm). Similarly, soil loss was greater in BBF (0.4 t^{-1}) than in flat seedbeds (0.2 t^{-1}). In 2021, seasonal rainfall decreased to 509.2 mm. However, the runoff was higher in BBF (210 mm) than in a flat seedbed (105 mm). Soil loss remained consistent, with BBF at 0.3 t^{-1} and flat seedbed at 0.2 t^{-1}. Finally, in 2022, the highest seasonal rainfall occurred at 940.3 mm. BBF had the highest runoff (315 mm), while flat seedbed had a lower runoff (237 mm). Soil loss followed a similar pattern, with BBF at 0.6 t^{-1} and flat seedbed at 0.4 t^{-1}. Vertisols have a high clay content and a unique characteristic that leads to low infiltration and poor permeability, causing the soil to become quickly saturated. Previous studies also demonstrated similar results and reported that runoff and soil loss are a combination of different factors such as rainfall intensity, soil type, and slope (Wang et al., 2018; Zhao et al., 2015; López-Vicente et al., 2008).

Table 3. 3 The effect of seasonal rainfall and tillage practices on runoff and soil loss

year	Tillage practices	Seasonal rainfall (mm)	No. of erosive events (No.)	Runoff (mm)	Soil loss (ton ha^{-1})
2020	BBF	753.4	18	279	0.4
	Flat seed bed		16	212	0.2
2021	BBF	509.2	12	210	0.3
	Flat seedbed		9	165	0.2
2022	BBF	940.3	21	315	0.6
	Flat seedbed		17	237	0.4

Effect of tillage practices and sowing dates on runoff and soil loss

The effect of tillage practices and sowing dates pooled over the years on runoff and soil loss is depicted in Table 3.4. The findings are shown in terms of the mean values for each combination of tillage practices and sowing dates. The BBF tillage practice had higher values of both runoff (301.9 mm) and soil loss (3.3 t ha^{-1}) compared to the flat seedbed practice, which had runoff of

144.7 mm and soil loss of 2.1 t ha^{-1}. BBF tillage practices showed 34% higher soil loss and 52% more runoff than flat seedbed practices. On the other hand, sowing dates also significantly affected runoff and soil loss. Mid-July planting resulted in the highest runoff of 310.9 mm, followed by mid-June with 253.5 mm. This is mainly due to high and consecutive rainy days and the full saturation of the soil. The least amount of runoff was recorded at the end of August. The cumulative June and July rainfall may have contributed to the highest runoff in July. As it is anticipated, by the end of August, runoff will be the least since rainfall is usually decreasing and the dry season is approaching. In terms of sowing dates and the effects on soil loss, we observed the highest values for mid-July, followed by mid-June and the end of August. The month of the year with the highest runoff and soil loss regarding sowing dates was mid-July. The second highest values are observed when sowing is done in mid-June, with a runoff of 253.5 mm and soil loss of 2785.8 kg ha^{-1}. The lowest values are observed when sowing is done at the end of August, with a runoff of 105.5 mm and soil loss of 1739.1 kg ha^{-1}. The interaction effect between tillage and sowing dates revealed that when the BBF tillage practice is combined with the mid-June sowing date, the runoff value (301.9 mm) is higher compared to when it is combined with other sowing dates. Similarly, the BBF tillage practice combined with the mid-July sowing date results in the highest soil loss value (3252.5 kg ha^{-1}). In contrast, when the flat seedbed tillage practice is combined with the end of August sowing date, the runoff value (105.5 mm) is the lowest among all combinations. Similarly, the lowest soil loss value (1739.1 kg ha^{-1}) is observed when the flat seedbed tillage practice is combined with the end of August sowing date (Figure 3.6). The table demonstrates that both tillage practices and sowing dates have a significant impact on runoff and soil loss. The BBF tillage practice and sowing in mid-July tend to result in higher values for both variables, while the flat seedbed practice and sowing at the end of August tend to result in lower values.

June is the start of the rainy season and planting time, and as the rainfall proceeds, Vertisols become saturated, causing waterlogging and flooding. July and early August are crucial periods of the year for runoff and soil loss. Planting crops at the start of the rainy season protects soil from erosion and reduces runoff. Erosion is generally more severe at the start of the rainy season rather than in the middle due to compacted and undisturbed soil that reduces its ability to absorb water. However, in this experiment, at the start and the middle of the rainy season, runoff and soil loss were higher. For the sake of planting crops, the land was cultivated, and higher runoff and soil losses were recorded in the middle of the main rainy season, justifying that land shaping and repeated cultivation have contributed to the initial infiltration and increased permeability. As the rainy season progresses and the soil becomes saturated. Vertisols become prone to runoff and soil loss and create a waterlogged condition (Shanshan et al., 2018). However, it's important to note that the severity of erosion can vary depending on various factors, such as slope gradient, soil type, land management practices, and the intensity and duration of rainfall events. These factors can influence the timing and extent of erosion throughout the rainy season (Rosas & Gutierrez, 2020).

Table 3.4 The effect of tillage practices and sowing dates on runoff and soil loss

Tillage practices	Runoff (mm)	Soil loss (kg ha^{-1})
Flat seedbed	144.7b	0.21b
BBF	301.9a	0.37a
Sowing dates		
Mid-June	253.5a	0.28ab
Mid-July	310.9a	0.36a
End of August	105.5b	0.18b

Vertisols can contain a lot of water, but when they become wet and dry, their volume fluctuates significantly. Carefully controlling soil moisture during early planting is essential. Crops should be sown when the soil is sufficiently moist and friable, but not overly so. The primary goal of improving drainage and managing nutrients on Vertisols is to enable early planting, which contrasts with the custom of late planting in agriculture (Sigunga et al., 2002). Soil erosion is exacerbated by late planting of Vertisols, which has detrimental environmental effects on the soil (Bhandari et al., 2021). Waterlogging while planting reduces seed germination if drainage is not improved. The difficult soil conditions cause seedlings to emerge later than expected and subject them to many kinds of stress. These soils are prone to erosion due to their high clay concentration, particularly during periods of intense rainfall. Applying suitable erosion measures can protect the soil and preserve its productivity.

ANOVA results showed that the effects of tillage practices and sowing dates on runoff and soil loss (Table 3.5) have significant effects ($P<0.001$). The interaction between sowing dates and tillage practices also shows a significant effect on runoff and soil loss. This implies that the combined effect of these two factors is important in determining the response variables. These findings highlight the importance of carefully selecting sowing dates and implementing appropriate tillage practices to manage and reduce runoff and soil loss in agricultural systems.

Table 3.5 ANOVA results on the effect of tillage practices and sowing dates on runoff and soil loss

Source	DF	SS	MS	F	P	DF	SS	MS	F	P
REP	2	14489	7244			2	103412	51706.1		
Sowing Error	2	404643	202321	69.49	0.0008	2	2.99E+07	1.50E+07	15.2	0.014
REP*Sowing date	4	11646	2912			4	3937068	984267		
Tillage	1	333940	333940	90.88	0.0000	1	1.69E+07	1.69E+07	35.85	0.001
Sowing*Tillage	2	86752	43376	11.8	0.0001	2	1.33E+07	6653749	14.14	0.001
Error	42	154331	3675			42	1.98E+07	470724		
Total	53	1005802				53	8.39E+07			
Grand mean	223.3					2694				
CV(REP*Sowing)	24.16					36.83				
CV (Error)	27.15					25.47				

Past research conducted regarding tillage practices showed that the impact of runoff can vary significantly depending on the tillage methods employed. The research indicated that raised beds, despite their benefits, can increase runoff due to the furrows created between the beds. The drainage furrows facilitate water flow and potentially exacerbate runoff (Holland et al., 2012). Furthermore, Erkossa et al. (2005) also investigated the impact of a BBF tillage practice and found in their study that the system induced increased runoff. In another study conducted in the northern part of Ethiopia, Lebay et al. (2021) observed lower runoff when utilizing the BBF drainage system. The disparity in runoff outcomes across different regions could be attributed to Vertisol characteristics, rainfall amount and distribution, and agroecological differences. Understanding the interplay between rainfall, tillage methods, local conditions, and soil characteristics is essential for effective water management and mitigating soil erosion and nutrient loss.

3.5 Conclusion and recommendations

Vertisols, with their unique characteristics and contrasting soil moisture dynamics, present challenges in determining the optimal moisture levels for planting and using traditional farm implements. Consequently, these soils are often considered marginal for crop production in developing countries. Another significant issue associated with Vertisols is the limited applicability of technologies developed in one area to other regions. The variability in soil characteristics, including clay content and agroclimatic factors, restricts the widespread adaptability of technologies. Therefore, soil-specific recommendations are necessary for Vertisols in a particular region, while extrapolating findings to other areas may not yield meaningful results. Considering these variations, it is important to adapt and tailor technologies and management practices to suit the specific soil, climate, and cropping conditions of each region. Localized research and evaluation are necessary to determine the feasibility and effectiveness of a technology in a new area before widespread adoption. When it comes to recommending technologies or management practices for different areas with Vertisols, it is crucial to consider the specific soil, climate, and cropping conditions of each region. It is crucial to invest in localized research to understand the specific characteristics and challenges of Vertisols in the target region. This research should focus on soil properties, water dynamics, nutrient availability, and crop requirements. Identifing crop species or varieties that are well-adapted to Vertisols in the target region. It is important to emphasize that localized research and adaptation are essential to determine the most suitable technologies and practices for each specific area with Vertisols.

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Chapter Four- The Effect of Land Preparation on Dry Matter Yield, Nitrogen Content, and Nitrogen Fixation of Legumes on Vertisols of the Central Ethiopian Highlands

4.1 Abstract

Traditional land management techniques on Vertisols frequently lead to soil fertility loss and land degradation. The objective of this study was to evaluate the impact of improved land preparation methods (BBF and camaber bed) on the dry biomass and nitrogen (N) content of two legume species grown under two phosphorus fertilizer applications. The experimental design employed for these experiments was a randomized complete block design, with six treatments and four replications. Land preparation methods and phosphorus application significantly ($P<0.05$) increased biomass production and N content in legumes. Over years and land preparation methods, vetch N accumulation was superior ($P<0.05$) to clover and teff (Eragrostis teff). Such a large amount of N accumulation may have a positive contribution to subsequent crops when incorporated into the soil. Land preparation methods and years influenced soil mineral N accumulation, particularly under legumes. The N balance values indicated that it differed among species, land preparation methods, and P treatments over the year. The N balance of vetch+P ranged from 67.1 to 185.9 kg N^{-1} over years and land preparation methods, whereas the comparable figure for vetch-P was 40.3 to 141.9 kg N^{-1}. Similarly, the N balance in clover-P ranged from 13.0 to 67.2 kg N^{-1}, and in clover+P from 13.8 to 98.6 kg N^{-1}. Teff's N balance has never exceeded 35 kg^{-1} over the years.

Keywords:-Vertisol~~,~~ land preparation, phosphorus, ~~legumes~~, teff, vetch, clover

4.2 Introduction

Black clay soils, or Vertisols, are clay-rich soils that shrink and swell with changes in moisture content. Vertisols cover approximately 335 million hectares worldwide, and about 200 million hectares of these soils are in the tropics. Vertisols are important agricultural soils found in the world's major agro-climatic zones (FAO, 2015). Crop production on Vertisols is constrained by their texture, shrinking, and swelling properties related to unfavorable soil-moisture relationships. In Africa, the largest Vertisol areas are in the Sudan, Chad, and Ethiopia, cultivated by subsistence-oriented smallholder farmers. Due to their physical limitations for land preparation and difficulty in cultivation, resource-poor farmers leave the land fallow during the long rainy season and opt to grow food crops on residual moisture after the cessation of the long rainy season due to fear of waterlogging. In dry periods, deep, wide cracks open, while in a wet state, the soil becomes sticky and plastic (Srivastava et al., 1989). The shrink-swell properties of Vertisols pose severe restrictions on land preparation for traditional farming practices. This practice exposes the land to land degradation and soil and water erosion and does not allow for the use of the full potential of the crop-growing season (Elias et al., 2022).

In the highlands of Ethiopia, Vertisols cover around 7.3 million hectares of land, cultivated under unpredictable, high seasonal and annual rainfall variability (Seid et al., 2020; Li, 2014; Bewket, 2009). The soils are considered fertile, but their physical characteristics and high and intense rainfall make them prone to land degradation and soil and water erosion, restricting their crop production potential. These soils are sensitive to an excess or shortage of rain, which causes severe limitations to land preparation and cropmanagement under traditional farming practices. The range of soil moisture in which Vertisols become suitable for tillage operations is very narrow (Manik et al., 2019; Society, 2016). Naturally, Vertisols are soils with high clay contents, and the physical properties change based on soil moisture fluctuation. When wet, Vertisols become waterlogged, sticky, and plastic, and when dry, the soils become hard and cloddy, restricting farm operations and lowering crop production (Gebreselassie et al., 2015; Berry, Leonard, J. Olson, 2003).

Farmers have developed several traditional practices to overcome the waterlogging constraints on Vertisols. These practices are ridges and furrows, opening shallow drainage furrows across the slope, hand-made broad bed and furrows (BBF), guie (soil burning), planting of tef on waterlogged soils, and growing crops on residual moisture after the end of the long rainy season. Guie is a unique traditional practice of burning sods of heavy clay soils to bring the soil aggregates together and enhance the drainage system. The system brings fallow land into cultivation (Mertens et al., 2015; Astatke et al., 2002). The other practice widely used by smallholder farmers on Vertisols is planting crops on residual soil moisture after the withdrawal of the long rains. Sowing crops on residual moisture after the long rains exposes the crops to thermal drought and frost damage (Society, 2016); Erkossa et al., 2014). From the perspective of protecting soil resources, the methods are not sustainable because each of these practices has its own drawbacks to the environmental sustainability of the resources. Teff is Ethiopia’s only food crop that grows in moderately waterlogged soil conditions and performs well under warm temperatures at mid-altitude (Chanyalew et al., 2019).

Realizing the potential and capacity of Vertisols to produce more food than the traditional system, the Ethiopian Institute of Agricultural Research, along with national and international agricultural research institutions, has made efforts to increase the productivity of the soil through improved technologies. In a food-deficit country like Ethiopia, putting the vast Vertisols areas under cultivation means attaining food self-sufficiency. Several researchers have also confirmed that removal of excess water from the farmland and addition of fertilizer on Vertisols can boost crop productivity (Lebay et al., 2021; Hamilton et al., 2000; Mekonen et al., 2013, Tekalign et al., 1993).

The research has developed a range of improved technologies, such as the construction of BBF by a broad bed and furrow maker (BBM) to drain the excess water from the field, improved crop varieties, optimum fertilizer application, and early planting. A broad bed and furrow maker (BBM) is an implement that creates beds that are 80 cm wide, 20 cm deep, and 40 cm wide, with furrows alternating between the two beds. A broad bed and furrow maker (BBM) is a tool that makes beds that are 80 cm wide, 20 cm deep, and 40 cm wide, with furrows between them. It is a covered metal sheet attached to a local plow, which scoops soil to the center to form a bed (Hamilton et al., 2000; Astatke et al., 2002). The construction of an improved BBF allowed farmers to plant early by removing the waterlogging condition rather than leaving the land fallow and planting on residual moisture after the cessation of the long rainy season. Early planting reduced soil and water erosion that would have occurred due to a lack of vegetative cover on the farmland. In addition to draining the excess water, N and P management are equally essential for crop production on Vertisols (Mamo et al., 2002; Mamo & Haque, 1987), because the soils have a long history of cultivation without applying the optimum amount of inorganic fertilizer, climate-induced land degradation, and mismanagement of agricultural lands. Most Ethiopian soils are deficient in major plant nutrients, and fertilizer consumption per unit of land is the lowest in sub-Saharan Africa (Jayne & Rashid, 2013). Lack of purchasing power by farmers, unavailability and distribution problems Food crops depend on native soil fertility for their nutrition (Haileslassie et al., 200 ; Haileslassie et al., 2005). The use of crop residues and manure is minimal due to their use as livestock feed and to fulfill household energy requirements, respectively (Vanlauwe et al., 2015; Tittonell et al., 2008).

For such a farming system, it is critical to developing a crop production system that is affordable, cost-effective, and environmentally friendly (Bado et al., 2018; Giller, 2005). Integration of legumes into the farming system may solve the fertility problem while improving the drainage system will maximize crop production on Vertisols. Farmers cultivate legumes as an essential component of their cropping system, typically as a break crop or on residual moisture. Commonly, grain legumes grow on Vertisols and are uprooted at maturity, leaving little nitrogen for succeeding crops (Huss-Danell et al., 2007). Forage legumes may provide N input into the system, but farmers rarely grow forage legumes. It is essential to design more sustainable agricultural production practices based on an appropriate level of technology (Reckling et al., 2016). The current study tried to explore the biomass production potential, nitrogen concentration, and nitrogen accumulation of selected legumes on Vertisols under drained conditions. Vetch and clover are the legumes employed in this research. Therefore, vetch and clover were used in these experiments. Vetch can tolerate wet soil, while clover tolerates it to a certain extent (Striker & Colmer, 2017; Pampana et al., 2018). So far, there is no information regarding their use to improve the soil fertility conditions.

Growing crops early at the start of the rainy season instead of the fallow period has many agronomic and environmental benefits. Integration of legumes in the cropping systems benefits farm-level resource optimization and protects the soil from erosion and runoff. The rationale for growing a forage legume as a long-season crop is that it could take the place of fallow in the traditional system provided the net benefit exceeds the latter. The rationale for growing forage legumes during the primary rainy season by improving the drainage system is that it could take the place of fallow to protect ground cover to minimize soil and water erosion during high-intensity rainfall. Legume-derived N is an alternative source of fertilizer that can maintain the productivity of crops and reduce the use of mineral fertilizers, which is economically and environmentally advisable. The objective of this study was, therefore, to assess the dry biomass and nitrogen content of legumes under drained Vertisol conditions with two levels of P application during the long rainy season. An article on the assessment of incorporated legume residues in the soil for subsequent wheat crop production is under preparation.

4.3 Methodology

4.3.1 Study site description

The field experiment was carried out for two years in a row (2018 and 2019) in the Holeta Agricultural Research Center (9^{o} 02' 12'' N and 38^{o} 29' 00'' E, and at an elevation of 2400 meters above sea level), 35 kilometers west of Addis Ababa, Ethiopia (Figure 1). The soil of the study site is typically pellic Vertisol, found in the highland-humid agro-ecology, poorly aerated, and waterlogged for a prolonged period. The soil exhibits impeded drainage due to high clay content (> 30%) in the upper soil profile and qualify for the classification of the World Reference Base, Update 2015, of the third edition (Soil & Reports, 2015; Elias, 2019). The soil is developed on alluvium and colluvium deposits from higher slopes with weathered rocks of volcanic origin

(Elias, 2019b). The study area have two distinct rainfall regimes and a dry period. A graph showing rainfall and temperature for the study site during the experimental periods is shown in Figure 4.2.

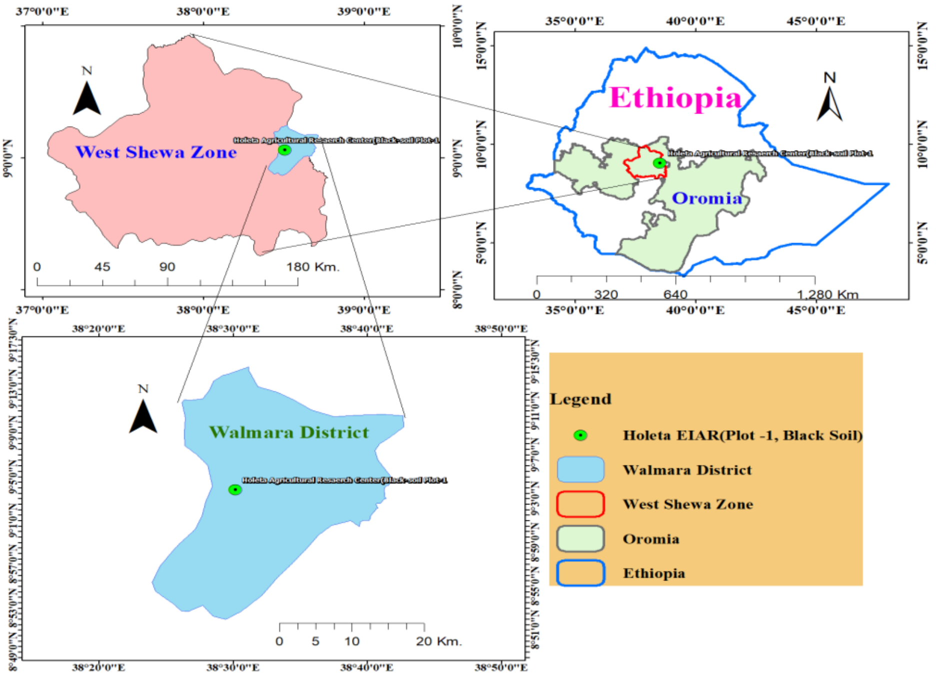


Figure 2.1 Geographical location and study area of Holeta research center

4.3.2 Land preparation methods and treatment arrangement

In the 2018 and 2019 cropping seasons, two experiments were established each year on BBF and camber-bed land preparation methods. Vetch (*Vicia villosa*, *Varia* (Host) Corb.), clover (*Trifolium quartinianum* A. Rich), and a cereal crop, teff, were sown on both land preparation methods in RCBD fashion with four replications. A tractor-mounted mouldboard plow digs camber beds of 50-cm-deep drainage ditches and piles soil in the center. Camber beds can have a width of 4 to 9 meters (in the present study, 6 m) with a concave raised bed, the top of which is about 50 to 60 cm above the bottom of the furrow. The camber bed needs maintenance every three to four years and can last several years. Vetch, clover, and teff were planted in both years, on BBF and cmaber bed land preparation methods, with and without P fertilizer in the form of triple superphosphate administered at 0 and 18 kg^{-1} for legumes and 0 and 26 kg^{-1} for tef. The test crops were applied with urea fertilizer at a rate of 46 kg^{-1}. In 2018 and 2019, the treatments had four and three replications, respectively.

The plot size of BBF was 12 m long and 11 m wide (i.e., nine beds), while the plots on camber beds were 6 m wide and 18 m long. In the last week of June, legumes were sown at a seed rate of 25 and 15 kg^{-1} for vetch and clover, respectively. During the last week of June, legumes were broadcast at 25 and 15 kg^{-1} rates for vetch and clover, respectively. Teff was sown at a seed rate of 30 kg^{-1} on June 12 for the 2018 experiment and June 15 for the 2019 experiment. Teff was used as a test crop in the study to assess dry biomass and nitrogen accumulation in comparison to legumes. Details of the summary treatments used in the experiments are shown in Table 4.1.

Table 4.1. Summary of treatment description

Year	Land preparation methods	Treatments	Treatment description	Fertilizer (kg^{-1})	
				Urea	TSP
2018	BBF (Exp I)	Vetch-P	Vetch without P	46	18
		Vetch+P	Vetch with P	46	18
		Clover-P	Clover without P	46	18
		Clover+P	Clover with P	46	18
		Teff-P	Teff without P	46	26
		Teff+P	Teff with P	46	26
	Camber bed (Exp II)	Vetch-P	Vetch without P	46	18
		Vetch+P	Vetchwith P	46	18
		Clover-P	Clover without P	46	18
		Clover+P	Clover with P	46	18
		Teff-P	Teff without P	46	26
		Teff+P	Teff with P	46	26

In the year 2019, the same experiments were conducted on both land preparation methods, with codes Exp III and IV on BBF and camber, respectively. +P and –P denotes crops applied with and without phosphorus fertilizer, respectively.

4.3.3 Soil sampling and analysis

The soil and plant nutrition laboratory at the Holeta Agricultural Research Centre conducted the physicochemical properties of soil samples collected from the experimental fields. The soil samples collected from 0–20, 20–40, and 20–60 cm soil layers from both land preparation methods were ground to pass a 2 mm sieve before determining the parameters indicated in Table 1. Soil samples collected to determine soil mineral N (ammonium and nitrate nitrogen) were immediately taken to the laboratory and kept in the refrigerator until the analysis was done (Bremner & Keeney, 1965).

4.3.4 Plant sampling and analysis

In Experiments I–IV, the main plots of legumes and tef crops were cut at ground level at maturity from an area of 25 m^2 of BBF of both land preparation methods between 8 and 13 December and sub-sampled to determine the fresh weight, dry weight, and N concentration. Subsamples of about 200 g were oven dried at 70^{o}C for 24 hours. The oven-dried plant materials were ground to pass through a 2 mm mesh and further subsampled and analyzed for total N content by the Kjeldahl method (Kirk, 1950). The N uptake and concentration were determined from the dry biomass of the crops under investigation. For calculation purposes, the dry biomass produced and the N accumulated were converted to kg^{-1}.

4.3.5 Calculations of N balance and atmospheric N input

To measure the increase in N in the plant-soil (0–40 cm) system between planting and crop harvest, the net N balance was determined (Sainju, 2017b). The N balance was explained as follows: -

Net N balance = (crop N content at harvest + residual soil mineral N at harvest) – (initial soil mineral N + added fertilizer N……………………………………………………...........Eq.1

Other N sources and sinks were not measured. The difference in N-balance between legumes and tef provides an estimate of the N input into the soil-plant system from fixation. Data from the tef+P treatment was used in these calculations, as crop N content in tef+P was always higher than in tef-P. Therefore, the N content in teff+P was the best estimator of the amount of N that could be derived from the soil. The amount of N fixed by legumes was estimated by the N-difference method, using tef as a reference crop:-

N fixed = N legume-N teff……………..(Eq. 2)

Where N is the total amount of nitrogen in legumes and the reference crop teff in the above-ground biomass.

4.3.6.Statistical analysis

An analysis of variance was done using the Statistical Analysis System computer package (IBM SPSS Statistics for Windows, Version 25.0) to determine the main treatment effects and their interactions on biomass, nitrogen concentration, and N accumulation. The main effects and interactions were determined using the Turkey LSD analysis of SPSS. At $P<0.05$, differences were considered significant for all statistical tests.

4.4 Results

4.4.1 Soil properties and weather conditions

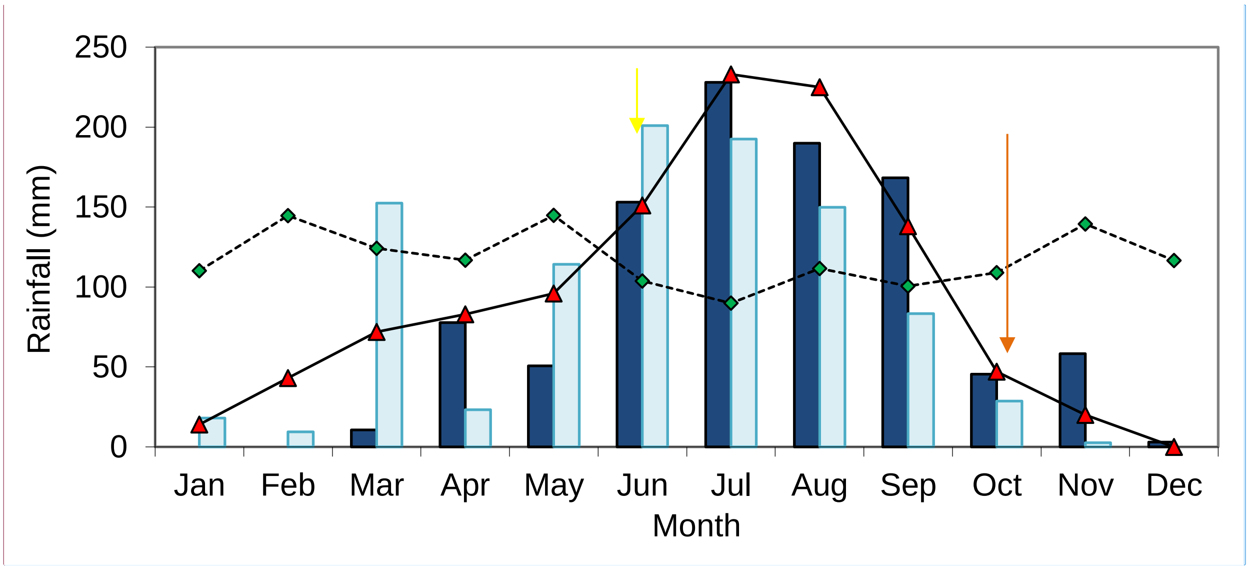
The soil was clayey in texture, having 66% clay at 0–60 cm depth with strong vertic properties. The mean physical and chemical characteristics for the 0-60 cm depth showed a pH of 5.6, a total N content of 0.08%, 1.13% organic matter content, and P (Bray II) of 8.1 mg kg^{-1}. The pH of the soil increases as total N and organic matter decrease with depth. The P status is low in the top 0–60 cm but tends to increase with depth (Table 4.2). Generally, the soil showed lower plant-available nutrients, which is the characteristic of Vertisols in the highlands of Ethiopia

Table 4.2. ***The physical and chemical characteristics of the experimental field***

Depth (cm)	pH (1:1 (H_2O))	N (%)	Organic carbon (%)	P Bray (mg kg^{-1})	Na^+	K^+	Ca^{2+}	Mg^{2+}	*Initial soil mineral N (kg^{-1})				Clay (%)
					cmol kg^{-1}								
0-20	5.3	0.09	1.29	9.2	0.32	1.58	35.3	14.2	14.1	10.9	6.3	9.7	64
20-40	5.8	0.07	0.97	7.1	0.35	1.58	35.3	12.8	7.4	6.9	9.2	11.4	61
40-60	6.5	0.07	0.66	14.8	0.59	1.69	45.3	15.9	- -	-	-		74

* the first two columns for BBF and and the second two for camber bed

The rainfall of the study area is bio-modal, having two peaks in a year, namely the long (June - September) and the short rainy season (February May). The short-rainy season rainfall is less in quantity and erratic and has no agronomic importance. The dry period extends from October to January. The long-term (39 years) mean rain was 1126 mm, showing considerable annual and seasonal variations. The mean long-term rainfall for the long-rainy season was 768.2 mm in 2018 and 509 mm in 2019, showing both years had lower rain than the long-term annual mean. The mean potential evapotranspiration (PET) calculated with the Penman-Monteith methodology exceeds rainfall from October through May. In particular, the year 2019 was relatively dry. The mean monthly minimum and maximum air temperatures range between 5–12°C and 22–28°C, respectively, without much variation over the study period. Figure 4.1. Monthly average rainfall at Holeta in 2018 (blue bars) and 2019 (light bars) and the average long-term (1982–2020) rainfall (red triangles and fully drawn lines). The solid arrow shows the long term average rainfall while the broken line with green diamonds represents the calculated potential evapotranspiration (Penman-Monteith). [Ma9][l10]The short arrow (June) shows the planting time of Expts I, II, III, and IV, while the long arrow (October) represents the planting time of crops on residual moisture (Figure 4.2).



[Ma11][l12]

Figure 4.-2 *Monthly average rainfall at Holetta for 2018 (blue bards) and 2019 (light blue bars)*

4.4.2 Performance of legumes and tef grown as main season crops (Expts I-IV)

4.4.2.1 Biomass productivity

The grand mean of dry biomass produced across treatments was 4930 kg^{-1} in 2018 and 2530 kg^{-1} in 2019, indicating that growth conditions were better in 2018 than in 2019. Across treatments and seasons, the mean dry biomass production amounted to 3843.3 kg^{-1} for vetch, 1615.8 kg^{-1} for clover, and 5724.5 kg^{-1} for tef (Table 4.3). The highest dry biomass was recorded with teff, followed by vetch, whereas clover performed relatively poorly in all experiments. Over years and land preparation methods, camber beds gave higher yield (4546.3 kg^{-1}) than BBF (2909.2 kg^{-1}) for all the tested crops. In both years, camber beds produced 38.3 and 23.5% more dry biomass than BBF. The dry biomass of crops was significantly ($P<0.05$) influenced by crop type in all four experiments. Phosphorus application also significantly (P<0.05) affected the biomass production of crops in 2018 on both land preparation methods, whereas in 2019, P application did not affect the biomass production of crops.

Table 4. 3 *ANOVA results for crop dry biomass over years and land preparation methods*

Treatment	BBF 2018 (Exp I)	Camber bed 2018 (Exp II)	BBF 2019 (Exp III)	Camber bed 2019 (Exp IV)
*Crop type				
Teff (T)	5376a	8620a	3674a	5228a
Vetch (V)	4087b	6410b	2202b	2674b
Clover	1445c	3613c	672c	733c
P level				
-P	2808b	5505.8b	1951b	2621a
+P	4464a	6923.3a	2415a	3135a
Interactions (crop type * P level)				
T+P	6522a	9320a	3720a	5276a
T-P	4230bc	7920ab	3628a	5180a
V+P	5230ab	7172bc	2945ab	3270b
V-P	2945cd	5647cd	1489ab	2078bc
C+P	1640de	4277de	610b	860c
C-P	1250e	2950e	734b	606c

**T-teff; V-vetch; C-clover; +P and –P denotes crops with and without P application; For each treatment factor, mean values with the same letter in the same column are significantly different at P<0.05.*

The interaction effects of crop type by P application were inconsistent among the crops tested. Considering the individual experiments, 2018 gave a higher biomass yield than 2019 (Figure 4.3). Over the years, the mean dry biomass produced by vetch-P on BBF and camber bed was 2220 and 3860 kg^{-1}, respectively, indicating a significant response to P application. The mean dry biomass produced by clover-P was 990 and 1780 kg^{-1} on the BBF and camber bed, while clover+P produced 1130 and 2570 kg^{-1} on the BBF and camber bed over years, respectively. Over seasons, tef-P gave 3930 and 6550 kg^{-1} on BBF and camber beds, respectively, while the dry biomass produced by tef with P was 5120 and 7030 kg^{-1} on the BBF and camber bed, respectively. A comparison of the four experiments across years and land preparation methods showed that the year 2018 was better for crop growth and camber bed created suitable environment for better crop performance. Camber bed of 2018 increased the dry biomass of crops by 41.5% compared to the BBF of the same year. In 2019, camber beds gave a 24.1% higher return than BBF of the same year.

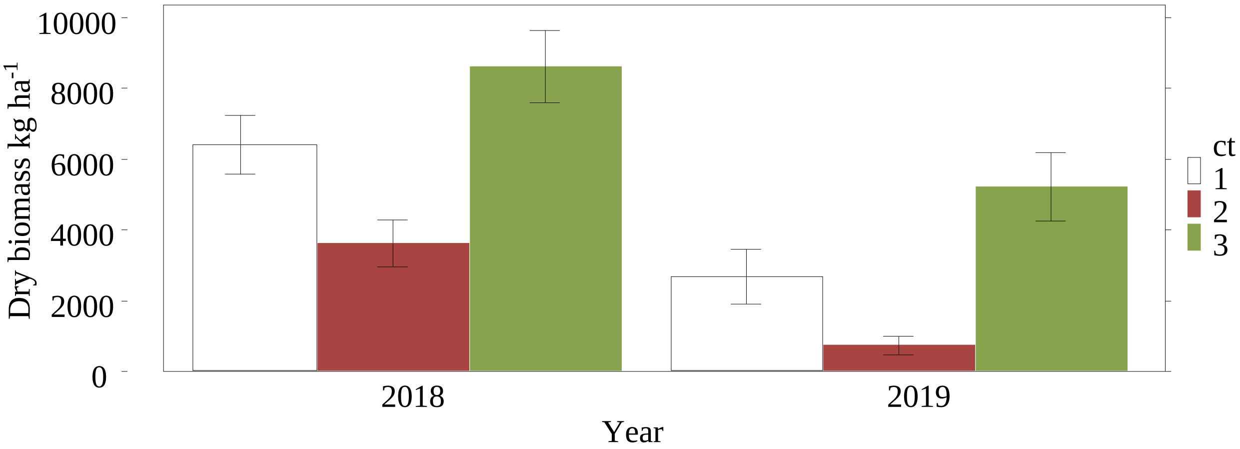


Figure 4. 3 *Error bar for dry biomass production over years*

Error bar showing dry biomass production of crops over years on camber bed land preparation methods, Error bar showing at 95% C.I. ct-crop type, 1-vetch, 2-clover, 3-teff

Among land preparation methods, in both seasons camber bed gave a higher dry biomass yield than BBF. Considering the crops tested in terms of biomass, higher dry biomass was recorded for teff, followed by vetch and then clover (Figure 4.4). On average, P application increased ($P<0.000$) the dry biomass of crops by 37% on BBF 2018 (Exp I), by 20% on camber bed 2018 (Exp II), by 19% on BBF 2019 (Exp III), and by 16% on camber bed of 2019 (Exp IV) over non-P applied treatments. Dry biomass was affected by crop type ($P<0.05$) in all four experiments.

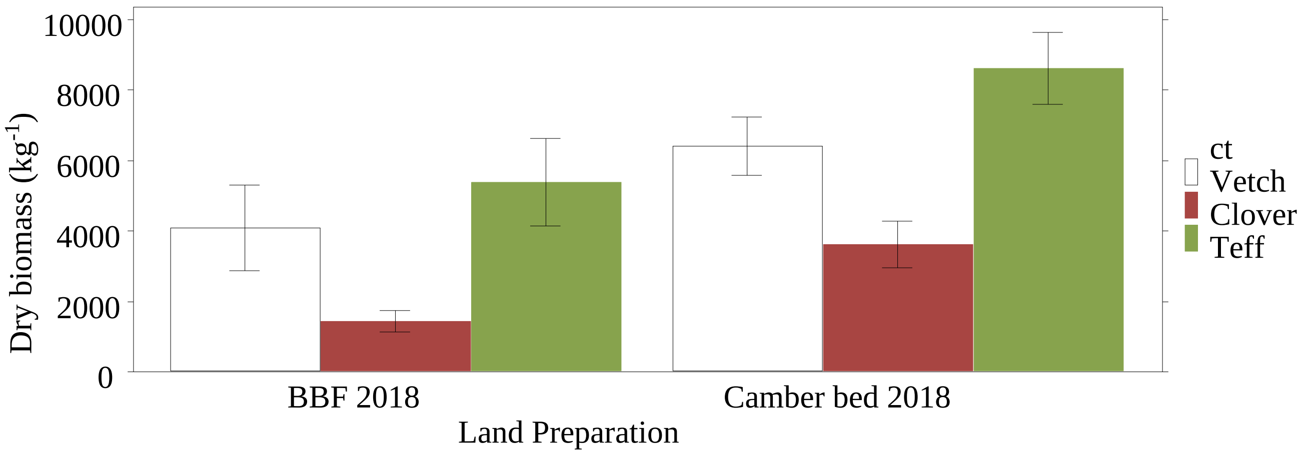


Figure 4. 4 Error bar chart showing dry biomass production on BBF and camber

Error bar showing dry biomass production of BBF and camber bed in 2018. Error bar showing at 95% C.I. ct-crop type, 1-vetch, 2-clover, 3-teff

4.4.2.2 Land preparation methods and seasonal effect

A combined analysis of variance for dry biomass across years (BBF 2018 and 2019 and camber bed 2018 and 2019) revealed that year and crop type had a significant (P<0.000) impact on the dry biomass. Phosphorus application was weakly correlated to dry biomass production, and the interaction effects were not statistically significant (Table 4.4).

Table 4.4 Analysis of variance for dry biomass over years

Source	DF	BBF 2018 and 2019		Camber bed 2018 and 2019	
		F	P	F	P
year	1	10.59	0.0028	76.54	0.001
ct	2	14.23	0.000	34.11	0.000
pl	1	6.56	0.0157	5.51	0.0257
year*ct	2	0.43	0.6527	0.1	0.904
year*pl	1	2.61	0.117	1.26	0.2708
year*ct*pl	4	0.92	0.4661	0.18	0.9464
Error	30			30	
Total	41			41	
Grand mean	3183.3			4714.7	
CV	42.3			28.29	

ct- crop type, pl-phosphorus level,

Land preparation methods influenced the dry biomass of crops. A combined analysis of variance for land preparation methods indicated that land preparation, crop type, and P application significantly influenced dry biomass in 2018, but their interaction effects were not statistically significant. In 2019, the only significant effects on the dry biomass were from the crop type (Table 4.5).

Table 4.5 Analysis of Variance for Dry Biomass Over Land Preparation Method

Source	BBF and camber bed 2018			BBF and cambeer bed 2019		
	DF	F	P	DF	F	P
LP	1	34.17	0.0001	1	1.51	0.2303
ct	2	20.19	0.0001	2	39.39	0.0001
pl	1	12.86	0.001	1	2.02	0.1684
LP*ct	2	0.48	0.6232	2	2.69	0.0882
LP*pl	1	0.15	0.6995	1	0.03	0.8749
LP*ct*pl	4	0.49	0.7436	4	0.9	0.4808
Error	36			24		
Total	47			35		
Grand Mean	5219.9			2678.1		
CV	29.57			35.73		

LP- land preparation, ct- crop type, pl.phosphorus

4.4.2.3 Nitrogen concentration and N accumulation

The N concentration in the dry biomass of crops varied among the crop species tested. On average, the N concentration in vetch was 3.13%, in clover 2.4%, and in teff 0.76% (data not shown). The N concentration in the dry biomass was significant among crops and, to a lesser extent, between crops. Phosphorus application did not affect the N concentration of crops in three out of four experiments across years and land preparation methods, except in BBF 2018 (Exp 1). The interaction effect of P application and crop type on N concentration showed significant differences among crops in 2018 compared to 2019 (Table 4.6). Over years and land preparation methods, N accumulation was higher for vetch than clover, and teff showed almost similar N accumulation but lacked statistical significance. Phosphorus application significantly ($P<0.05$) influenced the N accumulation in three of the four experiments. The interaction effects were more significant between crops than among crops. In general, the N concentration accumulatelation varied greatly among the crops tested, seasons, P application, and land preparation methods. On average, the N concentration of crops ranged from 2.8 to 0.9%, the highest for vetch, followed by clover and teff. The N concentration recorded on camber bed land preparation methods over the years was 2.4% for vetch, 2.3% for clover, and 0.8% for teff. The year had a significant ($P<0.05$) influence on the N concentration over years. Phosphorus application didn't show a significant difference over the years. A significant interaction effect for the independent variables was shown under BBF land preparation methods, but over years, camber bed land preparation methods showed no interaction effect except for year*crop type (Tables 4 4 and 4 5). N accumulation was significantly affected by the crop type. Vetch recorded the highest N yield over years under the same land preparation methods. P application and year has a significant effect on N yield. The interaction effects were also significant (Tables 4.4 and 4.5).

Table 4.6 *Anova results of N concentration and N accumulation over years*

Treatments	BBF 2018 (Exp I)		Camber bed 2018 (Exp II)		BBF 2019 (Exp III)		camber bed 2019 (Exp IV)	
	N Yield (kg^{-1})	N con. (%)	N Yield (kg^{-1})	N con. (%)	N Yield (kg^{-1})	N con. (%)	N Yield (kg^{-1})	N con. (%)
Crop type (ct)								
Teff (T)	23.0b	0.8c	31.6c	0.8c	14.8b	0.8b	20.7b	0.8b
Vetch (V)	127.6a	3.1a	163.6a	2.6a	53.7a	2.5a	58.8a	2.1a
Clovthe(C)	32.2b	2.2b	82.9a	2.3b	15.2b	2.3a	16.8b	2.3a
P level								
-P	43.9b	1.9b	79.4b	1.9a	23.9a	1.9a	26.1b	1.7a
+P	78.0a	2.1a	106.9a	1.9a	31.9a	1.8a	38.1a	1.8a
Interactions (crop type * P level)								
T+P	28.4c	0.9e	34.0e	0.7c	14.6b	0.8b	21.2bc	0.8b
T-P	17.6c	0.8e	29.2e	0.7c	15.0bc	0.8b	20.2bc	0.8b
V+P	168.3a	3.2a	185.9a	2.6a	67.1a	2.3a	72.4a	2.2a
V-P	87.1b	2.9b	141.9b	2.5ab	40.1b	2.6a	45.2b	2.1a
C+P	37.4c	2.3c	98.6c	2.3b	13.8c	2.2a	20.6bc	2.4a
C-P	27.0c	2.1d	67.2d	2.20b	16.5bc	2.3a	13.0c	2.1a

**T-teff; V-vetch; C-clover; +P and –P denote crops with and without P application; For each treatment factor, mean values with the same letter in the same column are significantly different at $P<0.05$.*

4.4.2.4 Land preparation methods and seasonal effects on crop productivity

A combined analysis of variance was conducted for dry biomass, N concentration, and N accumulation of experiments conducted in 2018 and 2019 (Table 4.7). The analysis indicates that the dry biomass of crops was highly influenced by crop type, P application, and land preparation methods. Phosphorus application significantly ($P<0.001$) affected the dry biomass in 2018, but in 2019 P application didn't show any significant difference. Land preparation methods significantly (P<0.000) increased the dry biomass of crops in 2018, but the effect of land preparation methods in 2019 showed a slight difference. In 2018, the N concentration in the dry biomass of crops was largely affected by crop type, P application, and land preparation methods; in 2019, there was no statistically significant difference found in P application or land preparation methods, except for crop type, which showed a slight difference among crop types. The interaction effect of P application and crop type on N concentration showed significant differences among crops in 2018 compared to 2019 (Table 4.7). Over years and land preparation methods, N accumulation was higher for vetch than clover, and teff showed almost similar N accumulation but lacked statistical significance. Phosphorus application significantly (P<0.05) influenced the N accumulation in three of the four experiments. The interaction effects were more significant between crops than among crops.

Table 4.7 *Analysis of variance for dry biomass, N concentration, & N yield*

Treatment	BBF and camber bed 2018 (Exp I and II)			BBF and Camber bed 2019 (Exp III and IV)		
	Dry biomass (kg^{-1})	N Concentration (%)	N accumulation (kg^{-1})	Dry biomass (kg^{-1})	N Concentration (%)	N accumulation (kg^{-1})
Crop type						
vetch	5249.1 b	2.8 a	145.8 a	2438.4 b	2.3 a	56.3 a
clover	2529.6 c	2.3 b	57.6 b	703.6 c	2.3 a	16.0 b
teff	6998.3 a	0.8 c	27.3 c	4451.3 a	0.8 b	17.8 b
P value	0.000	0.000	0.000	0.000	0.000	0.000
P rate						
-P	4157.8 b	1.9 b	61.7 b	2286.1 a	1.8 a	25.5 b
+P	5694.6 a	2.0 a	92.1 a	2775.3 a	1.8 a	35.0 a
P value	0.000	0.004	0.000	0.065	0.991	0.005
Land preparation						
BBF	3636.4 b	2.1 a	60.9 b	2183.4 b	1.9 a	27.9 a
Camber bed	6215.2 a	1.9 b	92.8 a	2878.5 a	1.8 a	32.2 a
P value	0.000	0.000	0.000	0.011	0.405	0.193
Interaction						
ct*pl	2.820	0.064	0.000	0.094	0.514	0.000
ct*LP	0.093	0.000	0.001	0.064	0.371	0.193
LP*pl	0.575	0.039	0.375	0.923	0.167	0.005
ct*LP*pl	0.156	0.644	0.022	0.884	0.787	0.003
Error	36	36	36	24	24	24
Grand Mean (kg^{-1})	4925.4	1.9	76.8	2531.7	1.8	30.1
CV (%)	14.8	4.8	18.4	30.2	15.6	31.8

**+P and-P denotes phosphorus applied and non-phosphorus applied treatments, mean values with the same letter in the same column are significantly different at P<0.05, Lp- land preparation, ct-crop type, pl-phosphorus level*

A combined analysis of variance conducted for dry biomass and N accumulation of the experiments conducted on the same land preparation methods across years (Table 4.8) showed that the effect of year, crop type, and P application significantly ($P<0.000$) influenced the dry biomass of crops. N yield was highly affected by P application and year. The effect of year and P application was more pronounced on the N accumulation in 2018, but N concentration was not affected by the P application in 2019.

Table 4.8 Analysis of variances for dry biomass, N concentration, and N yield over years on the same land preparation methods

Source	BBF 2018 and 2019 (Exp I and Exp III)						Camber bed 2018 and 2019 (Exp II and Exp IV)					
	Dry biomass (kg^{-1})			N accumulation (kg^{-1})			Dry biomass (kg^{-1})			N accumulation (kg^{-1})		
	DF	F	P	DF	F	P	DF	F	P	DF	F	P
year	1	35.1	0.000	1	61.6	0.000	1	238.2	0.000	1	289.8	0.001
ct	2	67.5	0.000	2	120.9	0.000	2	161.0	0.000	2	203.3	0.001
pl	1	18.7	0.000	1	24.9	0.000	1	20.0	0.000	1	29.5	0.001
year*ct	2	2.0	0.157	2	24.0	0.000	2	1.3	0.282	2	58.8	0.001
year*p	1	5.9	0.021	1	9.6	0.004	1	4.4	0.045	1	4.3	0.046
ct*pl	2	4.2	0.025	2	15.4	0.000	2	0.8	0.447	2	7.0	0.003
year*ct*p	2	1.1	0.346	2	2.8	0.078	2	0.5	0.636	2	0.7	0.516
Error	30			30			30			30		
Total	41			41			41			41		
Grand mean (kg^{-1})	2910				44.431		4547				62.489	
CV (%)	27				30.4		15.25				18.29	

y- year; ct- crop type; P-phosphorus level; CV-coefficient of variation; N concnitrogen concentration

4.4.2.5 Initial and residual soil mineral N

For determination of the N balance, soil mineral N assessment was performed before and after planting and harvesting the test crops. At the start of the experiments, the total initial soil mineral N at 0-40 cm was 21.4, 17.8, 15.5, and 21.1 kg^{-1} on BBF 2018 (Exp 1), camber bed 2018 (Exp II), BBF 2019 (Exp III), and camber bed 2019 (Exp IV), respectively. Soil mineral N detected after the harvest of legumes and tef ranged from 7 to 46, 53 to 82, 9 to 45, and 7 to 23 kg N^{-1} in Expts I, II, III, and IV, respectively. Excluding fallow plots, the mean soil mineral N on BBF in

2018 was higher than on the camber bed of the same year. Soil mineral N detected after harvest of legumes was higher compared to soil mineral N monitored after harvest of teff plots. The mean soil mineral N increment after vetch and clover harvest was different from that of the initial soil mineral N following tef harvest, and ranged between 3.5 to 50 and 0.6 to 26 kg N^{-1}, respectively, over years and land preparation methods (data not shown). The ratio of NO_3^--N to NH_4^+-N in the 0–40 cm soil layer for both land preparation methods and over years was between 1 and 0.4, indicating a slight predominance of ammonium-N over nitrate-N. When compared to teff, a non-leguminous planted plot, the mineral N content of the soil is often higher in soils where legumes are planted.

4.4.2.6 The Nitrogen balance

The mean N balance varied widely ranging from 53.7 to 163.9 kg^{-1} for vetch, 15.2 to 82.9 kg^{-1} for clover and 14.8 to 31.6 kg^{-1} for tef over years and land preparation methods. The N balance of clover and tef were lower than vetch in all the experiments. Over years and land preparation methods, the N balance of vetch+P ranged from 72.5 to 168.3 kg^{-1}, while vetch-P ranged from 40.1 to 141.9 kg^{-1}. In Expts I, III, and IV, the N balance of clover with and without P treatments showed negative values, except in Expt. II (67.2 versus 98.6 kg^{-1}). The N balance of tef-P ranged from 15.0 to 29.2 kg^{-1}, while tef+P ranged from 14.6 to 34.0 kg^{-1} across years and land preparation methods. In clover and tef, the effects of P on the N balance correspond with the effects of P on biomass accumulation. The N balance of all crops was higher in 2018 and on camber beds compared to 2019 and on BBF.The N balance of crops was higher under P applied treatment. The N balance calculated was positive for all crops, but the values differed between species, land preparation methods, P treatments, and years (Table 4.9).

Given that the crops were grown on the same type of soil, with the same amount of fertilizer supplied, and under the same management conditions, the variation in N accumulation could be attributable to a differential in N uptake between N_2 fixing and non-fixing crops. Therefore, the difference in N accumulation could be due to the differential in N uptake between N_2 fixing and non-fixing crops, as shown in Equation 2. Variations in meteorological conditions, crop type, soil conditions, and management approaches can all contribute to uncertainty. The calculated N fixation will be obtained from the N balance of crops minus teff+P, which is a reference to a crop without nutrient limitations in this case.

Table 4. 9 The amount of N fixed (kg^{-1}) by legumes over the reference crop teff using the total N difference method

Crop type	Experiment I (BBF 00)		Experiment II (camber bed 00)		Experiment III (BBF 01)		Experiment IV (camber bed 01)	
	N balance	N fixed	N balance	N fixed	N balance	N fixed	N balance	N fixed
Vetch-P	87.1	58.7	141.9	107.9	40.1	25.5	45.2	24.0
Vecth+P	168.3	139.9	185.9	151.9	67.1	52.5	72.4	51.2
Clover-P	27.0	-1.4	67.2	33.2	16.5	1.9	13.0	-8.2
Clover+P	37.4	9.0	98.6	64.6	13.8	-0.8	20.6	-0.6
Tef-P	17.6		29.2		15.0		20.2	
Tef+P	28.4		34.0		14.6		21.2	

4.4.2.7 Estimation of nitrogen fixation

The estimation of N fixation by the N balance method using tef+P as a reference crop ranged from 13 to 95 and 61 to 127 kg^{-1} for vetch-P and vetch+P over seasons and land reparation methods, respectively. In three out of four cases, no net contribution to fixation was calculated for clover (Expts I, III, and IV), while estimated N fixation amounted to 10 and 50 kg^{-1} for clover–P and clover+P in Expt II, respectively. Across seasons and land preparation methods, the estimated N fixation of vetch-P ranged from 44 to 132 kg^{-1} and 78 to 165 kg^{-1} for vetch+P. Comparable clover figures were 14.6 kg^{-1} for clover-P and 14.9 kg^{-1} for clover+P.

The calculated or estimated atmospheric N fixation of vetch varied with year, land preparation methods, and P nutrition in this study. To explain the variation in the estimated N fixation of clover, a graph was plotted as a function of the N content of teff and as a function of the biomass of teff at its maturity (Figure). The three plots show a strong association between clover N fixation and tef performance, as measured by N content or biomass. The associations between N fixation in vetch and teff performance differed for the two levels of P supply, indicating that vetch had a stronger positive response to extra P than teff. Apart from the different levels of P supply, the teff data are from plots with essentially identical input. The association between tef performance and N fixation can be essential to assessing the N fixation that may be expected from clover when no direct data are available (Figures 4 and 5).

4.4.2.8 Correlation between N_2 fixation and N balance

The N balance of after crops were positive, with significant differences between species, P application, and land preparation methods across years. The mean N balance varied widely, ranging from 74 to 156, 9 to 83, and 19 to 70 kg^{-1} for vetch, clover, and tef over years and land preparation methods, respectively. The N balance of clover and tef was lower than vetch. These values can be influenced by soil nitrate, crop growth, dry matter yield, and the N harvest index. The N balance of vetch was highest for P-applied treatments than non-P applied. This experiment could not find any clear trend for the increase in the N balance of clover and tef with P application or the difference in N balance between these two crops. However, approximately a 50 % increase in N balance was recorded for clover over tef in 2018 on camber beds. Using tef + P as a control, the estimation of N fixation revealed positive values for vetch but positive and negative values for clover (Figure 4.5). Thus, maintenance of soil fertility can be achieved only if legumes grow in low-nitrate soils and yields are sufficiently high to provide a reasonable potential for N fixation.

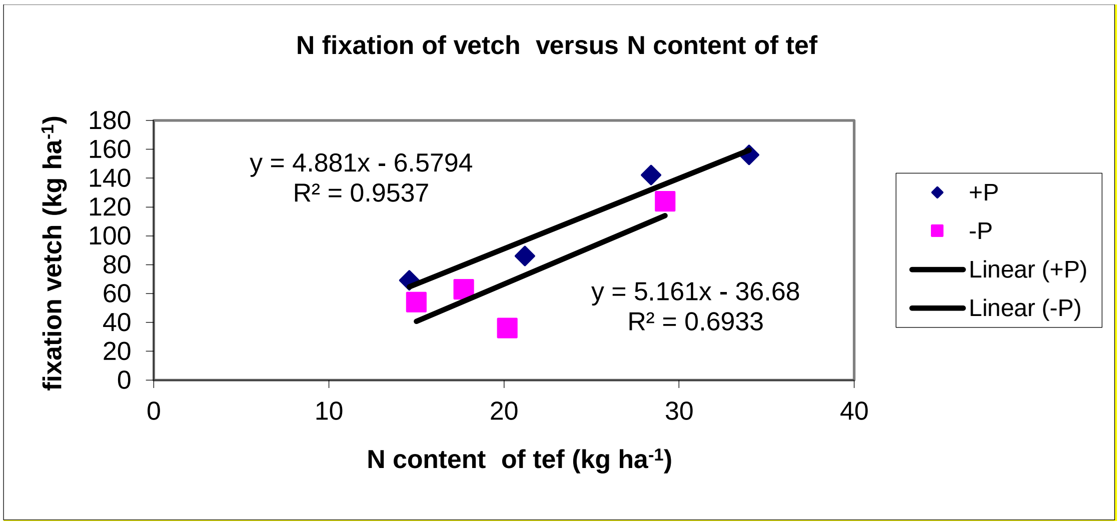


***Figure 4. 5**. The relationship between total N in dry biomass of teff and N fixation of vetch calculated using N balance method*

We observed that the calculated (or estimated) atmospheric nitrogen fixation varied depending on the year, land preparation method, and P nutrition. In an attempt to explain this variation, the estimated fixation of clover was plotted as a function of the N content of teff and as a function of the biomass of teff at its maturity. The plots show a strong association between clover N fixation and teff performance, as measured by its N content or biomass. The associations between N fixation in vetch and performance in teff differed for the two levels of P supply, consistent with a positive response to extra P in vetch than in teff.

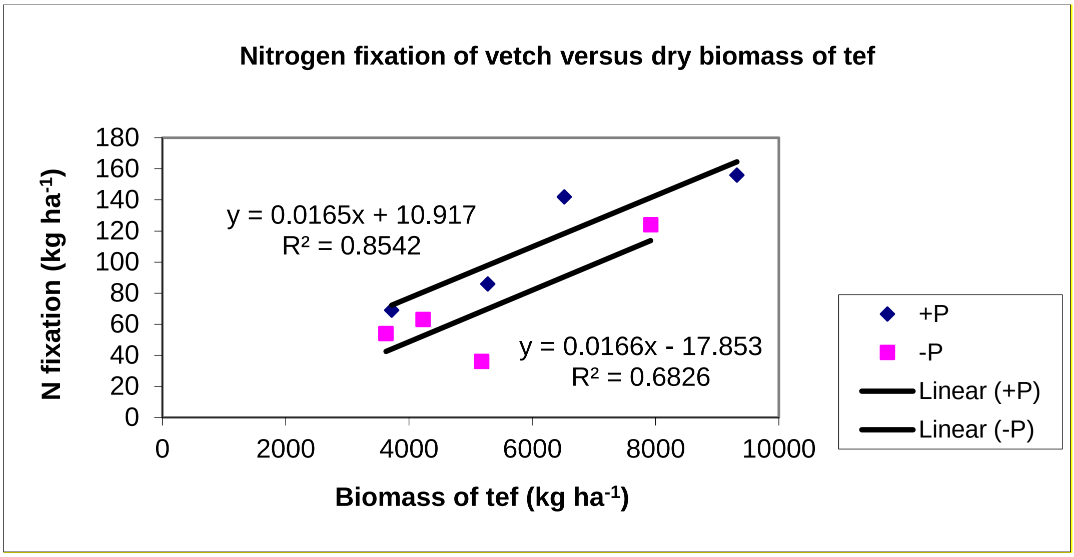


Figure 4.6. Tthe relationship between dry biomass of teff and N fixation of vetch using N balance method

Teff data are from plots with essentially similar inputs, aside from different levels of P supply. The variation in teff performance, reflects the variation in growth conditions. Vetch N-fixation appears to be similarly affected by growth conditions as teff performance (Figure 4.6). The association between tef performance and N fixation can be used to assess the N fixation that may be expected from clover when no direct data are available, while data on tef performance are at hand.

4.4.2.9 Legume N Fixed calculated using the N difference method

The N fixation estimated by the N-difference method showed a wide variation between legume type, P application, land preparation, and across years (Table 9). On BBF and camber beds in 2018, vetch+P fixed 139.9 and 151.9 kg ha1 N, respectively. Vetch-P fixed 58.7 and 107.9 kg^{-1} on BBF and camber beds in 2018, respectively. Regardless of P application, clover N fixation was lower and showed inconsistencies across years and land preparation methods. The calculated N balance considering the inputs and outputs in the system indicated that vetch crops with and without P applied showed a high N gain in the system, particularly in 2018 (Appendix A) with a positive N balance under all experiments. Based on the calculation of N balance and gain clover showed positive values in camber bed of 2018. Clover showed positive and negative N balances.

When calculating the N balance, the following inputs and outputs are required. Some of these parameters are biological N fixation, atmospheric N depositions, and Nitrogen losses due to volatilization, denitrification, leaching, surface runoff, soil erosion, and gaseous emissions. However, collecting these parameters is difficult due to several limitations. Therefore, we anticipate that the data at hand may provide some initial insight into variables that may be assessed and controlled using mineral nitrogen from fertilizer and residues. For N management, the N balance calculation helps to determine the N depletion from the soil under similar soil and climatic conditions, a genotypic difference of the crops under test.

4.5 Discussion

4.5.1 Drainage improvement and soil fertility

Improving the drainage system on Vertisols is one of the prerequisites for sustainable crop production. These soils are prone to waterlogging during the long rainy season, sticky when wet, and hard when dry, restricting the traditional farm implements' use for plowing. In this study, two drainage systems were tested by planting legumes during the crop growing season for their contribution to increasing dry biomass production and N accumulation in two legume species. Growing crops during the crop growing season may reduce the impact of rain on the land, as the traditional farming system leaves the farmland due to fear of waterlogging. In particular, camber beds showed better drained excess water and a substantially increased biomass production and N accumulation of legumes. Crop production on Vertisols is dependent particularly on the efficiency of the drainage system to remove the excess water from the farmland (Manik et al., 2019; Erkossa et al., 2005; Hess et al., 2020). The camber beds produced drier biomass than the BBF (Tables 4 4 and 4 5). Camber beds have higher raised and deeper drainage furrows and can effectively drain excess water from farmland. In years of above-average rainfall, BBF beds settle down, and the silt is deposited in the BBF furrows, prohibiting the safe disposal of the extra water from the farmland. The performance and ground cover of the vetch was better than the clover, whereas the clover showed poor germination and vegetative growth. A study conducted on Australian soils also showed that the poor performance of clover on heavy clay soils was a problem (Striker & Colmer, 2017; Striker & Colmer, 2017b; Roughley & Date, 1986). This study confirmed the importance of drainage on Vertisols for sustained crop production (Elias et al., 2022; Tekalign et al., 1993)

Waterlogging is a problem on the Vertisols of the highlands of Ethiopia in years of high rainfall, which affects crop growth and hinders nutrient availability (Striker & Colmer, 2017a). Farmers in the Ethiopian highlands typically avoid planting crops during the crop-growing season and instead rely on residual moisture to grow crops. An improved drainage system allows for planting crops on time, creates vegetative cover for the farmland, and reduces soil erosion. Planting legumes under an improved drainage system may improve soil fertility in this low-input agriculture and allow farmers to practice double cropping with reduced inorganic fertilizers. However, the crops that take the place of the crop growing season need to improve the soil's fertility and take up fewer nutrients from the soil. Legumes can be the best alternative for this farming system because they fix nitrogen and ameliorate the soil for the subsequent crop. A yearly variation in weather conditions and the land preparation methods significantly influenced the biomass production and N accumulation of these legumes during the two growing seasons. In particular, 2019 had less rainfall and reduced the biomass produced by legumes. Improving the drainage system on Vertisols creates better soil-moisture relationships for plant growth and increases crop productivity (Arduini et al., 2019). In 2019, the biomass of crops on both land preparation methods was reduced by at least 40%. In particular, rainfall in 2018 was excessive, and the improved drainage system increased dry biomass production and N accumulation. In years of below-average annual rainfall, crops may suffer from dry spells, and improving the drainage system may further deplete the soil moisture. Therefore, agro-climatic data analysis is essential for this farming system (Regassa & Elias, 2022, accepted and under publication), Optimal moisture availability is required for Vertisol farming because excess or shortage is a crop production constraint for plant growth, nutrient availability, and the development of rain-fed agricultural planning.

4.5.2 Phosphorus nutrition and biomass productivity

Vertisols are typically nitrogen- and phosphorus-deficient (Elias, 2019; Mamo et al., 2002; Tekalign et al., 1993). As result, improving soil drainage and applying the necessary nutrients are critical for successful crop production. In low-input agriculture, such as in Ethiopia, incorporating legumes into the farming system may reduce chemical fertilizer input while increasing crop production. For soil fertility improvement, legumes play an essential role in the farming systems of resource-poor farmers. On the other hand, improving drainage increases nutrient efficiency and availability (Tripolskaja & Asakaviciute, 2019). However, growing legumes during the long rainy season can reduce biomass productivity and nutrient uptake (Arduini et al., 2019).

The performance and growth of legumes and teff were good because the environmental conditions, particularly rainfall distribution, were conducive in 2018. However, the opposite trend was observed in weather conditions in 2019. Both land preparation methods resulted in lower dry biomass and N accumulation. In particular, lower values of dry biomass and N accumulation were recorded for clover, explaining the poor nitrogen fixation capacity and low

N fertilizer use efficiency manifested in the lower dry biomass production and N concentration. Legumes' nitrogen fixation is usually restricted because nodule formation is retarded without P nutrition (Faucon et al., 2015; Castagno et al., 2014). There is a lot of evidence in the literature that nutritional restrictions can affect a legume's ability to develop and fix N (Stagnari et al., 2017; Journal & Agriculture, 2001). A nutritional imbalance also influences the creation of less dry biomass. In general, to maintain the high dry biomass of legumes, P application becomes very important for legume production (Moir et al., 2016).

4.5.3. N concentration and accumulation

A positive relationship was found between biomass production, N concentration, and N accumulation. Past studies indicate that the N concentration and N accumulation are closely related to crop dry biomass production (Grüner et al., 2021; Chilagane Emmanuel et al., 2018; Anglade et al., 2015). However, the reference crop teff produced a higher dry biomass yield, but the N concentration was typically less than 1%. The study is in agreement with the previous studies conducted regarding the relationship between dry biomass and N concentration (Manoj et al., 2021; Adams et al., 2018; Anglade et al., 2015). The uptake of teff is solely dependent on soil mineral N as it is a non-N-fixing cereal crop with a high C/N ratio (Santi et al., 2013), whereas legumes use both N from the atmosphere and inorganic N from the soil (Pampana et al., 2018). Over years and different land preparation methods, the dry biomass of the tested crops showed wide variations. The variation is mainly associated with climatic conditions, land preparation methods, and P applications. The effects of year, land preparation methods, P rate, and crop type and their interactions with crop type by P application had a substantial impact on nitrogen concentration in dry biomass (Tables 4 and 5). The highest biomass was produced by vetch, which also had a high (3.1%) N content. The teff crop had the lowest N concentration (0.76%). Phosphorus application significantly increased the N content of the dry biomass of the crops studied ($P<0.001$). In general, in the dry biomass of crops, nitrogen concentration and N accumulation increased as the rate of P increased. It implies that the soil is deficient in P nutrition and that a response is expected (Faucon et al., 2015; Mamo et al., 2002).

4.5.4.The N balance and estimated N fixation

The estimated values for each parameter for the N input and output computations are shown in Table 9. Positive and negative N balances were detected, with significant differences between crop types, P application, land preparation methods, and over years. Climatic factors, soil management practices, and soil mineral N in the soil determine the N balance in a system

(Tripolskaja & Asakaviciute, 2019; Sainju et al., 2017). Soil nitrate, crop characteristics, dry matter yield, and the N harvest index can also influence the N balance. The total N difference for this cropping system indicated that vetch+P showed higher values in 2018 under both land preparation methods than in 2019.

The N fixation was higher on the camber bed across the years. The estimation of fixed N was closely correlated to the amount of the total biomass, which concurs with the findings of Sanginga (1996). The low amount of N fixed in clover was related to limited biomass production due to the early establishment problem and poor vegetative growth. Climate conditions, soil type, soil moisture, and the amount of total soil N directly or indirectly affect crop uptake and N balance in crops. In this experiment, the P application significantly influenced N balance, while clover was less affected by the P application. The variation in estimated N fixation across seasons and land preparation methods was related to the suitability of each season for crop production because N fixation was strongly associated with the accumulation of dry matter and nitrogen in tef. For example, Figure 4.5 shows the association between N fixation in vetch and biomass production in tef; the data points for +P and –P treatments fall on separate lines.

Taking into account uncertainties due to pool substitution between 14N and 15N and the uneven distribution of 15N in the soil profile, it can be assumed that results obtained with the total N difference method are more reliable than those obtained with the 15N isotope dilution method. The total N difference method is believed to be a cheap and simple alternative to the other methods. The calculation of the amount of N fixed by legumes using the total N difference method is shown in Table 10. The N fixation estimated by the N-difference method showed a wide variation between legume type, P application, and year. Planting legumes in the system may ameliorate the soil and reduce the use of inorganic fertilizer for smallholder farmers of low socioeconomic status (Kebede, 2021; Sánchez-Navarro et al., 2019).

4.6 Conclusion

Among the land preparation methods tested, camber beds had an advantage over BBF in all measured crop parameters. Clover performed poorly in all experiments, whereas vetch has consistently performed well over time and with various land preparation methods. However, the dry biomass of teff was higher than that of both legumes, but the N concentration and N content were significantly lower. Teff tolerates and performs well in water-logged conditions. Our study showed that teff on drained soil also showed excellent performance and higher biomass production, which needs further investigation. Phosphorus application boosted the dry biomass, N accumulation, and N concentration of the crops studied considerably. Crop N concentration and accumulation are related to crop species and dry biomass yield. However, this was not true for non-nitrogen-fixing teff crops, which produced higher dry biomass than vetch and clover on both land preparations but had lower N concentration and N accumulation. Short-duration crop cultivars are necessary for maintaining soil fertility and implementing double cropping on Vertisols. Improving the drainage system on Vertisols and sustainable agricultural practices are crucial to boost crop productivity. Nitrogen accumulated in the dry biomass of vetch was very high compared to clover. The potential of vetch N accumulation in the dry biomass can fulfill the N requirement of subsequent crops if incorporated into the soil. This may drastically reduce the use of chemical fertilizers for smallholder farmers.

4.7 Reference

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Appendix 4 A The calculated N gain from legume cropping systems

	Exp I (BBF 2018)					Exp II (Camber bed 2018)				
Crop type	DM (t^{-1})	% N content	N Fertilizer Yield (kg^{-1})	(Uptake + harvest N min)-(Initial N min-fertilizer N)	Total N difference method (gain)	DM (t^{-1})	% N content	N Fertilizer Yield (kg^{-1})	(uptake + harvest N min)-(Initial N min-fertilizer N)	Total N difference method (gain)
Vetch-P	2.95	3.1	87.1	77.2	28.2	5.65	2.51	141.9	136	119
Vetch+P	5.23	3.2	168.3	157.1	130.8	7.17	2.59	186.0	169	144
Clover-p	1.25	2.2	27	20	-29	2.95	2.28	67.20	60	43
Clover+P	1.64	2.3	37.4	20	-6.3	4.28	2.3	98.60	98	73
Tef-P	2.48	0.9	17.6	49		4.62	0.8	29.20	17	
Tef+P	3.81	0.9	28.4	26.3		5.44	0.8	34.01	25	
S.E	300.8	0.03	7.8	8.5		265.7	0.06	6.3	5.7	
Crop type* P	0.001	0.001	0.001	0.001		0.001	0.001	0.001	0.001	

	Exp III (BBF 2019)					Exp IV (Camber bed 2019)				
Crop type	DM (t^{-1})	% N content	N Fertilizer Yield (kg^{-1})	(Uptake + harvest N min)-(Initial N min-fertilizer N)	Total N difference method (gain)	DM (t^{-1})	% N content	N Fertilizer Yield (kg^{-1})	(Uptake + harvest N min)-(Initial N min-fertilizer N)	Total N difference method (gain)
Vetch+P	1.49	2.64	40.1	66	62	2.09	2.17	45.3	75	2
Vetch+P	2.92	2.30	67.2	81	61	3.27	2.22	72.5	126	65
Clover-p	0.73	2.26	16.6	9	5	0.62	2.16	13.1	53	-20
Clover+P	0.61	2.25	13.8	11	-9	0.86	2.45	20.7	54	-7
Tef-P	2.12	0.80	15.0	4		3.02	0.80	20.2	73	
Tef+P	2.17	0.8	14.6	20		3.08	0.9	21.2	61	
S.E	320.1	0.11	5.8	8.2		251.6	0.2	5.6	5.2	
Crop type* P	0.01	0.001	0.001	0.001		0.001	0.001	0.001	0.001	

Chapter Five- Nitrogen Release from Mineralization of Legume Residues Incorporated into Vertisols of the Ethiopian Highlands

5.1 Abstract

The use of legumes in cropping systems for smallholder farmers in developing countries has been shown to increase plant nitrogen (N) availability in the soil, leading to higher crop yields. To better understand this process, a study was conducted to monitor the release of N from legume residue over time. Calculating the percentage difference in cumulative mineral N between residue added and control treatments helped us understand N mineralization patterns and optimize the timing of N release for plant uptake. This knowledge can help smallholder farmers make more informed decisions about incorporating legumes into their cropping systems to improve yields. This involves conducting regular sampling and calculating cumulative mineral N levels at different intervals. By adjusting the amount of legume residue used and the timing of its incorporation, farmers can ensure a steady supply of plant-available N for their subsequent crops, leading to higher yields. Additionally, using nitrogen-fixing cover crops or intercropping legumes with other crops can also help optimize N release and uptake in the soil. Smallholder farmers can determine the optimal timing for incorporating legume residue by considering factors such as the rate of N release from the residue, the N needs of their subsequent crops, and the climate and soil conditions of their specific location. Conducting small-scale trials and closely monitoring the N mineralization patterns can also help farmers determine the best timing for incorporation. Consulting with local agricultural experts or participating in farmer networks can also provide valuable insights and knowledge on optimal timing for legume residue incorporation.

Keywords: legume residue, incorporation, nitrogen mineralization, nitrogen availability, Vertisol,

5.2 Introduction

The soils of Sub-Saharan Africa (SSA) are considered one of the most fragile soils that suffer from unsustainable land use practices and population pressure (Tully et al., 2015). These challenges are combined with climate change, soil erosion, and land degradation, causing a decline in crop productivity and posing a serious threat to food security (Obalum et al., 2012). Unpredictable rainfall and poor soil fertility have a particularly significant impact on the small-scale farmers of the region (Bjornlund et al., 2022). To increase food production, there has been a gradual encroachment on natural habitats and the expansion of agricultural land by clearing forests. If the trend continues without proper oversight, it could result in the loss of valuable natural habitats and potentially trigger an environmental crisis in the future (D. R. Williams et al., 2021). It is important to note that soil fertility depletion has far-reaching consequences for the long-term sustainability of agricultural land, leading to decreased crop yields and ultimately leading to food insecurity (Pedro A. Sanchez, 2015).

Ethiopia, located in the SSA region, faces significant challenges from climate change, land degradation, soil fertility depletion, and population pressure (Drechsel et al., 2001). The high price of chemical fertilizers, shortage of supply, socio-economic constraints, and nutrient mining practices worsen the situation, impeding the improvement of soil fertility (Bingxin & Alejandro, 2014; Shiferaw et al., 2009). Vertisols are one of the dominant soil types in the highlands of Ethiopia, where soil fertility depletion emerges as a significant biophysical factor leading to decreased crop production. These soils are generally considered fertile, but their physical properties pose limitations on crop production potential (Tekalign et al., 1993; Tekalign Mamo, 1988). Additionally, excessive rainfall on Vertisols leads to waterlogging, making Vertisol unfavorable for crop production under traditional farming practices. Vertisols become sticky when wet and hard when dry, impeding farm implements from cultivating the land. During dry seasons, wide and deep cracks appear down the profile (Ababa, 1993). Subsequently, Vertisols are typically left bare during the main rainy season, and planting crops is done after the rain arrives in September. Fallowing the soil aggravates soil erosion because the soil is unprotected, which deteriorates the soil's physical properties. To address the issue of waterlogging and late planting on Vertisols, the Ethiopian Institute of Agricultural Research has proposed several management options, including drainage improvements and the application of chemical fertilizers. The broad bed and furrow maker were recommended to drain excess water from the farmland. The yield of crops was improved due to improved drainage, early planting, and inorganic fertilizer application (Astatke, Jabbar, et al., 2002).

For low-input agriculture like Ethiopia, organic materials such as incorporating legumes into the cropping systems and incorporating their residues into the soil may have important benefits because legumes can supply plant-available N to succeeding crops when decomposed and mineralized (Rusinamhodzi et al., 2016; Jamont et al., 2013). In terms of environmental sustainability, it provides important benefits in preserving soil organic composition to maintain and improve soil fertility, soil structure, and biodiversity, and reduce erosion (Foyer et al., 2019). Smallholder farmers may benefit if a more sustainable, low-cost, and efficient integrated nutrient management system compatible with the existing farming system is adapted and implemented.

Therefore, alternative sources of soil ameliorating mechanisms that are economically feasible and environmentally friendly must be devised.

Legumes play an important role in ameliorating the soil through the decomposition of their biomass, biological N fixation capacity, and rotation. Legumes grown in rotation or in association with cereals can serve as important N sources for smallholder subsistence-oriented agriculture in tropical regions (Stagnari et al., 2017). But with grain legumes, most of the above-ground parts of the grain are removed at harvest; residual effects must come from the below-ground parts and any leaves that fall to the soil during crop growth. In this case, the use of forage legumes may have a two-fold advantage. Incorporating legume residues into the soil not only adds organic matter and meets the immediate N requirement of crops through subsequent mineralization but also enhances the soil infiltration rate. Additionally, the surplus residue can be utilized as feed for animals during dry periods. Nutrient mineralization patterns during the decomposition of organic materials are related to legume biomass accumulation, the chemical composition, or quality, of the organic inputs, climatic conditions, soil physico-chemical properties, and the nature of soil micro-organisms (Neely et al., 1994), cultural practices (method and rate of application), soil properties, and its decomposition rate.

The decomposition of any residue can be regulated by microorganisms (Abera et al., 2012). The environment, or microclimate (temperature and moisture), may override all these factors, making it difficult to predict their decomposition when grown under different conditions. Gupta (2016) reported that residue decomposition can be governed to some extent by placement on the soil surface (mulch) or incorporation into the soil. In Ethiopia, we lack information regarding legume residue decomposition, N-mineralization, and its availability to succeeding crops. This experiment was initiated to study N-mineralization from legume residue incorporation under field conditions on Vertisols of the Ethiopian highlands. In 2018 and 2019, we initiated a study on wheat-legume residue, incorporating trials to observe how the seasonal dynamics of soil N are influenced by the addition of legume residue. We conducted an experiment under field conditions, using BBF and camber bed land preparation methods. In this experiment, we tested three different legume residue management options to study N-mineralization. The study aims to address the knowledge gap regarding legume residue decomposition, N mineralization, and their availability to succeeding crops in the context of Vertisols in the Ethiopian highlands. The study will examine how different ways of managing legume residues affect soil N levels throughout the seasons. This will help us understand if legume residues are effective in restoring soil fertility and meeting the N needs of crops. The main objectives of this study are to evaluate the patterns of N mineralization that occur when incorporating legume plant materials into Vertisols in the Ethiopian highlands.

5.3 Materials and methods

5.3.1 Study site description

The experiments were conducted over two cropping seasons, starting in 2018 and 2019, on two tillage practices at the Holeta Research Center (located at 09^{0} 02' 12’’ N, 38^{0} 29' 00” E, and an elevation of 2400 masl), situated approximately 35 kilometers west of Addis Ababa, Ethiopia. The soil at the study site is black clay soil, a type known as Vertisol. The soil exhibited very low levels of total N (0.08 %), (Kirk, 1950), available phosphorus (8.1 mg kg^{-1}) (Pierzynski & Sharpley, 2009), and a pH of 5.6 (Kalra, 1995) at a depth of 0–40 cm. The bulk density of the soil was measured at 1.3 g m^{-3} (Walter et al., 2016), and the initial soil mineral N (Bremner, 1985) at 0–40 cm depth was between 25.8 and 38.3 kg^{-1} for both land preparation methods and across the years (Table 5.1).

Table 5. ***1*** *Summary of soil characteristics of the experimental plots*

Depth (cm)	pH (1:1) (H_2O)	Total N (%)	P, Bray II (mg kg $^{-1}$)	OC (%)	Na^+	K^+	Ca^{2+}	Mg^{2+}	Initial soil mineral N (kg^{-1})			
									BBF		Camber bed	
					cmol kg^{-1}				NH_4^+	NO_3^-	NH_4^+	NO_3^-
0-20	5.3	0.09	9.2	1.29	0.32	1.58	35.3	14.2	14.01	10.90	6.3	9.7
20-40	5.8	0.07	7.0	0.97	0.35	1.58	35.3	12.8	7.43	6.91	9.2	11.4

5.3.2 Weather conditions

The study area has a long-term average rainfall of 1095 mm, with two peaks occurring during the long rains (June to September) and the short rains (February to May). Approximately 75% of the annual rainfall is received during the long rains, which is the main cropping season, while the remaining 25% is received during the short rainy season (February to May). The total and monthly rainfall for the experimental periods exhibited significant variability, with 597 and 384 mm between December and June in both the 2018–2019 and 2019–2020 periods, respectively. In particular, the year 2019 experienced the highest precipitation levels, while the year 2020 had below-average rainfall, resulting in drought conditions. The rainfall distribution from April to June was characterized by alternating wetting and drying cycles. Temperature variations during this period were minimal, with the minimum recorded at around 11°C and the maximum at around 27°C (Table 5.2).

Table 5. 2 Monthly distribution of rainfall and temperature (2018-2020)

Month	Rainfall (mm)		Temperature (^{0}C)			
			2018/2019	2018/2019	2019/2020	2019/2020
	2018/2019	2019/2020	Max. T	Min. T	Max. T	Min. T
December	3.0	0	24.1	5.4	24.4	3.0
January	18	99	24.9	7.0	25.7	6.5
February	10	22	26.6	7.5	26.7	7.5
March	196	88	24.9	10.4	27.4	10.4
April	31	24	26.7	9.4	26.1	11.0
May	124	8	25.2	10.2	26.0	10.6
June	215	143	22.2	9.5	24.2	9.6
Total	597	384				

5.3.3 Experimental setup and treatments

In 2018 and 2019, vetch (*Vicia dascarpa*), clover (*Trifolium quaratinianum*) and tef *(Eragrostis tef* (Zucc.) Trotter) were planted on broad bed and furrow (BBF) and camber bed land management systems, comprising eight treatments with a code: Vetch-P, Vetch+P, Tef-P, Tef+P, Fallow-P, and Fallow. Where - P was no P applied, while + P denotes crops planted with P application at the rate of 18 and 26 kg^{-1} for legumes and tef, respectively. A fallow treatment was not included on camber beds. The experiments that were conducted starting in 2018 were named BBF 2018 (Exp I) and Camber Bed 2018 (Exp II), while the experiments that were conducted starting in 2019 were named BBF 2019 (Exp III) and Camber Bed 2019 (Exp IV). The BBF consists of raised beds of about 80 cm wide, alternating with furrows of 40 cm wide and 15 cm depth between beds. BBF is made every year at planting crops by using the broad bed and furrow maker (BBM), assembled with two unmodified, traditional plows, and is usually oxen-drawn (Astatke, Mohamed Saleem, et al., 2002). A tractor-mounted mouldboard plow constructs Camber beds by opening drainage ditches of 50 cm depth and piling the soil to the center. A tractor-mounted mouldboard plow constructs Camber beds by opening drainage ditches of 50 cm depth and piling the soil to the center. The camber bed needs maintenance every three to four years and can serve for several years.

The experiment was designed in RCBD with four replications on both land preparation methods. The plot sizes of the treatments were 11 m by 12 m on BBF and 6 m by 18 m on camber beds. The crops were planted in late June and harvested around mid-December. In December, the plots of legumes were split, and subplot treatments were established based on the pre-planned harvest and legume residue management treatments. The sub-treatments identified were: N-residue harvested in December (control); S-residue harvested (removed) in December and reapplied to the same plot in April; R-residue retained on the plots until incorporation time in April; RS-residue retained on the plots; and an extra amount of residue equal to the amount of S was added at incorporation time in April. A summary of the experimental details is shown in Table 3. The legume residue was incorporated into the soil using a hand hoe. In each replication of BBF, one bed of tef and fallow plot was divided into five parts. These parts were then incorporated into the legume residues of Vetch-P, Vetch+P, clover-P, and clover+P in April. Additionally, a control plot with no residue applied was also established. In each replication of BBF, one bed of tef and fallow plot was divided into five parts. These parts were then incorporated into the legume residues of Vetch-P, Vetch+P, clover-P, and clover+P in April. Additionally, a control plot with no residue applied was also established. The plot area for these treatments was 2 m^2. On the camber bed of tef-P plots, the same treatments were applied to plot sizes of 1.75 m^2. Code OM is given to these subplots. The amounts of legume residue incorporated into these plots were determined based on the amount of legume residue incorporated into S plots of the respective legumes and land preparation methods. To avoid having varying amounts of legume residues returned, the weights of the residues were adjusted for moisture content, and equal amounts were returned for each treatment in the replication. Table 5.3 provides a summary of experimental details, while Table 5.4 presents the amount of plant material and N added as legume residue to each treatment in the replication

Table 5.3 Summary of experimental treatments on BBF and camber bed

Main plot treatment	P level (kg^{-1})	N fertilizer (kg^{-1})	Residue management* Treatments (subplot treatments)
Vetch-P	0	46	N, S, R, RS
Vetch+P	18	46	N, S, R, RS
Clover-P	0	46	N, S, R, RS
Clover+P	18	46	N, S, R, RS
Teff-P	0	60	OM, V-P, V+P, T-P, T+P
Teff+P	26	60	OM, V-P, V+P, T-P, T+P
Fallow-P	0	0	OM, V-P, V+P, T-P, T+P
Fallow+P	26	0	OM, V-P, V+P, T-P, T+P

N/P fertilizer applied- in the form of urea and triple superphosphate

5.3.4 Procedures and Methods of soil sampling

On both land preparation methods, measurement of soil mineral N was conducted to a depth of 0–20 and 20–40 cm. Soil mineral N sampling was done in two phases, i.e., a) the period covering the planting time of legumes and tef (June) until legume residue incorporation time (April) and b) the period covering legume residue incorporation time in April until the planting time of the following year's test crop wheat planting (June). The sampling dates identified were: i) initial soil mineral N before the start of the experiments; ii) at harvest of legumes, tef, and fallow plots in December; iii) before legume residue incorporation time in April; and vi) before planting the test crop wheat. Samples were collected at the sampling date identified, simultaneously from inside and outside (around) the PVC tubes installed. To measure mineralization in situ (Raison et al., 1987), 40 cm PVC tubes with a diameter of 10 cm were driven into the treatments (3 each) with their top 5 cm above the soil surface. The cylinders were closed with a can to prevent the entry of rain. Near the top, a 1.0 cm diameter hole was drilled in the PVC wall to facilitate gas exchange. By comparing the initial (December/April) and final (April/June) values, an estimation of the net mineralization during the specific period was obtained. This allowed for a comparison between the soil mineral N of legume residue incorporated and the soil without residue applied. Soil bulk densities were calculated from core samples 100 mm cm^3 collected at each depth. The bulk density was used to convert ammonium and nitrate data from mg N kg^{-1} to kg N^{-1}.

5.3.5 Soil analysis

Immediately after collection, soil samples were stored in a refrigerator at 4°C and processed, usually within one or two days. KCL-extractable soil mineral N for 0–20 and 20–40 cm depths were determined according to procedures described in Bremner (1985). NO_3^- N in KCL extracts was determined by CD reduction and absorption measurements at a wavelength of 540 mm. NH_4-N was determined by steam distillation. Separate sub-samples were weighed for the determination of moisture content by oven drying at 105°C for 24 hours.

Table 5. 4. *Legume residue incorporated and N added in terms of legume residues*

a)

Precursor crop	Treatment*	BBF 2019		Camber bed 2019		BBF 2020		Cambered bed 2020	
		Residue applied (kg^{-1})	N added from legume residue (kg^{-1})	Residue applied (kg^{-1})	N added from legume residue (kg^{-1})	Residue applied (kg^{-1})	N added from legume residue (kg^{-1})	Residue applied (kg^{-1})	N added from legume residue (kg^{-1})
Vetch-P	N	0	0	0	0	0	0	0	0
	S	2659	79	5368	135	1482	39	2077	45
	R	2447	72	4136	104	1688	44	1050	23
	RS	4874	144	9293	233	2872	75	3134	68
Vetch+P	N	0	0	0	0	0	0	0	0
	S	5406	174	7130	184	2980	69	3242	72
	R	3716	120	4684	121	2242	52	1593	26
	RS	9573	308	12049	311	5450	125	4732	79
Clover-P	N	0	0	0	0	0	0	0	0
	S	1444	31	2808	64	496	11	608	13
	R	898	19	2717	62	207	5	342	7
	RS	2444	53	5262	120	666	15	972	21
clover+P	N	0	0	0	0	0	0	0	0
	S	1682	38	4028	93	578	13	971	24
	R	1243	28	3720	86	446	10	433	11
	RS	2852	65	7016	161	980	23	1396	34

**Treatment- C- control, legume residue removed, S-legume residue harvested, stored, and reapplied in April, R-legume residue retained on the plots and incorporated in April, RS-legume residue retained on the plots and the respective amount of S added and incorporated in April*

5.3.6 Statistical analysis

An analysis of variance (ANOVA) using Statistics 10.2 (http://statistix.software.informer.com/) software was used to examine soil mineral N, setting the precursor crop as the main factor and soil mineral N collected from legume residue management treatments as sub-treatments. The resulting ANOVA tables were used to determine treatment differences for various sampling dates and depths. Analyses of variance were also performed, and the means separated by Duncan's were used to examine the main treatment effects, soil mineral N of the sub-treatments, and their interactions.

5.4 Results

5.4.1 Soil and weather conditions

The study site exhibits poor total N and moderately available phosphorus levels according to the analysis done at Holeta Research Center (Table 5.1). The physical characteristics of the soil pose challenges to nutrient availability due to their tendency to become waterlogged, sticky, and plastic when wet and hard with wide, deep cracks when dry. The rainfall experienced during the experimental periods was highly variable, with a total of 597 mm and 384 mm between December and June of 2018/19 and 2019/20, respectively. Specifically, 2019 was the wettest year, while 2020 had below-average rainfall and experienced drought conditions. From March to June, the rainfall pattern consisted of alternating wetting and drying cycles. The temperature variation during these periods was minimal, ranging from around 11°C to 27°C, as indicated in Table 5.2.

5.4.2 Dry matter production, N concentration, and N yield of legumes

The biomass production of legumes in this experiment was found to be influenced by various factors, including weather conditions, species differences, phosphorus application, and tillage practices. In the case of vetch, the dry matter production ranged from 1490 to 7173 kg^{-1} across different years and land preparation methods. Similarly, for clover, the range was observed to be from 610 to 4270 kg ha^{-1}. The N content within the dry biomass also displayed variation, with vetch ranging from 40 to 186 kg^{-1} and clover ranging from 14 to 99 kg^{-1}, depending on the specific year and land preparation methods employed.

5.4.3 Initial and residual soil mineral N accumulation

The initial total soil mineral N detected in June at 0–40 cm was typically between 26 and 38. without clear differences between land preparation methods. Soil mineral N detected at the harvest of crops in December didn’t show any significant difference between crops but showed significant ($P<0.05$) differences between seasons. The total soil mineral N levels varied across the four experiments. In Experiment I, the range was from 45.3 to 54.5 kg ha^{-1}; in Experiment II, it was from 32.0 to 49.4 kg ha^{-1}; in Experiment III, it was from 51.3 to 84.1 kg ha^{-1}; and in Experiment IV, it was from 92.7 to 113.1 kg^{-1} (Table 5.5).

Table 5.5 Soil mineral N accumulation at harvest of crops in December

Treatment	BBF 2018	Camber 2018	BBF 2019	Camber 2019
	Total soil mineral N (kg ha^{-1})			
Vicia-P	51.7	44.4	84.1	90.4
Vicia+P	50.4	33.1	62.2	113.1
Trifolium-P	54.5	43.2	51.3	99.6
Trifolium	44.6	49.4	52.8	92.7
Teff-P	45.3	32.0	80.5	108.3
Tef +P	53.2	34.4	65.7	93.3
Fallow	84.5			
average	54.9	39.4	64.9	99.3
SD	9.9			
SE	2.8	2.4	2.45	2.4

The initial soil mineral N levels in June were lower compared to December sampling, and the increase was 13 kg ha^{-1}, 15 kg ha^{-1}, 23 kg ha^{-1}, and 64 kg ha^{-1} for Expts I, II, III, and IV, respectively. Experiments III and IV showed significant soil mineral N accumulation, and in Exp I, where fallow was included, the average accumulation of total soil mineral N in December was the highest at 84.5 kg ha^{-1} (Table 5.1). Preceding crops and land preparation methods didn't show any significant difference in the accumulation of soil mineral N in December, but above all, the season had a significant ($P<0.05$) effect on the higher soil mineral N accumulation. In both years, preceding crop by depth had a significant ($P<0.001$) effect on the accumulation of soil mineral N over years and land preparation method. Table 5.1 shows the distribution of soil mineral N from June to December under the different treatments.

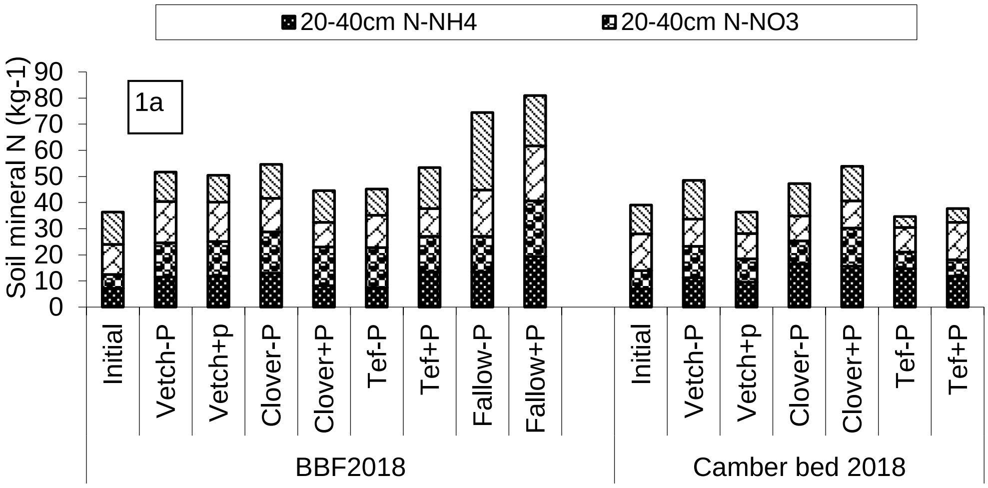
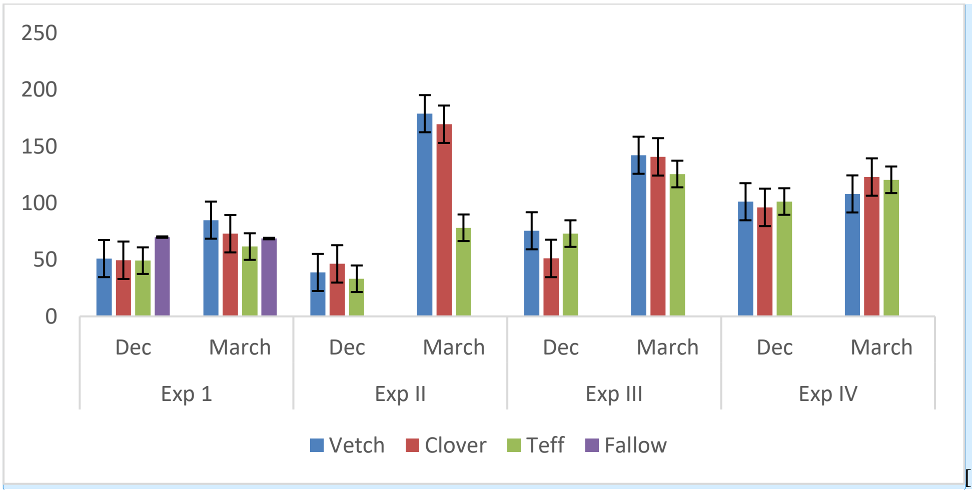


Figure 5. 1 Initial and residual soil mineral N

Figures 5 1 a and 1b: Initial amount of soil mineral N at planting in June and at harvests of legumes and tef in December (a) data from 2018, b) data from 2019. From top to bottom, sections of each bar represent nitrate-N at 0–20 cm, ammonium-N at 0–20 cm, nitrate-N at 20–40 cm, and ammonium-N at 20–40 cm. The error bars represent the standard deviation of the mean total amount of soil mineral N at a depth of 0–40 cm.

5.4.4 N mineralized in March

Total soil mineral N levels in March, before legume residue incorporation, exhibited a significant and gradual increase compared to the levels observed in December. This increase was found to be statistically significant (P<0.05) across all experiments and land preparation methods, as shown in Figure 5.2.



[Ma13]

Figure 5.2 . Soil mineral N accumulated under crops and tillage practices (December and March)

ANOVA results show that soil mineral N accumulation was significantly affected by legume types, depth, and their interactions (Table 5.6) for the four experiments (Exp 1, Exp II, Exp III, and Exp IV) during December and March. In Experiment IV, the crop type and depth had a highly significant effect on soil mineral N accumulation in both December and March (p-value < 0.0001). In Experiment I, the crop type had a significant effect in December (p-value < 0.0048) and March (p-value < 0.0358). In Experiment II, the crop type had no significant effect in December (p-value = NS) but a highly significant effect in March (p-value < 0.0001). In Experiment III, the crop type and depth had a significant effect in December (p-value = 0.0004 and p-value < 0.0018, respectively) but not in March (p-value = NS). The interaction between crop type and depth also had a significant effect in Experiment I in December (p-value < 0.0143) and in Experiment III in March (p-value < 0.0112). Overall, the ANOVA table shows that crop type, depth, and their interaction all play a significant role in soil mineral N accumulation during these periods.

Table 5.6 ANOVA results for total soil mineral N accumulation in March.

ANOVA	Exp 1		Exp II		Exp III		Exp IV	
	Dec	March	Dec	March	Dec	March	Dec	March
Crop type	<0.0048	<0.0358	NS	<0.0001	<0.0001	<0.0004	<0.0001	<0.0001
Depth	NS	NS	NS	<0.0001	<0.0001	NS	<0.0001	<0.0018
Crop type* depth	<0.0143	<0.0112	NS	<0.0001	<0.0001	<0.0112	<0.0001	<0.0001

5.4.5 Soil mineral N monitored in April

Total soil mineral N accumulated inside and outside the PVC tubes in April showed an increasing trend compared to December and March sampling, under both land preparation methods and over the years (Table 5.7). In general, the average soil mineral N values obtained from inside the PVC tubes in April ranged from 91 to 107.5, 78.2 to 180.3, 119.0 to 165.4, and 99 to 131.1 kg ha^{-1} in Expts I, II, III, and IV, respectively. Overall, the net N mineralization over years and land preparation ranged between 0 and 0.5 for Exp I, II, and III. Exp IV. There was no clear trend observed for the higher accumulation of mineral N between land preparation methods and legume species, while lower mineral N accumulation was detected for previous tef plots inside the PVC tubes. Total soil mineral N detected on both land preparation methods ranged from 23.2 to 114.4 kg ha^{-1} on average over the years. The N mineralized from inside PVC tubes of previously vetch-planted plots ranged from 36 to 95 kg ha^{-1} and from 44 to 78 kg ha^{-1} for clover over seasons and land preparation methods. Crop type was significant at the $P<0.05$ probability level on the accumulation of total soil mineral N for all the experiments.

The accumulation of soil mineral N outside the PVC tubes was lower than that inside the PVC tubes and on average decreased by 31, 67, 30, and 28% for Expts I, II, III, and IV, respectively. The values ranged from 45.7 to 116.9 kg ha^{-1} for legume treatments over the years. Higher N mineralization values were recorded for BBF land preparation methods in 2019 and 2020. Total soil mineral N detected on both land preparation methods ranged from 50.3 to 103.2 kg ha^{-1} on average over the years. Soil mineral N detected in April outside the PVC tubes ranged from 45.7 to 116.9 kg ha^{-1} for legume treatments over the years. Soil mineral N detected on the plots was very low (39.4 kg ha^{-1}) in Exp II (camber bed 2018), while 61.6, 97.8, and 98.9 kg ha^{-1} were monitored on BBF and camber bed of 2019 and 2020, respectively.

Table 5.7 Legume residues N mineralization (kg ha^{-1}) and net N mineralization over years (kg^{-1}/day)

Tillage practices	Crop type	December	April outside PVC	N mineralized	Net N mineralized	April (inside PVC)	N mineralized	Net N mineralized
BBF 18	Vetch-P	51.7	91.9	40.2	0.3	96.3	44.6	0.4
	Vetch+P	50.4	77.9	27.5	0.2	107.5	57.1	0.5
	Clover-P	54.6	87.1	32.5	0.3	102.1	47.5	0.4
	Clover+P	44.6	58.9	14.3	0.1	117.3	72.7	0.6
	Tef	45.2	61.6	16.4	0.1	91.0	45.8	0.4
	Fallow	53.4	68.7	15.3	0.1	102.0	48.6	0.4
Cam 18	Vetch-P	44.4	62.5	18.1	0.1	180.3	135.9	1.1
	Vetch+P	33.1	45.7	12.6	0.1	177.5	144.4	1.1
	Clover-P	43.2	52.1	8.9	0.1	148.1	104.9	0.8
	Clover+P	49.4	51.7	2.3	0.0	191.1	141.7	1.1
	Tef	33.2	39.4	6.2	0.0	78.2	45.0	0.4
BBF 19	Vetch-P	84.2	96.5	12.3	0.1	119.0	34.8	0.3
	Vetch+P	72.1	102.5	30.4	0.2	165.4	93.3	0.7
	Clover-P	51.1	116.9	65.8	0.5	141.9	90.8	0.7
	Clover+P	55.3	101.4	46.1	0.4	139.7	84.4	0.7
	Tef	45.3	97.8	52.5	0.4	125.7	80.4	0.6
Cam 19	Vetch-P	89.5	67.3	-22.2	-0.2	99.9	10.4	0.1
	Vetch+P	112.8	82.4	-30.4	-0.2	116.3	3.5	0.0
	Clover-P	99.6	83.6	-16.0	-0.1	114.8	15.2	0.1
	Clover+P	92.7	95.2	2.5	0.0	131.1	38.4	0.3
	Tef	80.3	98.9	18.6	0.1	120.5	40.2	0.3

Fallow plots, which were established only in 2018, on BBF plots, had an average of 102 kg ha^{-1} mineralized N at 0–40 cm depth. P applied to legumes didn’t show any significant increase in N accumulation Figure 5.3.

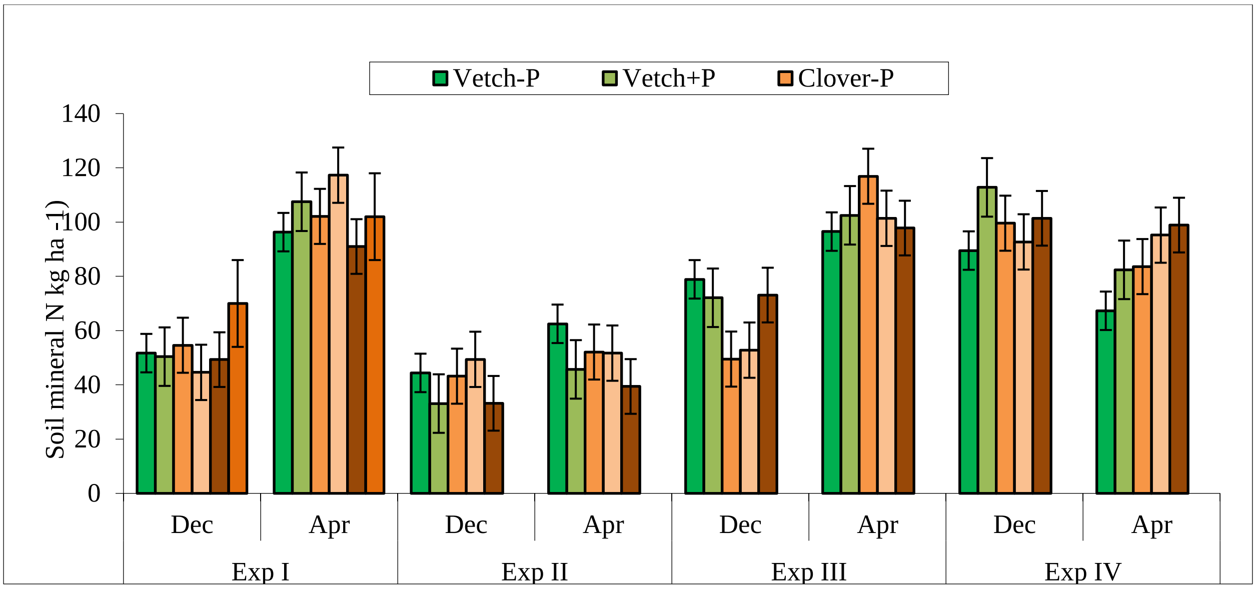


Figure 5.3 Soil mineral N accumulation under different crops and land preparation methods between December and April (outside PVC tubes in April)

5.4.6 Soil mineral N in June

In June, the long rainy season begins, and it is the main cropping season under rainfed conditions. The total soil mineral N levels in June, both outside and inside the PVC tubes, during the planting of the test crop wheat, consistently decreased over time. This decrease occurred regardless of the legume residue placement treatments and land preparation methods used in all the experiments. The decrease was more pronounced on N plots and R treatments of both legume residues and under both land preparation methods. Levels of total soil mineral N to 40 cm depth under legume residue placement treatments in 2020 varied between 101 and 192 kg N^{-1} in April and were in the range of 45 to 97 kg^{-1} in June. There were significant interaction effects (P<0.001) between crop type, legume residue placement treatments, and their interactions (Table 5.8). Ammonium nitrate to 0-20 cm depth was affected by residue placement treatments and remained relatively constant and lower throughout the season. Over time, as the total soil mineral N levels decreased under the three-residue management treatments, there was a gradual reduction in the relative contribution of ammonium nitrate to the soil mineral N content. Total soil mineral N accumulated in June outside the PVC tubes was higher than in June outside the PVC tubes and ranged from 43.4 to 56.4, 41.4 to 58.2, 96.5 to 116.9, and 67.3 to 98.9 kg^{-1} for Exp I, Exp II, Exp III, and Exp IV, respectively

***Table 5.8** ANOVA results for legume residue placement treatments on soil mineral N accumulation over years and tillage practices*

ANOVA	BBF 2018	Camber 2018	BBF 2019	Camber 2019
*Crop type	0.0063	0.0034	ns	ns
*Treatment	0.0004	0.0001	0.0001	0.0001
Depth	Ns	0.0041	ns	ns
Crop type* treatment	0.0001	0.0001	0.0001	0.0022
Crop type*depth	0.0035	0.0005	0.0049	0.0406
Treatment * depth	0.0022	0.0001	0.0001	0.0005
Crop type*treatment * depth	0.0002	0.0001	0.0001	0.0058

**Crop type-vetch and clover; Treatment – legume residue placement (N, S, R, and RS)*

5.4.7 The Relationship between Soil Mineral N Inside and Outside the PVC Tube

Simple regression functions for soil mineral N inside and outside PVC tubes are presented in Table 5.9. Soil mineral N was strongly correlated with legume residue N applied for inside the PVC tubes, in Expts I and II (R2=0.70, 0.74) and weakly correlated in Expts. III and IV (R2= 0.45, 0.55). For every amount of legume residue applied 34. 69, 38, and 45 kg^{-1} soil mineral N was mineralized for Exp I, II, III, and IV. The slope and intercept do not differ much from each other with in the experiments between vetch and clover residue N applied. The relationship between soil mineral N inside the PVC tubes and field plots showed a close relationship in at least 2 experiments out of four. In summary, both experiments show that an increase in legume residue N applied is associated with an increase in soil N mineralized inside and outside the PVC tubes in June. However, the BBF experiment has lower intercept and slope values compared to the camber bed experiment, indicating a smaller overall effect of legume residue N on soil N mineralization. The Camber Bed experiment has higher intercept and slope values, suggesting a stronger relationship between legume residue N and soil N mineralization. Table 5.9 shows the slope values for each experiment and we can observe that values of the slope inside the PVC tubes are higher than the outside one in three out of four experiments, suggesting the relationship between legume residue N incorporated and soil N mineralization in June inside had a stronger relationship. In the Camber bed 2019 experiment, the inside PVC tube slope value (0.94) is significantly higher than the outside PVC tube slope value (0.37). This indicates a much stronger relationship between legume residue N incorporated and soil N mineralization in June inside the PVC tubes than outside in that particular experiment. Soil mineral N was strongly correlated with legume residue N applied (R2 = 0.69, 0.65) for Exp I and Exp III. The correlation was very poor for soil mineral N (outside PVC) and legume residue N applied. The relationship between soil mineral N inside the PVC tubes and outside was highly correlated in three out of four experiments (R2 between 0.65 and 0.86).

Table 5.9 Regression Equation of the relationship between Soil N mineralization in June inside and outside the PVC tubes vs legume residue N incorporated

	June inside		June outside	
Expts	Intercept	slope	Intercept	slope
BBF 2018	93.76	0.11	60.5	0.16
Camber bed 2018	124.9	0.36	59.52	0.08
BBF 2019	111.89	0.24	89.07	0.07
Camber bed 2019	120.3	0.94	93.32	0.37

5.4.8 Soil mineral N on teff and fallow plots

Total soil mineral N accumulated after harvest of tef and on fallow plots in December was 24.6 and 35 kg ha^{-1} at 0–40 cm depth. In April, these values increased, and they were 45.2 and 50.9 kg ha^{-1} for teff and fallow plots, respectively. Legume residues of vetch and clover were incorporated into the soil, and PVC tubes were installed in each treatment of previously planted teff and fallow plots in April. The determination of the decomposition and N mineralization of the legume residue was monitored inside and outside the PVC tubes in May. The ANOVA result showed that there was no significant difference observed in the accumulation of total soil mineral N between legume residues and land preparation methods.

5.4.9 Effect of Legume residue placement on N mineralization

Relatively uniform mineral N accumulation in the 0–40 cm soil layer persisted in the absence of legume residue in S plots, while comparatively higher soil mineral N was detected under legume residue-retained plots of R and RS plots in all the experiments. Both residue placement and the season had a significant ($P<0.001$) effect on N mineralization for all the experiments. The difference in soil mineral N during this period was mainly due to the removal of legume residue (S) and the different amounts of legume residue retained on the plots (R, RS). The soil mineral N increase due to legume residue retention was highly variable between treatments, land preparation methods, and seasons. The increase over the control (S) ranged between 16 and 28, 9 and 26, 5 and 18, and 4 and 28 kg ha^{-1} for vetch-P, vetch+P, clover-P, and clover+P, across years and land preparation methods, respectively. This suggests that gradients of net N mineralization developed in response to increased available substrate on the soil surface due to retained plant residues, which were likely decomposed and mineralized over time. Higher levels of inorganic N were observed in Experiments III and IV compared to Experiments I and II, indicating a significant seasonal effect on the overall N accumulation and subsequent mineralization of legume residue. In all experiments and across multiple years, treatments without residue application exhibited lower values of soil mineral N compared to treatments with legume residue amendments.

The initial total soil mineral N accumulated under tef and fallow plots in December showed higher values under fallow plots, and it was usually in the form of nitrate N. Soil sampled in April for nitrate N and ammonium nitrate determination showed higher concentrations compared to those in December, with greater values for nitrate N under fallow plots. The net N mineralization between December and April ranged from 9 to 28 kg ha-1. The apparent N mineralization between legume residue amended and control ranged between 10 and 85 and 9 and 42% in May and June, respectively, for the plots. For fallow plots of the same period, it ranged from 22 to 73 and from 12 to 95%. A tendency toward immobilization was detected under tef and fallow plots from TP0 residue-incorporated plots, showing higher total soil mineral N accumulation under the control plots. There was no consistency observed for the higher apparent N mineralization for both sampling periods among legume residue-incorporated treatments.

5.5 Discussion

Crop residues are one of the most important sources of N mineralization and available N supply for succeeding crops (Chen et al., 2014; Peoples et al., 2015). Crop residue incorporation and compost application are farming practices that play a critical role in maintaining soil fertility in low-input agricultural systems in developing countries (Sarkar et al., 2020). The practice helps to maintain the level of soil organic matter, release nutrients, enhance soil moisture conditions, and can be used as an environmentally friendly waste management strategy as well as a means of improving soil organic matter. Crop residues are an important source of organic matter that can be returned to the soil for nutrient recycling and to improve soil physical, chemical, and biological properties (Kumar & Goh, 2000).

The dry biomass production of the legumes tested in these studies showed a variable value. This is mainly due to the crop's growth characteristics and N-fixation abilities, which can influence their biomass production capacity and N content (Danso & Eskew, 1984). The higher N content of legumes compared to teff is attributed to legumes' ability to fix atmospheric N in addition to soil mineral N from the soil. The lower N content in the dry biomass of teff may be due to the lower availability of N in the soil, which can lead to lower N uptake by cereals, resulting in lower N content compared to legumes. Nutrient mineralization patterns during the decomposition of organic materials are related to legume biomass accumulation, the chemical composition, or quality, of the organic inputs (Palm et al., 2015), climatic conditions, soil physico-chemical environment, the nature of soil organisms (Swift et al., 1979), cultural practices (method and rate of application), soil properties, and its decomposition rate (Grzyb et al., 2020).

5.5.1 Initial and root N-min

The baseline measurement of inorganic N in the soil didn’t show a significant difference between the two tillage practices over the years. The experiments were conducted with similar management practices and environmental conditions, and that may have contributed to lower variability of the baseline soil mineral N measurements. In December, after the harvest of the crops, residual soil mineral N (root and litter) under all treatments showed an increasing trend. Root N mineralization from legumes-harvested plots can contribute to the overall nutrient availability in the soil, as legume roots contain high levels of Nand other essential nutrients (Fornara et al., 2009). This mineralization process can also impact the decomposition rate of residues left on the soil surface, as the presence of legume roots can increase microbial activity and nutrient cycling. However, the effect of root mineralization on soil nutrient dynamics may vary depending on the type of legume and its placement in the soil (Li et al., 2020). The increase in soil mineral N under the harvested legumes is attributed to the decomposition and subsequent N mineralization of N-rich litters and roots. The role of microbial activity in this process is instrumental in breaking down organic matter and releasing N into the soil (Khatoon et al., 2017). The higher soil mineral N detected under the fallow plots may be due to immobilization or the decomposition of previous organic matter in the soil. Over time, as the microbial activity slows down or the organic matter becomes depleted, the immobilized Nis gradually released back into the soil in the form of mineralized N. The application of phosphorus had a notable impact on the production of dry biomass in crops, while the mineralization of N remained unaffected. Seasonal variability primarily influenced the highest levels of N mineralization observed under the crops, as revealed by the analysis. Specifically, it was observed that the favorable moisture and temperature conditions in 2019 created a conducive environment for plant growth, residue decomposition, and subsequent N mineralization.

5.5.2 April N-min

In December, after the harvest of the crops and on fallow plots, three PVC tubes were inserted into each treatment in the replication of all the experiments. Measurements of soil mineral N were collected for the determination of soil minerals from inside and outside the PVC tubes in April from the legume residue treatments and the control. A tendency for soil mineral N to increase was observed for all the treatments, including those outside and inside the PVC tubes. The increase in soil mineral N accumulation in April of 2018 and 2019 indicates that, in addition to root and litter decomposition, legume residue incorporation treatments had a greater influence. The N mineralized during April is considered to be the difference in soil mineral N between December and April in legumes minus that of tef or plots without cover crops. A wide variation in soil mineral N was observed due to preceding crops, legume residue placement treatments, seasons, inside and outside PVC tubes, and land preparation methods (Figure 5.2 and 5.3). The effect of residue placement on N mineralization is an important factor to consider when studying residue decomposition in soil. When residues are left on the soil surface, there is less inorganic N immobilization compared to when they are incorporated into the soil (L. J. Li et al., 2013; Coppens et al., 2006). This is because there is less contact between the residues and soil microorganisms, resulting in slower decomposition rates (Coppens et al., 2006). It is also important to note that moisture and temperature can play a significant role in N mineralization, as well as the type of residue and its exposure to sunlight. In fact, climatic conditions, non-limiting inorganic N conditions, and contact between soil and residues will affect these potential decomposition values in field conditions (Grzyb et al., 2020).

At the time of sampling in April 2001, 290 mm of unusual early rain occurred through March to early May, and a substantial soil mineral N flush was apparent. The flush of soil mineral N detected during this time can be traced back to the decomposition of legume roots, mineralization of soil organic matter, a combination of root and litter decomposition, and the mineralization of N from legume residue incorporated. The comparatively dry season in May and the optimum soil environment may have also contributed to microbial activities activating properly, so that nitrate loss is apparent in 2020 under both land preparation methods. Wetting of the soil after the dry season (January through February) results in an increase in available N, as earlier reported by several researchers (Borken & Matzner, 2009; Lu et al., 2020; Gregory et al., 1997). This is attributed to an increase in net N mineralization upon moistening of dry soils (Birch, 1958). The magnitude of the flush depended on the organic matter content and length of the preceding dry period. The decomposition of organic materials depends on rainfall received, C/N ratio, soil temperature, and microbial activities (Parr & Papendick, 2015). The accumulation of nitrate-N is higher compared to ammonium-N during this period, and the potential loss of nitrate-N is high due to leaching by leaching.

5.5.3 Comparsion between N min inside and outside pvc tubes

The study investigated the mineralization dynamics of legume residue inside and outside PVC tubes following residue incorporation. The findings revealed higher levels of soil mineral N within the PVC tubes. The controlled environment in the tubes facilitated decomposition and N mineralization, resulting in higher soil mineral N levels compared to the natural conditions outside the tubes (Raison et al., 1987). Outside the PVC tubes, various factors, such as higher soil temperatures and rainfall, come into play. These factors can potentially lead to the loss of readily available inorganic N through processes like denitrification and leaching (Khanna & Raison, 2013). Consequently, the mineral N levels observed outside the tubes may be lower due to these environmental factors. However, it is crucial to acknowledge that the results obtained within the PVC tubes may not perfectly reflect the actual mineralization rates in the field. The controlled environment of the tubes may not fully represent the complex dynamics of soil ecosystems, which can influence the rates of mineralization and nutrient availability in real-world conditions.

5.5.4 Soil mineral N in June

The rapid decline of soil mineral N that occurred during July compared to April sampling in both years might be mostly due to the movement down the soil profile of nitrate N. The proportion of nitrate N to ammonium nitrate increased under both land preparation methods during this period. Depth, legume residue management treatments, and their interactions significantly affected the total soil mineral N. In addition, residue management treatments were also highly significant ($P<0.001$) on the accumulation of soil mineral N under both land preparation methods and over the years. As June is the planting time for main-season crops in the highlands of Ethiopia, there has been a big difference between inside and outside the PVC tubes in soil mineral N from incorporated legumes. In particular, legume residue outside the PVC tubes was lower, and this can be attributed to environmental conditions that prevailed during the end of May and early June, representing the start of the rain that may have caused a flush of nitrate N, resulting in a decrease. June is the best time for evaluating the availability of previously incorporated into the soil, which can be monitored to evaluate the potential contribution of legume residues to the overall N supply in the cropping system. If we compare the available soil mineral N with the recommended fertilizer rate for wheat, which is 60 kg^{-1}, more or less comparable amounts of soil mineral N were detected in June. However, several factors affect the availability of inorganic N from legume residues, making it possible to reduce the recommended fertilizer rate by half. Considering these potential environmental effects, it is crucial to carefully assess and manage the application of legume residue N, even if it exceeds the recommended rate. Sustainable agricultural practices aim to optimize nutrient use efficiency while minimizing negative environmental impacts. Implementing strategies like precision nutrient management, adjusting application rates based on soil and crop needs, and adopting conservation practices can help mitigate potential environmental effects.

5.5.5 Effect of residue placement on N mineralization

Microorganisms present in the soil typically consume the available N, resulting in the initial soil mineral N being lower than the residual soil mineral N. Additionally, N can undergo various processes in the soil, such as mineralization, immobilization, leaching, and volatilization (Khanna & Raison, 2013). Based on this experimental design, the initial soil mineral N refers to the amount of available N present in the soil before the legumes and tef were planted. Factors such as previous fertilization, organic matter decomposition, and residual N from previous crops can influence the baseline level of mineral Nin the soil at this stage. As the legumes and tef grow and develop, they have the ability to fix atmospheric N through symbiotic relationships with N-fixing bacteria. This biological N fixation process allows legumes to convert atmospheric N into plant-available forms, increasing the overall N content in the soil (Khanna & Raison, 2013). Consequently, during the harvest of the legumes, the soil mineral N levels are expected to be higher than the initial levels due to N fixation by legumes and the subsequent release of mineral N into the soil. On the other hand, the residual soil mineral N refers to the remaining Nin the soil at the time of the tef harvest. This residual Nis influenced by various factors, including the N uptake by legumes and tef, N losses through processes such as leaching and volatilization, and the potential mineralization or immobilization of N by soil microorganisms. The residual soil mineral N levels will depend on the balance between N inputs from the legumes and losses from the system.

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Chapter Six- The Nitrogen Fertilizer Replacement Values of Incorporated Legumes Residue to Wheat (*Triticum eastivum*) on Vertisols of the Ethiopian Highlands

6.1Abstract

Soil fertility depletion and continuous cereal cropping are reducing crop production in Ethiopia. Integrated Soil Fertility Management (ISFM) is a good approach for resource-poor farmers because ISFM can help reduce the need for inorganic fertilizer by increasing nitrogen (N) availability in the soil. The study aimed to investigate the effect of precursor crops, legume residue management practices, tillage practices, and N levels on wheat yield. The experiment was set up using a split plot in randomized complete block design with three replications. The N fertilizer replacement value method was used to estimate the N contribution of legumes to a succeeding wheat crop. The results showed that grain yield and N uptake of wheat crops varied in response to N fertilizer, legume residue management treatments, and tillage practices. Legume residue incorporation positively influenced the agronomic parameters of wheat compared to teff and fallow wheat rotations. The average N fertilizer replacement value from legume rotation was 18 to 46 kg ha^{-1}. This study showed that a one-year legume-in-biannual wheat rotation is preferable to lying bare fallow during the cropping season. Nevertheless, drainage during legume and wheat cropping is a condition for providing full positive impacts.

Keywords: fertilizer replacement value, residue management, rotation, ISFM, tillage practice, Vertisol

6.2 Introduction

Smallholder farmers are the primary food producers in Sub-Saharan Africa (SSA), where climate change, soil degradation, and mismanagement of agricultural lands are challenging sustainable crop production (1, 2). The soils have lost their natural fertility, and organic matter is depleted, causing aggravated food insecurity and poverty (3, 4). Given that low soil fertility is the major crop production constraint for substance-oriented smallholder farmers, several researchers in the field of soil fertility have proposed ISFM for such environments (3, 4, 5). Integrated Soil Fertility Management (ISFM) is an approach that aims to improve soil fertility and crop productivity through the combined use of organic and inorganic nutrient sources. Integrated Soil Fertility Management (ISFM) is an approach that aims to improve soil fertility and crop productivity through the combined use of organic and inorganic nutrient sources. ISFM is important because it can improve soil health, increase the availability of nutrients and soil organic carbon, help increase crop yields, reduce the environmental impact of agriculture, and also be a promising opportunity for sustainable crop production (5, 6, 7). Legumes can fix atmospheric N and are essential in ISFM because they provide organic resources, alleviate soil constraints by improving soil fertility and fertilizer uptake, and suppress weeds (8). Among others, legumes play a significant role in crop rotation with cereals since they assist poor resource farmers in reducing inorganic fertilizer use, which is constantly increasing (Matusso & Mucheru-Muna, 2014). Particularly deep-rooted legumes have access to deep residual soil N and increase the amount of N available to successive shallow-rooted crops (Thilakarathna et al., 2016). Legumes improve soil fertility and instantly increase the availability of nutrients and soil organic carbon while being environmentally friendly and sustainable. Particularly deep-rooted legumes have access to deep residual soil N and increase the amount of N available to successive shallow-rooted crops (Thilakarathna et al., 2016). Forage legume rotations have benefits beyond just boosting the availability of N but also improving the productivity of the farming systems (Bell et al., 2022). Concerns over the increasing cost and environmental impact of high inorganic N inputs have led to a reappraisal of the role of legumes in maintaining soil fertility and in providing environmental and economic benefits (11, 12).

Ethiopia is a country in the SSA where substantial land degradation and soil fertility depletion are the result of environmental factors and unsustainable land management practices (Megerssa & Bekere, 2019). Cultivation of steep slopes, deforestation, erosive rainfall patterns, excessive grazing, and a lack of effective conservation measures cause land degradation (14, 15). Continuous cereal cropping predominates in agricultural practices and significantly worsens soil erosion and soil fertility depletion (13, 15). Legumes are highly recommended as a natural N source for farming systems in Sub-Saharan Africa (SSA), particularly in countries like Ethiopia. These legumes provide essential N for soil health and crop growth, making them valuable in low-input and resource-limited agricultural settings. Additionally, they have the potential to restore organic matter in degraded soils (Snapp et al., 2018). Legume leftovers provide N to future crops in the short term and contribute to long-term soil fertility. They do this by promoting the growth of beneficial microorganisms, recycling nutrients, and helping to maintain or increase soil organic matter (Kermah et al., 2018). Thus, the identification and recommendation of techniques that are both environmentally friendly and produce acceptable crop yields in a sustainable and profitable manner is important for crop production in order to meet the current increase in demand for food. Management practices are the major drivers of sustainable farming because they can modify soil quality through improvements in soil physical, chemical, and hydrological properties. Thus, agricultural practices that conserve natural resources without compromising yields and depend less on inorganic fertilizer are at the center of sustainable agriculture.

Although chemical fertilizer applications increase crop yields, Ethiopian farmers use below-optimal rates of inorganic fertilizers due to a lack of resources and a shortage of cash. Therefore, farmers grow grain legumes after two to three years of continuous cereal cropping. Crop-livestock integration plays an essential role in farming systems because it consists of a range of resource-saving practices that favor the efficient recycling of natural resources by creating a beneficial synergy between crop and livestock production, thus using the outputs of one system as inputs or resources for the other system. The effects of preceding crops, tillage practices, rotation, N application, and crop residue management can be an important venture for low-input agriculture like Ethiopia because the soils are inherently low in soil fertility status. In addition to soil degradation, suboptimal fertilizer application, soil and water erosion, and drought are undermining sufficient crop production. In particular, Vertisols are soils that face physical constraints and suffer from soil and water erosion, resulting in reduced crop yields and trapping smallholder farmers in a vicious cycle of poverty. Thus, the identification and recommendation of techniques that boost crop production in a sustainable and profitable manner without affecting the environment is important for this environment in order to meet the current increase in demand for food. Sustainable farming preserves soil quality and protects the environment from adverse effects. Management practices are the major drivers of sustainable farming because they can modify soil quality.

The low system productivity created a competing interest between soil fertility, livestock feed, and household energy requirements. Crop residues are used for livestock feed, while manure is used to fulfill household energy requirements (Mengistu, 2018). The legume stover is uprooted at harvest, and hence there is little or no N buildup in the soil to assist the following cereal crop (Cabrera et al., 2005). The legume stover is uprooted at harvest, and hence there is little or no N buildup in the soil to assist the following cereal crop (G. Alemayehu et al., 2020). The benefits of legumes for this farming system in terms of N availability, environmental sustainability, and a pollution-free environment are a priority when considering legumes in cropping systems. Incorporating legumes into crop rotations can help improve soil fertility and reduce the need for synthetic fertilizers. Legumes are known to fix atmospheric N into the soil through their root nodules, which can be used by other crops in the rotation. For low-input agriculture like Ethiopia, where the majority of farmers are economically poor to purchase the ever-increasing inorganic fertilizers, low-cost agricultural technologies that increase soil fertility, reduce soil erosion, are environmentally acceptable, and increase crop productivity are paramount (Stagnari et al., 2017). The advantages of legumes in the cropping system are explained in terms of direct N transfer, residual fixed N, nutrient availability and uptake, effect on soil properties, breaking of pests' cycles, and enhancement of other soil microbial activity (Kebede, 2020). The best benefits from legumes and the biological nitrogen fixation (BNF) system can be utilized by integrating them into cropping systems. In a legume-based BNF system, nutrients are transferred from legumes to cereals through the decomposition and mineralization of legume residues. (22, 9). Legume residues are a better source of mineral N for succeeding crops than cereal residues. This is because legume residues have a relatively high N content and a relatively low C: N ratio compared to cereal residues. Given the growing concern for the sustainability of the highland farming system, this study has been initiated, giving due emphasis to tillage practices, residue management treatments, and better crop rotations. The study aims to enhance and conserve soil fertility, which is vital for farm productivity among smallholder farmers. The study will help smallholder farmers improve their crop yields and income by providing them with information on how to improve soil fertility and increase crop yields. For resource-poor farmers, ISFM is a good option because crop rotation or legume residue incorporation can help reduce the inorganic N fertilizer needs of the subsequent crop due to the increased availability of nutrients.

Vertisols cover approximately 7.6 million hectares of land in the Ethiopian highlands. Cereal-based cropping systems are the dominant farming system in the Vertisols of the Ethiopian highlands. These soils are prone to land degradation and soil fertility losses due to environmental factors and mismanagement of agricultural lands. When wet, it becomes plastic, sticky, and waterlogged; when dry, it shrinks, and wide cracks open down the profile, limiting the use of conventional farming equipment (23, 24). Climate change and rainfall variability (Regassa & Elias, 2022c) adversely affect tillage practices under traditional farming systems and contribute to low crop production (26, 27). In addition to drainage improvements, Vertisols are poor in available plant nutrients due to their physical limitations. In this connection, to overcome the prevailing situations, the use of both organic resources and a reasonable quantity of chemical fertilizers may help poor resource farmers reduce the high cost of chemical fertilizers to be purchased. The inclusion of legumes in systems based on cereals is a crucial alternative to increasing soil fertility and crop productivity. In particular, Vertisols constrain crop yields and expose smallholder farmers to a vicious cycle of poverty due to soil and water erosion impacting them and reducing crop productivity. However, we lack information regarding legume residue incorporation and the N transfer to subsequent crops under Vertisol conditions in Ethiopia.

Therefore, the aim of this study was to evaluate the N fertilizer replacement values of incorporated legume residues and the N contribution to subsequent wheat crop yields in vulnerable agroecosystems facing challenging conditions in the central highlands of Ethiopia.

6.3.Materials and methods

6.3.1.Description of the study site

The experiments were conducted at the Holeta Agricultural Research Center, located at 9° 02' 60" N, 38° 29' 59" E, and at an altitude of 3800 meters above sea level in the central highlands of Ethiopia, some 35 km west of Addis Ababa. The four months of the growing season rainfall (June–September) varied considerably for the three-year experimental period: 655, 509, and 755 mm for 2019, 2020, and 2021, respectively (Figure 6.1). The 35-year mean rainfall of the growing period for the study area is 768.2 mm. The trend shows that rain for the experimental periods was lower than the long-term mean and showed high variability. The mean monthly minimum and maximum air temperatures for the study periods ranged between 5^{o}C to 12^{o}C and 22^{o}C to 28^{o}C, respectively.

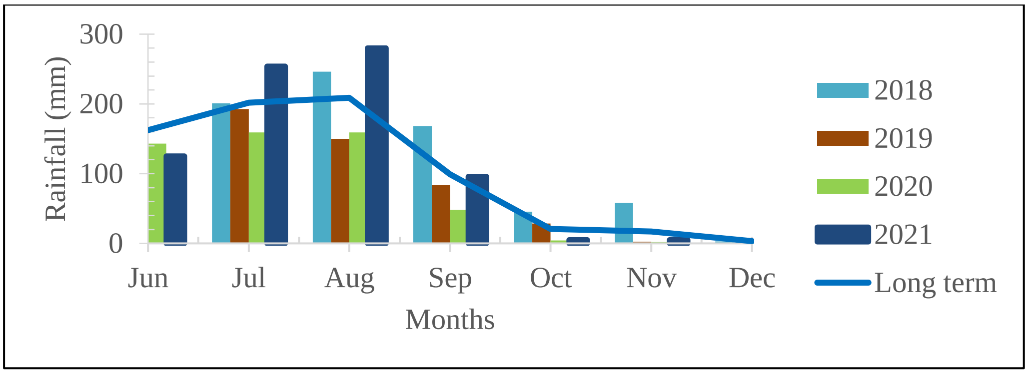

Figure 6.1 *Seasonal and long-term (35-year) rainfall for the crop growing period (2019-2021)*

6.3.2 Soil sample collection and analysis

Prior to establishing the wheat experiments, soil samples were collected from each treatment under legumes and tef plots of both tillage practices. Soil samples were taken randomly from each treatment at three specific depths (0–20 cm, 20–40 cm, and 40–60 cm) using an auger. Each depth of the treatment was replicated three times. One composite sample was created from each depth by thoroughly mixing the collected replicate samples. A total of 36 composite soil samples, 18 from each tillage practice, were sent to the Holeta Agricultural Research Center soil and plant nutrition laboratory for the determination of soil properties. Soil properties were determined on an air-dried base, sieved with a 2-mm mesh. We analyzed the total N using the micro-Kjeldahl method (Nitrogen, 1965) total phosphorus by Bray II (Bray R H & Kurtz L T, 1945), particle size distribution using the hydrometer method (Bouyoucos, 1962), and organic carbon by Walkley and Black (Walkley, 1935). The simple barium chloride method was used to determine cation exchange (Hendershot & Duquette, 1986). The physical and chemical characteristics of the soil showed an average of 0.8% total N, 0.97% organic carbon, 10.4 P (Bray, mg kg-1), and a pH of 5.9 (1:2.5 soil: water).

6.3.3 Experimental design and treatment arrangements

The wheat experiments were conducted on plots of land that had previously been planted with legumes and teff, using BBF and camber bed tillage practices, along with the application of P fertilizers. The results of this study were published in Heliyon (Regassa & Elias, 2022a). Upon reaching maturity, the legumes were either removed, incorporated, or retained on the plots to be used as a treatment during wheat planting. Then, the wheat experiments were established on these tillage practices by dividing the legume plots into six subplots. Wheat was planted on sub-plots with three different N rates (N0-control, N1-30 kg N ha^{-1}, and N2-60 kg N ha^{-1}) and three different legume residue management treatments. The legume residue management treatments were: S: legume residue was removed in December and re-applied in April. R: legume residue was retained on the plots and incorporated in April. RS: legume residue was retained, with the same amount as S, from their respective treatments and incorporated in April. The previously planted teff plots and the newly established bare fallow plots were subdivided into three subplots for N fertilizer application only. The schematic representation of the field layout is presented in Figure 6.2.

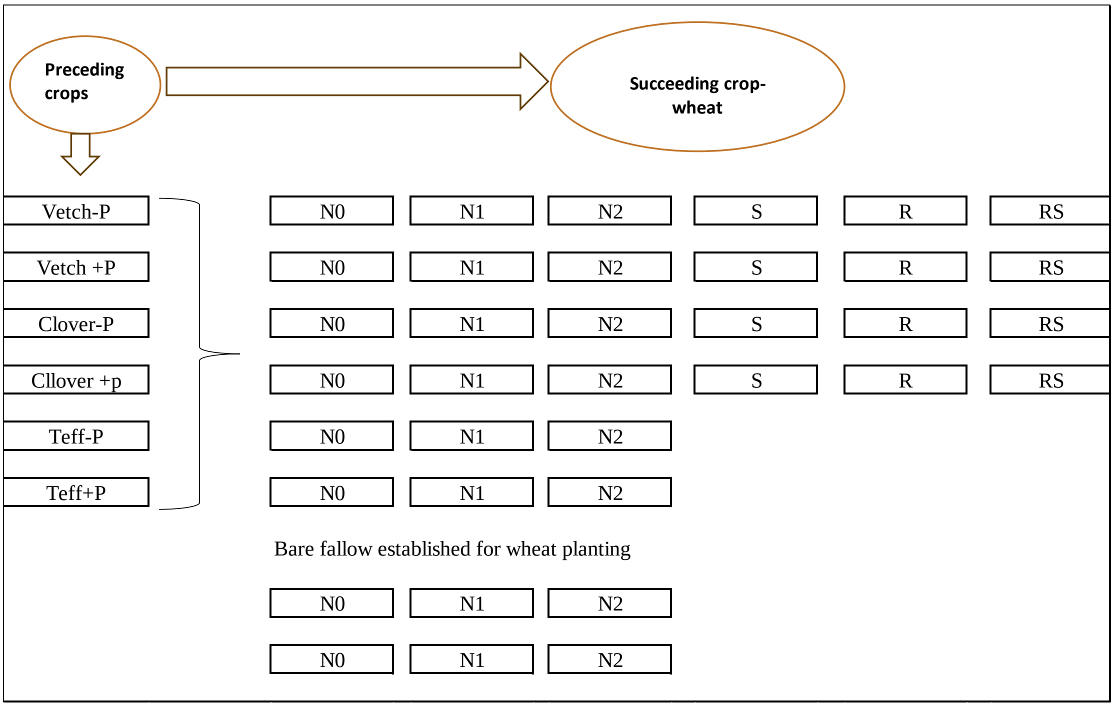

Figure 6.2 Schematic representation of experimental treatments

The experiments were designed as a randomized complete block with a split-plot design, replicated three times. The main factor of the experiment was the preceding crops, while the subplot factors consisted of N fertilizer and legume residue management treatments. The wheat variety HAR 1685 was used as the test crop. The experiments were conducted using both tillage practices for two consecutive years (2019–2020). The plot size for the BBF experiment was 7.2 m^2, whereas for the camber beds, it was 6.25 m^2. A summary of the treatment arrangements for wheat planting is provided in Table 6.1. The wheat planted on BBF and camber beds in 2019 was named Experiment I and II, representing the first series of first-season BBF and camber bed experiments. Similarly, the wheat planted on BBF and camber beds in 2020 was named Experiment III and IV, representing the second series of first-season experiments on BBF and camber beds. The wheat experiments were continued in 2020 and 2021 and were referred to as the second series of second-season experiments.

Table 6.1. *Preceding crops and subplot treatments for wheat planting*

Preceding crops	*Sub treatment	Fertilizer and legume residue N added kg ha^{-1}			
		Experiment I (BBF 2019)	Experiment II (Camber bed 2019)	Experiment III (BBF 2020)	Experiment IV (Camber bed 2020)
Vetch-P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
	S	79	135	39	45
	R	72	104	44	23
	RS	144	233	75	68
Vetch+P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
	S	60	184	69	72
	R	174	121	52	26
	RS	120	311	125	79
Clover-P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
	S	31	64	11	13
	R	19	62	5	7
	RS	55	120	15	21
Clover+P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
	S	39	93	13	24
	R	29	86	10	11
	RS	66	161	23	34
Tef-P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
Tef+P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
Fallow-P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60
Fallow+P	N0	0	0	0	0
	N1	30	30	30	30
	N2	60	60	60	60

Tillage practices

BBF is constructed by attaching a curved metal sheet to both sides of a local plow (maresha). The maresha opens drainage ditches 20 cm in depth, while the metal sheets scope the soil to either side to construct a bed of 80 cm in width when the plowing oxen turn to the other side. The implement constructs raised beds about 80 cm wide, alternating with furrows 40 cm wide and 20 cm deep. The BBF has been constructed annually at the time of crop planting. A tractor-mounted moldboard plow creates camber beds by opening drainage ditches of 50 cm depth and piling the soil to the center, making a concave-shaped bed. Camber beds can have a width of 4 to 9 meters (in the present study, 6 meters), the top of which is about 50–60 cm above the bottom of the furrow. The camber bed needs maintenance every three to four years and can serve for several years. We maintained weed-free conditions in the plots by performing hand-weeding. No insecticide or fungicide was applied since there was no outbreak of insects or diseases. Harvesting was done manually using a hand sickle.

6.3.4 Plant sampling and analysis

At full maturity, the wheat was harvested from 7.2 and 6.25 m^2 of BBF and camber bed tillage practices. Grain and straw yields were determined for each plot. Subsamples were taken to determine grain yield at 12.5% and dry biomass production by putting them in an oven at 70°C for 24 hours. Sub-samples from each plot were ground to pass through a 2 mm mesh and analyzed for total N in the grain and straw by a micro-Kjeldahl procedure (Guebel et al., 1991). The harvest index was calculated as the fraction of grain dry matter to total dry matter. The total dry biomass was obtained by summing up grain and straw yields. The various components of fertilizer N use efficiency, namely the N agronomic efficiency (NAE), N recovery efficiency (% NRE), and N physiological efficiency (%NPE), were calculated using Equations 1–3 below (Fageria et al., 2008).

$NAE = (Yf-Y0)/FN$……………………………………………………… (1)

$NRE (\%)= 100(NUf-NU0)/FN$…………………………………................ (2)

$NPE (\%) = 100 (GY/NU)$………………………………………………… (3)

Where Yf is the grain yield of fertilized crops (kg ha^{-1}) and Y0 is the grain yield of unfertilized crops (kg ha^{-1}), FN is the amount of fertilizer N applied (kg ha^{-1}), NUf and NU0 are the nutrient uptake, by fertilized and non-fertilized crops, respectively; GY is the grain dry matter (kg ha^{-1}), and NU is the total N uptake.

We converted the grain yield to a protein percentage at 12.5% moisture content by multiplying it by 5.073. We estimated the fertilizer N equivalence from legume rotation by calculating the ratio of the increase in wheat grain yield after legumes without N to the yield increase with 30 kg N ha^{-1} applied after tef or fallow, multiplied by 30 kg ha^{-1}. We calculated the legume N fertilizer replacement factor by dividing the apparent N recovery from legume residue (ANRL) by the apparent N recovery from fertilizer (ANRF) (Fageria et al., 2008).

6.3.5 Limitation of the study

Research on Vertisols has some limitations because it requires a package of technologies to solve crop production constraints under smallholder farmers' conditions. The BBF and camber bed tillage practices help drain excessive rainwater during heavy storms, minimize water stress at critical crop growth stages, and increase crop yields. However, the study didn't consider soil and water erosion and its impact on wheat agronomic parameters due to resource and time constraints, and the tillage practices significantly differ in construction, practical use, and drainage efficiency. Instead, a comparison was made over years for BBF and Camber beds and within years separately for both tillage practices.

6.3.6 Statistical analyses

An analysis of variance (ANOVA) using Statistics 10.2 (http://statistix.software.informer.com/) software was used to examine the previous crop rotation effects on the subsequent wheat yield, N yields of wheat grain and straw, and tillage practices. We set up the studies using a split plot in a randomized complete block design with three replications. The main-season wheat planted following the harvest of previous crops consisted of three factors: preceding crops: legume species (vetch and clover), teff crops sown with and without P application, and bare fallow. In the experiment, we considered eight preceding crops, applied three N levels (N0-control, N1-30 kg N^{-1}, and N2-60 kg N^{-1}) as urea after the preceding crops, and used three methods for managing legume residue incorporation (S, R, RS). The ANOVA also included the pooled effect of wheat agronomic parameters for BBF and camber bed tillage practices over the years. The least significant difference (LSD) method was used to compare means. The least significant difference (LSD) in means was used for treatment comparison, and statistical significance was referred to at $P<0.05$. We conducted regression, correlation, and ANOVA to analyze grain yield, N uptake, N agronomic efficiency (NAE), apparent N recovery (ANR), and physiological efficiency (PE) factors for the various legume residue management treatments and N levels.

6.4 Results

6.4.1 Wheat grain yield

A field experiment was conducted on two tillage practices over two years (2019 and 2020) to assess the grain yield of wheat in different treatments, including varied rotation, N rates, legume residue management, and tillage practices. Seasonal variation, rotation, N rates, legume residue management treatments, and tillage practices affected the grain yield of wheat. During 2019, the mean gain yield of wheat on BBF was 1255.3 kg ha^{-1} (95% CI: 2094.4, 2342.0), while in 2020, this value was 1787.4 kg ha^{-1} (95% CI: 1620.7, 1954.1). Camber beds in 2019 and 2020 produced a mean grain yield of 1643.1 kg ha^{-1} (95% CI:1531.6, 1756.3) and 4523.9 kg ha^{-1} (95% CI: 4242.9, 4804.8), respectively. In both years and tillage practices, the ANOVA showed that year and N treatments had a significant ($P<0.000$) effect on the grain yield. A combined analysis variance over years for BBF showed that the mean grain yield of wheat was 1460.1 kg ha^{-1} (95% CI: 1373.1, 1546.9), while for the camber bed, it was 2787.7 kg ha^{-1} (95% CI: 2576.8, 2998.6). In both years, wheat grain yield was higher on camber beds (1643 vs. 1255.3 kg^{-1}) and in 2019 (4312 vs. 1987.4 kg ha^{-1}) than on BBF in 2019 and 2020, respectively. Pooled ANOVA over years for BBF indicated that year and treatments and their interactions significantly ($P<.0001$, $F = 19.85$) affected wheat grain yield. The same trend was observed for camber beds, in which wheat grain yield was significantly ($P<0.0000$, $F = 11.68$) affected by year, treatment, and their interactions. Among the preceding crops, the legume-wheat rotation without N fertilizer applied gave a better wheat yield than the fallow-wheat and teff-wheat rotations. The effect of rotation (preceding crops) on wheat grain yield was more pronounced during the first wheat crop phase, even without N fertilizer application. When rotation and fertilizer application were considered, the highest wheat grain yield was recorded when N was applied at 60 kg^{-1} under both tillage practices, followed by N at 30 kg^{-1} for all the preceding crops. Wheat planted with N rates following legumes, tef, and fallow rotation showed that the application of N fertilizer increased wheat grain yield by 44% compared to teff-wheat rotation and a 33% increase in fallow-wheat rotation. The lowest grain yield of wheat was from teff plots in rotation with wheat (973 kg^{-1}).

6.4.2 Effects of different treatments on wheat yield

The grain yield of wheat in the absence of fertilizer (legume wheat rotation), tef-wheat rotation, and fallow-wheat rotation was highly variable. Preceding crop legumes significantly ($P < 0.05$) enhance wheat grain yield and N uptake compared to teff and bare fallow treatments. The previous crop effect was more pronounced on camber beds than on BBF plots. In the first and second series of first-season experiments, wheat grain yields following legume rotation, particularly vetch, were generally higher than those following tef-wheat. The grand mean of wheat grain yield for non-N applied treatments following legumes, tef, and fallow plots ranged from as low as 0.9 to as high as 3.6 t ha^{-1}. Over the tef-wheat rotation, the percent increase in grain yield of wheat succeeding vetch for non-N-applied treatments ranged from 9 to 44 kg ha^{-1}. The clover wheat rotation showed positive and negative values, lacking consistency between seasons and tillage practices. The grain yield advantage of vetch wheat rotation over fallow wheat rotation was 14% for non-N-fertilized treatments in the first and second series of first-season experiments.

The most consistent effect ($P< 0.001$) was that of N fertilizer, which increased the dry biomass, grain yield, and N uptake of wheat at 60 kg N^{-1} (Table 6.2 and 6.3). However, the interaction effect of the previous crop on N rates was non-significant. The lack of a significant difference between fertilizer applied to the second-season camber bed and BBF is not clear. This may be attributed to the residual effects of legume residue mineralization, seasonal variations, rainfall amount, distribution, and drainage efficiency of the tillage practices. On the other hand, the response of wheat to N fertilizer application varied greatly between seasons and tillage practices. In the first and second series of first-season experiments, the grain yield of wheat ranged from 1.3 to 4.4 t^{-1}, while in the second series of first- and second-season experiments, it ranged from 1.5 to 3.0 t^{-1}. The average wheat grain yield in BBF in 2020 and 2021 was 2.3 and 3.0 kg^{-1}, respectively, during the second season, while it was 1.5 and 1.8 t^{-1} on cambered beds in 2020 and 2021. The wheat grain yield was higher in the first season in cambered beds than in BBF, while in the second season, the opposite trend was observed. The grain yield was found to be highly significant ($P<0.001$) when analyzed against N levels in both seasons of the BBF and camber bed experiments. The R^2 values ranged from 29% to 79% over years and tillage practices (Table 6 4b). The slope of the linear equation revealed that the response of grain to N fertilizer has more of an influence on seasonal variation than on tillage practices. As expected, the teff-wheat rotation showed poor agronomic performance and low grain yield, showing the lowest grain yield and N uptake. Almost comparable wheat grain yield was recorded between legume residue-applied treatments and fallow-wheat roration in the absence of N fertilizer applied, even though leaving the land fallow is not recommended due to environmental reasons.

Table 6.2. *ANOVA results for wheat grain yield, dry biomass, and N uptake by preceding crops, N fertilizer, and interaction (P-Values)*

Wheat agronomic parameters	Source of variations	First and second series first season experiments			
		BBF 2020	Camber bed 2020	BBF 2021	camber bed 2021
Grain yield	Preceding crops	0.014	0.001	0.003	0.001
	N levels	0.001	0.001	0.001	0.001
	Preceding crops * N levels	ns	ns	ns	ns
Dry biomass	Preceding crops	0.014	0.001	0.003	0.001
	N levels	0.001	0.001	0.002	0.001
	Preceding crops * N levels	ns	ns	ns	ns
Total N uptake	Preceding crops	0.003	0.001	0.001	0.001
	N levels	0.001	0.001	0.001	0.001
	Previous crop * N levels	ns	ns	ns	ns

6.4.3.Legume residue incorporation and wheat grain yield

The type and amount of legume residue incorporation affected the dry biomass and grain yield, as well as the N uptake of wheat. The N content of legume residues and legume residue management treatments influenced the grain and dry biomass yield of wheat. The grand mean of wheat grain yield ranged from 1.1 to 4.3 t ha^{-1} for the first and second series of first-season experiments, while for the first and second series of second-season experiments, it ranged from 1.4 to 1.9 t ha^{-1}. Among legume residue management treatments, RS gave comparatively higher wheat yields, followed by R and S. Legume residue management treatments override in wheat grain yield over the no fertilizer application (control) under teff and fallow. ANOVA results showed that the choice of preceding crops and legume residue treatments had a significant ($P < 0.05$) effect on grain and dry matter yields of wheat in 6 out of 8 experiments, however, the interaction of legume residue management treatments with the preceding crops was only significant in two out of eight experiments.

Table 6.3. *ANOVA results for wheat grain yield, dry biomass, and N uptake by preceding crops, N fertilizer, and interaction (P-Values)*

Wheat agronomic parameters	Source of Variations	First and second series second season experiments			
		BBF 2020	Camber bed 2020	BBF 2021	Camber bed 2021
Grain yield	Preceding crops	0.002	0.001	ns	0.01
	N levels	0.001	0.001	ns	0.005
	Preceding crops * N levels	ns	ns	ns	ns
Dry biomass	Preceding crops	0.001	0.001	ns	0.01
	N levels	0.001	0.001	ns	0.43
	Preceding crops * N levels	ns	ns	ns	ns
Total N uptake	Preceding crops	0.001	0.001	ns	0.004
	N levels	0.001	0.001	ns	ns
	Preceding crops * N levels	0.05	0.003	ns	ns

A linear relationship was found between N uptake and wheat grain yields. The N in the residue of legumes incorporated into the soil varied due to P application. In the first series of experiments, higher incorporation of legume residue had a positive impact on wheat grain yield and showed a significant correlation ($P < 0.05$). Legume residue incorporation significantly affected wheat N uptake, with R^2 values ranging from 0.35 to 0.96 over years and tillage practices. A linear relationship and positive correlation were found between residue incorporation of individual legumes and N uptake, with R^2 values ranging from 0.56 to 0.97. The slope of the regression equation for N applied in terms of legume residue ranged from 0.5 to 1.4 for Exp. I (first series, first season BBF experiment), while these values ranged from 1.7 to 4 for Exp. III (first series, second season BBF experiment). The slope of the linear regression equation was weak for the first series of the first-season camber bed experiment but tended to be higher (between 0.6 and 3) for the first series of the second-season camber bed experiment.

6.4.4 Wheat biomass yield, harvest index, and N concentration

Seasonal variations, preceding crops, N fertilizer, and legume residue management treatments positively affected ($P < 0.001$) the dry biomass of wheat. The highest straw yield was recorded at the N rate of 60 kg ha^{-1} followed by 30 kg N ha^{-1}. The straw yield of wheat was not consistent due to the application of different legume residue incorporation treatments. The dry biomass of wheat varied between residue treatments and tillage practices. The rotation effects of legumes, teff, and fallow without N fertilizer application indicated a positive effect when legumes were rotated on straw yield, but the results were non-significant. The significantly highest values were recorded in the treatments where mineral fertilizers were used at either 60 kg N ha^{-1} or 30 kg N ha^{-1}. The lowest ones (ANOVA, $p < 0.05$) were obtained in the unfertilized treatment or non-residue amended treatments. The harvest index (HI) of the dry shoot biomass showed that under both tillage practices and over years, it ranged from 0.38 to 0.42. Regardless of the growing environment, camber beds produced the highest HI (0.42) among the different treatments. The control treatments over the years and under both tillage practices recorded the lowest HI. The ANOVA results showed that treatment had no significant effect on HI in six out of eight experiments.

We observed the highest grain and straw N concentrations when there was an interaction between the year and N rate, specifically when 60 kg N ha^{-1} was applied in both growing years. In contrast, the lowest grain N concentration was recorded in the control treatment, which was statistically similar to the grain N content obtained with the N rate of 30 kg ha^{-1} in 2019. As for N level, grain and straw N content increased with increasing N level in both growing years and under both tillage practices, showing the highest values always with the application of the highest N rate (60 kg N ha^{-1}). In general, as compared to 2019, grain and straw N concentrations on both tillage practices increased in 2020, in contrast to 2019.

6.4.5 Nitrogen uptake of wheat

Similar to grain yields, the N uptake of wheat was affected by preceding crops, the N rate, legume residue, seasons, and tillage practices, but it was not consistent between years and tillage practices (Table 3). The mean total N uptake for the first and second series' first-season wheat ranged from 29 kg ha^{-1} (Exp. I) to 102 kg ha^{-1} (Exp. IV), while for the first and second series' second-season wheat, it ranged from 37 kg ha^{-1} (camber bed) to 41 kg^{-1} (BBF). The N uptake of wheat was higher on camber beds than on BBF during the first and second series of first-season experiments, but in the first and second series of second-season crops, it tended to be higher on BBF than on camber beds (Table 3). The mean N uptake for unfertilized plots varied between 19 and 83 kg ha^{-1} for the experiments, with the greatest for Exp IV. The values were higher for the first and second series of first-season experiments on camber beds than on BBF. Previous crop treatments were significant in three out of eight experiments, while legume residue-incorporated treatments and N rates showed a significant effect ($P<0.05$) on total N uptake in all experiments. A significant ($P<0.05$) effect of the legume residue management treatments (N0, S, R, RS) was evident in the relationship between grain yield and N uptake for the experiments, with R2 ranging from 0.59 to 0.95. For every kg of total N uptake, a wheat grain yield ranging from 24 to 53 kg was obtained.

The relationship between grain yield and N uptake was highly correlated for all the experiments (Figure 6.3) and more pronounced in BBF experiments than on camber beds. However, interaction effects were not significant (Table 6.3). The N uptake of wheat was higher on N-fertilized plots than on legume residue management treatments. The N content of wheat grain following tef-wheat and legume-wheat

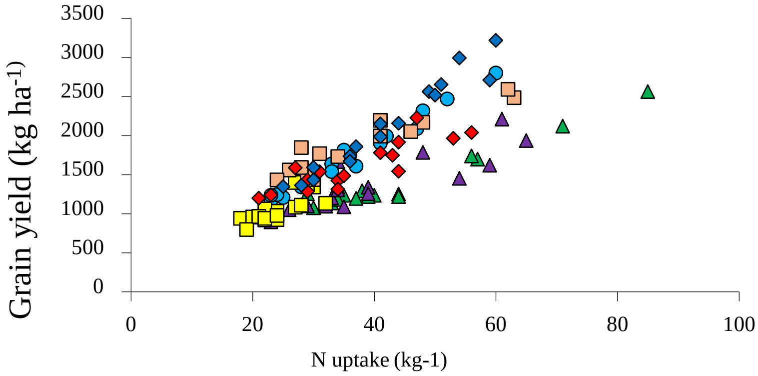

Figure 6.3 Relationship between grain yield and N uptake

Figure 1. The relationship between grain yield and N uptake 🟨 - Exp I, 🟧 - first series second season BBF, ▲ Exp II, ▲- first series second season camber bed, ◆- second series first season BBF, ◆- second series second season BBF, ● - second series second season camber bed.

without N fertilizer declined relative to legume-wheat applied with fertilizer and legume residue N. The pre-wheat legume residue management treatments resulted in varying amounts of N uptake by wheat, with higher values under legume residue treatments that had treatment S and ranged from 18 to 61 kg ha^{-1}. The N uptake of wheat increased in 2020 when wheat was planted during the second season on previously applied legume residue.

6.4.6 Wheat agronomic parameters relationships

There was a positive correlation between the grain yield of the crop and the total amount of nitrogen uptake from the incorporated legumes. The slope of the linear equation indicates the rate at which the grain yield increased with each additional kilogram of nitrogen uptake from the legume residues. The range of 3 to 37 kg^{-1} suggests that the impact of nitrogen uptake on grain yield varied among different legume species or management practices. The difference may be a combined effect of different factors, such as legume species and legume residue management. The close relationship between grain yield N uptake and the grain yield increase per unit of N uptake after legume treatments explains the positive effects of legume-induced indirect effects. Legume residue incorporated and N fertilizer applied treatments were positively correlated with grain yield and N uptake of wheat (Tables 6.4a–d). The regression analysis shows a strong coherence between the values of dry matter and grain yield of wheat when we consider the R2 value and the slope of the regression, which are close to one under both tillage practices for Exp I, II, III, and IV. The contribution rate of dry biomass to grain yield was 84% in Exp. I and 55% in Exp. II. Correlation analyses showed different relationships between grain yield, dry matter, and HI under different yield levels. For the first series and second season of BBF and camber bed experiments, R^2 was 0.95 and 0.99, $P<0.001$, respectively. The regression constants for the dry biomass of wheat were higher for camber beds in the first series of second-season experiments of both tillage practices.

Table 6.4 Regression analysis of wheat grain yield based on legume residue N

a)

Tillage practices	First series first season wheat			First series second season wheat		
	Slope	Intercept	R^2	Slope	Intercept	R^2
BBF (Exp. I)	32.8	262.6	0.59	27.9	825.2	0.89
Camber bed (Exp. II)	25.6	281.8	0.94	23.7	443.5	0.73
Tillage practices	**Second series first season wheat**			**Second series second season wheat**		
	Slope	Intercept	R^2	Slope	Intercept	R^2
BBF (Exp. III)	25.7	658.1	0.75	52.7	87.5	0.95
Camber bed (Exp. IV)	2.9	3930.8	0.013	43.4	166.8	0.98

b) Grain vs N fertiliser applied

Tillage practices	First series first season wheat			First series second season wheat		
	Slope	Intercept	R^2	Slope	Intercept	R^2
BBF (Exp. I)	14.7	882.1	0.78	25.3	1579.9	0.79
Camber bed (Exp. II)	13.4	1404.9	0.44	15.9	988.7	0.65

Tillage practices	Second series first season (2020)		
	Slope	Intercept	R^2
BBF (Exp. III)	20.2	1261	0.54
Camber bed (Exp. IV)	24.4	3652.7	0.29

d) Grain yield vs. N uptake for fertilizer applied treatments

Tillage practices	First series first season wheat			First series second season wheat		
	Slope	Intercept	R^2	Slope	Intercept	R^2
BBF (Exp. I)	35.3	237.1	0.96	55.8	23.3	0.96
Camber bed (Exp. II)	25.1	478.8	0.75	38.7	28.7	0.96

Tillage practices	**Second series first season (2020)**		
	Slope	Intercept	R^2
BBF (Exp. III)	39.2	203.2	0.92
Camber bed (Exp. IV)	34.9	812.1	0.82

6.4.7.Nitrogen use efficiency of wheat

Seasonal variations and treatment effects had an impact on the N-use efficiency (NUE) of all the components. The interaction of year × N rate revealed a significant effect on agronomic efficiency. The highest agronomic efficiency was obtained from the first series second season (19.8 kg kg^{-1}) and the second series second season (29.4 kg kg^{-1}) wheat experiments at an N rate of 60 kg^{-1}. This result shows that BBF agronomic efficiency was higher on BBF than on camber beds over the years. The lowest agronomic efficiency values ranging from 6.2 to 12.2 kg kg^{-1} were recorded on camber beds over the years, which is lower than BBFs in all circumstances. The average values obtained from ANOVA for the NUE parameters indicated that fertilization had a significant and positive influence on all the agricultural components (Table 6.5). The nutrient efficiency was higher for the inorganic fertilizer than for the N incorporated in terms of legume residues. Averaged over treatments, NAE for the experiments ranged from 7.2 (Exp. II) to 16.3 kg^{-1} (Exp. III) for the first and second series of first-season experiments. These values were between 6.2 and 29.4 kg kg^{-1} for the first and second series of second-season wheat experiments, respectively. The NAE tended to increase for the second-season experiments compared to the first-season experiments, except for the second-series camber bed experiment. Wide variations were observed for ANR between seasons and tillage practices. The mean ANR ranged from 0.22 to 27% over seasons and tillage practices for the first and second series of first-season wheat, while for the first and second series of second-season wheat, it ranged from negative to 0.11 to 0.35, with higher values for BBF experiments. PE varied widely between tillage practices and between seasons, with values ranging from negative to 63 kg kg^{-1}.

***Table 6.5**. Grand means across treatments for the NAE (kg kg^{-1}), ANR (%) and PE (kg^{-1}) for wheat experiments*

Tillage practices	First series first season (2019)			First series second season (2020)		
	NAE	NRE	PE	NAE	ANR	PE
BBF (Exp I)	10.3	0.26	50	19.8	0.35	-60.3
Camber bed (Exp II)	7.2	0.22	77	8.4	0.2	23.2
	Second series first season (2020)			Second series second season (2021)		
	NAE	ANR	PE	NAE	ANR	PE
BBF (Exp III)	16.3	0.27	63	29.4	0.11	47.7
Camber bed (Exp IV)	12.2	0.29	18.8	6.2	0.12	-41

*NAE, ANR, and PE denotes N agronomic efficiency, apparent N recovery, and physiological efficiency, respectively

6.4.8 Rotation benefit and N fertilizer equivalence of legumes

Both rotation benefit and N fertilizer equivalence are important concepts in agriculture as they contribute to sustainable farming practices, efficient nutrient management, and improved crop production. With no-N- applied, the mean grain yield of wheat following legumes ranged from 932 to 1439 kg^{-1} for the experiments. The mean values for tef-wheat and fallow-wheat rotations without N application were 924 and 1489 kg^{-1} for fallow and between 713 and 1372 kg^{-1} for tef. Based on this and the response to 30 kg^{-1}, the mean fertilizer equivalence of legumes was estimated, and the values ranged from 6 to 10 kg N for fallow on BBF plots. The fertilizer equivalence for legume rotation compared with tef rotation ranged from 8 to 19 kg N for the experiments. Higher fertilizer equivalencies were recorded on camber bed plots than on BBF plots kg^{-1}.

6.5 Discussion

The physical characteristics of Vertisols, particularly their tendency to become sticky, plastic, and waterlogged when wet and hard and cloddy when dry due to rainfall variability, make Vertisols difficult to cultivate under traditional farming practices (Regassa & Elias, 2022b). These properties restrict nutrient availability and hinder plant growth. The efficiency of any drainage system and crop productivity depends on the rainfall amount, duration, and intensity. In the Ethiopian highlands, where the rainfall is erratic, crop production heavily relies on the drainage efficiency of tillage practices and management options. The challenges of waterlogging and nutrient deficiencies are major constraints on crop production in Vertisols. In the Ethiopian highlands, wheat is a crucial food crop that relies heavily on costly inorganic fertilizers. To address this issue, we explored alternative methods to improve soil fertility and increase crop yields. Legumes, known for their nitrogen-fixing abilities, are widely used to restore soil fertility and reduce the need for nitrogen fertilizers. Introducing legumes into cropping systems is seen as a sustainable approach to intensifying agriculture in Sub-Saharan Africa, including Ethiopia (39, 38, 19). In this study, camber beds increased the grain yield of wheat, ranging from 24 to 59% over the years, due to their better drainage efficiency. However, planting wheat on camber beds for two consecutive years following legumes without fertilizer application declined compared to BBF. The wheat grain yield decline in the first and second series of second-season experiments on the camber bed can be explained by the leaching and denitrification of the available nutrients due to higher beds. Drainage is crucial for Vertisols, and while improving the drainage system, one has to take caution about soil and water erosion hazards related to improper tillage practices and furrow construction.

Seasonal rainfall amount and distribution, tillage practices, and N fertilizer applied in terms of inorganic fertilizer and legume residue incorporation have a positive impact on wheat grain and dry biomass yield and N uptake. Soils with low organic matter usually do not respond to applied fertilizers due to depleted organic matter (Stewart et al., 2020). Therefore, the inclusion of legumes in the cropping system is important. In this study, legume-wheat rotation and residue incorporation significantly affected the test crop's grain yield and N uptake. This is in agreement with past studies conducted regarding organic amendments (40, 41). Waterlogging and nutrient deficiencies are the major crop production constraints on Vertisols (42, 8), coupled with drainage improvement (43, 24). However, while improving the drainage system, one has to take caution about soil and water erosion hazards related to improper tillage practices and during furrow construction.

6.5.1 Legume-wheat rotation, residue incorporation, and N application

Using organic amendments in low-input agriculture can enhance crop production by reducing the reliance on chemical fertilizers. These amendments release beneficial nitrogen for the subsequent crop while minimizing negative environmental impacts (18, 44). In regions with high rainfall, planting crops during the long rainy season can help conserve soil nitrogen by reducing runoff and leaching from mineral fertilizers. Incorporating legume residue into the soil has been observed to effectively reduce soil and water erosion compared to bare and cereal-cereal rotations. Early planting with improved drainage systems can assist farmers in reducing soil and nutrient loss. Legume-wheat rotation and the incorporation of legume residues can fulfill the nitrogen requirements of subsequent crops through the decomposition and mineralization of legume residues, as well as the soil nitrogen-conserving effect of legumes (40, 45). The lower nutrient export from the soil by legumes and their ability to fix atmospheric nitrogen are additional factors contributing to increased wheat grain yield (45, 46). The response of wheat crops to legume residue nitrogen varies depending on the legume species, management of legume residues, nitrogen content of legumes, and soil nitrate levels at sowing. In the absence of nitrogen fertilizer application, wheat grain yield is typically higher in legume-wheat rotations compared to teff-wheat rotations due to the retention of nutrient inputs in available soil nutrient pools (47, 48). Legumes' capacity to conserve soil N and fix N can enhance wheat grain yield in legume-wheat and tef-wheat rotations compared to non-fertilized legume-wheat. Legumes' capacity to conserve soil N and fix N can enhance wheat grain yield in legume-wheat and tef-wheat rotations compared to non-fertilized legume-wheat. Past studies on rotation, legume residue decomposition, and further mineralization have shown the positive impact of legumes on the subsequent grain yield of crops. Legumes' ability to conserve soil N and their N-fixing capacity can also contribute to increased crop yields (41, 48).

Legume-wheat can enhance wheat grain yield through the conservation of soil nitrogen and nitrogen fixation by legumes. Several studies have confirmed the positive impact of legumes on subsequent wheat yield (49, 48, 46). Factors such as legume species, carbon-to-nitrogen ratio, residue incorporation methods, soil type, microorganisms, rainfall, and temperature influence the availability of soil mineral nitrogen for the following crops (Kiran Kumar et al., 2019). The presence of inorganic nitrogen in the soil may also affect the mineralization of decomposing agricultural waste. Additionally, timing and losses through leaching, denitrification, immobilization, or volatilization may have influenced the availability of necessary nitrogen concentration from legume residues for wheat crops (Hartz & Johnstone, 2006). It's possible that the necessary N concentration in legume residues was not fully reached at the time when wheat needed more N or that it was lost as a result of leaching, denitrification, immobilization, or volatilization. A comparison made between wheat yield under S and N0 showed that the S treatment gave a higher wheat grain yield because the soil mineral N under legume residue treatments was still sufficient for the yield difference. However, an important observation was that grain yields of wheat under the different legume residue treatments varied widely and lacked consistency concerning the amount of N added in terms of legume residue. These can be related to several external factors such as environmental factors, legume species and , and time and type of legume residue application (50, 51).

6.5.2 Nitrogen uptake and use efficiency

N use efficiency is a crucial parameter in agricultural systems as it reflects the plant's ability to convert absorbed nitrogen into biomass or grain yield. The predominant influence on wheat N uptake was the addition of N fertilizer at a rate of 60 kg ha^{-1}, but this varied between tillage practices (Fischer et al., 2002). It is reasonable to conclude that N is the main factor limiting crop production in these soils. However, the efficiency of N uptake by wheat grain varied greatly under legume residue management treatments related to legume species difference and the C: N ratio. The residual effect of legume residue was more pronounced on N uptake in wheat when it was planted for the second time (Salim & Raza, 2020). Several studies have shown that applying inorganic N to crops increases NUE because it is immediately available to succeeding crops. However, as N rates rise, cereals' agronomic, physiological, and apparent recovery efficiencies decline (53, 54). However, the N contribution from legume residues is usually released slowly and may be available to the second and third succeeding crops (55). Based on seasonal variations and tillage practices, the mean NAE ranged from 6.2 to 29.4 kg ha^{-1}. Study conducted on Vertisols of Bale highlands in Ethiopia showed that the NUE of wheat for applied N ranged from 9.5 to 18.3 kg ha^{-1} on waterlogged Vertisol sites. Several factors may contribute to various NUEs, in particular the availability of moisture, the soil's nutritional status, and its ability to retain nutrients.

6.5.3 Recovery of residue N

The N recovery from residues in succeeding wheat crops varied widely. Our results showed that the contribution of legume residue N to wheat yield and N uptake was variable based on the amount of legume residue incorporated and legume residue management treatments. The findings are in agreement with previous research Ladd et al. (Ladd et al., 1983). The total N uptake for wheat following legume rotation or residue incorporation had tremendous variations in residue N recovery, suggesting that the influence of residue management treatments was not equal. Comparisons of direct residue N recovery between treatments are the most appropriate way to compare treatments, as varying amounts of N were added as residues. The lack of an appreciable benefit from legume residue incorporation in some cases could be attributed to N losses or may be affected by the timing of incorporation, which was three months before planting wheat for these experiments.

6.5.4 Fertilizer replacement value

The highest fertilizer replacement value for legumes in this study was much better on camber beds, at about 25 kg of grain per kg N, while on BBF it was between 19 and 23 kg per kg N, varying between seasons and tillage practices. The value is nearly equal to the half-N recommended fertilizer rate for wheat in Ethiopia (Dargie et al., 2022). However, an actual yield increase of 30 kg N^{-1} may not be achievable due to differences in the N sources and some external factors governing the sources. Field conditions are influenced by multiple factors that can counteract the estimation process (Sainju, 2017a) for this cropping system since several factors counteract field conditions. Several factors can affect the decomposition and mineralization of legume residue, making it challenging to estimate the N balance (58, 59). It would be instructive to look at some of these for further research. The study showed that optimal fertilizer savings were recorded for all treatments, justifying legume residue incorporation as having an advantage. On camber beds, the N fertilizer savings decreased by 50% compared to BBF plots. This is probably attributed to the leaching of the mineralizable N below the root zone. In the case of 2020, fertilizer savings decreased drastically on BBF, while camber beds showed an increasing trend. The variation in fertilizer N equivalence values can be influenced by factors such as the dependence of legumes on N fixation, the soil mineral N sparing effect, dry biomass production, and the amount of N incorporated from residue sources. Fertilizer N equivalence values for this environment are optimal; even low fertilizer equivalence may help farmers with limited access to commercial fertilizers.

6.6 Conclusion

From the study, it can be concluded that grain yields of wheat can be maximized with N application rates of 60 kg ha^{-1} which significantly affected all the agronomic parameters. Among the preceding crops to wheat, teff-wheat rotation without N fertilizer application significantly reduced wheat grain yield, while fallow-wheat rotation without applying N comparatively gave better wheat grain yields. The inclusion of legumes in rotation or incorporation into the soil drastically increased the grain yield of wheat. Improved drainage systems helped Vertisols respond to added N from legume residue or inorganic fertilizer. In the absence or limited availability of inorganic fertilizers, poor resource farmers can take advantage of growing forage legumes and incorporating residues to replenish the soil with organic matter, which may serve as an essential source of nutrients. Fertilizer N equivalence values for this experiment were minimal. The average N fertilizer replacement value from legume rotation was 18–46 kg^{-1}. This study showed that a one-year legume-in-biannual wheat rotation is preferable to lying bare fallow during the cropping season. Nevertheless, drainage during legume and wheat cropping is a condition for providing full positive impacts. For sustainable crop production on Vertisols, location-specific agro-climatological studies, tillage practices, and nutrient management are crucially important. Even legumes with low fertilizer equivalence may be of interest to farmers who have limited access to commercial fertilizers.

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Chapter Seven- General Discussions/Conclusions and Recommendations

7.1. Overview of the PhD study

The Ph.D. study focused on five specific but interrelated topics requiring extensive data acquisition, field experimentation, and analysis. These topics included studying rainfall variability, runoff, and soil loss; legume growth during long rains and biomass production; legume nitrogen fixation and nitrogen balance using teff as a reference crop; decomposition and nitrogen mineralization of incorporated legume biomass in the soil; and nitrogen transfer and fertilizer replacement values of these legumes for subsequent wheat crops. The experiments were conducted at the Holeta and Ginchi research centers on Vertisols. Chapters two to six of the dissertation provide a detailed account of these experiments. This section will provide a summary of each study.

7.2 Summary of research findings

7.2.1 Rainfall variability

The rainfall variability study used 39 years of daily rainfall data to study the impact of rainfall variability on the sustainable use of Vertisols, with a specific objective of how rainfall variability affects farming practices on Vertisols. Vertisols are soils of unique character concerning moisture content, which determines the success or failure of crop production. Because rainfall variability has a significant impact on society, agriculture, and the environment, it is a critical factor in agricultural production as it directly affects the amount and distribution of water available for crops. It also helps in assessing the availability of water resources, predicting potential drought or flood events, adjusting crop growing calendars, and choosing suitable crops for the region. The variability of rainfall can provide information on climate change and its potential impacts on rainfall patterns. The study is very important for countries like Ethiopia, where agriculture is rainfall-dependent and food security is a major problem. In regions characterized by high rainfall variability, particularly in the Ethiopian highlands where Vertisols are prevalent, investigating rainfall variability assumes critical importance for both food security and environmental protection.

The study of rainfall variability for Ginchi revealed that dependable rainfall at a 75% probability level commences in June. The dependable weekly rainfall begins the week of May 22 (May 28–June 3), with a probability of greater than 20 mm. The study confirmed that the short rainy season rainfall (February to May) is unreliable for growing crops at Ginchi as opposed to other highland areas of Ethiopia. The major crop-growing season is therefore confined to periods of the long rainy season (weeks 22nd to 39th, or May 28th to September 30th). During this period, the water balance indicates that the moisture availability index is greater than 0.5, explaining that potential evapotranspiration is lower than precipitation during these months. The long-term annual rainfall has decreased in amount since 2000. In effect, for the 39 years (1982–2020), the total average rainfall amount is declining yearly by an average of 351 and 267.2 for the long and short rainy seasons, respectively. The magnitude of the rainfall in the study area declined at a rate of 4.51 mm/year. Negative anomalies were common for two to three years. Since 2000, the annual total rainfall has been far lower than the long-term mean. The five-year moving average shows that six of the eight years had rainfall below the long-term average (75%). Only two of the five-year moving average rainfalls were above the long-term mean. In particular, since 2000, the continuous decline in yearly rainfall below the long-term average indicates the need to find alternative management options and farming strategies considering rainfall variability and soil conditions.

The 75% probability level indicates that dependable monthly rainfall begins in June, while at a 50% probability level, it begins around May. The monthly PET reveals a positive water balance from June to September. Throughout the remaining months, rainfall falls below PET; therefore, short-duration crops can likely be cultivated with the assistance of additional irrigation. Considering the 50% probability level, precaution should be taken because the lower the probability level, the higher the threshold values, but dependability matters. The weekly and monthly rainfall probability levels indicate that an MAI of more than 0.75 starts in June. The MAI is at a 75% probability level, which implies that more than 20 mm of rain is likely, which shows the least threshold level for crop growth.

An effective measure of the water balance is the computed ratio of 75% dependable rainfall and PET, defined as MAI. Weekly rainfall at a 75% probability level and an MAI greater than 0.5 were considered optimal for plant growth in this study area. The dependable rainfall at a 50 and 75% probability level exceeds PET, starting in weeks 23 and 25 and ending in weeks 38 and 36, respectively, showing a positive water balance. The rest of the weeks had a negative water balance, meaning PET was greater than the dependable weekly rainfall. Thus, on average, for 16 weeks a year, the climatic water balance is positive, while for 35 weeks, the climatic water balance is negative. The mean annual rainfall of the study area is 1099 mm, while the mean annual PET is 1412 mm, indicating that the annual water deficit is 313 mm. According to Hargreaves (1975), the value of MA1 > 0.34 could be considered the lower value for dryland crops. The MA1 values exceed the lower threshold value of 0.34 in all the rainy months of Ghinchi, and the data for the length of the rainy seasons show that there are 133 days in Ginchi (19th to 38th weeks), which is 280 days. During the 1st to 17th weeks and the 40th to 52nd weeks, MA1 values are below the lower threshold value. The MAI exceeds 0.5 falls from June to September (22nd–40th weeks), which indicates a crop-growing period. However, MA1 during the 40th and 41st weeks was low. In some years, the October MAI falls short of the total water requirement for crops grown on residual moisture. MA1 at a 50% probability level falls between the 25th and 35th weeks, which is more than 1.00, indicates excess water, and requires an improved drainage system. The high water availability during this period would be sufficient to meet the moisture requirements of the crops in the latter part of the season. The construction of water harvesting structures that help crops grow to full maturity during dry spells is advantageous in years of unusually low precipitation. On Vertisols, negative impacts of the climate are more likely to result from excess rainfall and a poor drainage system during the crop-growing period.. In the other year, crop yield anomalies did not attain the levels at which they could be considered impacts. This is not sufficient for forecasting crop yields or the impacts of climate change. In the Ethiopian highlands, crop-livestock integration is very strong.

7.2.2 Runoff and soil loss

On the other hand, a three-year (2020–2022) study on runoff and soil loss was conducted using conventional field-based small run-off plots. The study tried to investigate the effect of sowing dates (early sowing in June, mid-July sowing, and end-of-September sowing) and two tillage practices on runoff and soil loss. The results of this study indicated that BBF practice consistently outperformed flat seedbed practice in terms of wheat grain yields across all sowing dates. Results showed that tillage practices, combined with early sowing, significantly increased crop yields by 51% compared to traditional flat seedbed planting. However, this increase in crop production came at the cost of improving the drainage system, which simultaneously increased runoff and soil loss. This suggests that implementing the BBF practice can result in higher agricultural productivity and improved soil-water relationships. Furthermore, the study emphasized the importance of improving drainage systems and adopting early sowing practices to establish favorable soil-water relationships for optimal crop growth and development. In the Ethiopian highlands, where the study was conducted, researchers identified high-intensity rainfall during the main cropping season from June to September as the primary driver of runoff and soil loss on Vertisols. Additionally, they found that early sowing and drainage improvements significantly enhanced wheat grain yields. Interestingly, the BBF practice induced higher runoff and soil loss compared to the flat seedbed practices. The BBF practice may indeed cause increased runoff and soil loss due to repeated cultivation and the creation of raised beds. Another promising strategy to overcome dry spells in Vertisols is the construction of water-harvesting structures. These initiatives can help maximize agricultural productivity and mitigate the challenges posed by unpredictable rainfall patterns, mainly related to rainfall shortages.

7.2.3 Legume biomass, production, N mineralization and transfer to subsequent crop

The other three experiments are closely interrelated, and the experiments were conducted one after the other using inputs from the previous experiment. In June, researchers initially planted two legume species using the BBF drainage system, both with and without phosphorus fertilizer application. The objective of this study was to quantify the biomass production of these legumes, N concentration, and N accumulation. We conducted a nitrogen fixation and nitrogen balance study using the reference crop tef and found that employing BBF and applying phosphorus significantly increased biomass production and nitrogen content in legumes ($P<0.05$). Among different legume species, vetch exhibited superior N accumulation ($P<0.05$) compared to clover and teff (*Eragrostis tef*) over years and land preparation methods. This substantial N accumulation has the potential to positively contribute to subsequent crops when incorporated into the soil. The influence of land preparation methods and years on soil mineral N accumulation was particularly noticeable in the presence of legumes. The N balance values varied among species, land preparation methods, and phosphorus treatments over the year. For vetch+P, the N balance ranged from 67.1 to 185.9 kg N ha^{-1} across different years and land preparation methods, while the corresponding range for vetch-P was 40.3 to 141.9 kg N ha^{-1}. Similarly, the N balance for clover-P ranged from 13.0 to 67.2 kg N ha^{-1}, and for clover+P, it ranged from 13.8 to 98.6 kg N ha^{-1}. The N balance for teff never exceeded 35 kg ha^{-1} throughout the years of observation. In the central highlands of Ethiopia, where Vertisols are the dominant soil type, soil fertility maintenance and drainage improvement are prerequisites. Phosphorus application boosted the dry biomass, N accumulation, and N concentration of the crops studied considerably. Crop N concentration and accumulation are related to crop species and dry biomass yield.

After the harvest of these legumes in December, three legume residue incorporation treatments into the soil were identified and superimposed on the same plots where the legumes were harvested. The objective of this experiment was to quantify the decomposition and N mineralization of legume residues through time, that is, from harvest time in December up to the wheat planting time in June. Soil samples were collected from inside and outside the PVC tubes installed along the different legume residue-incorporated treatments to a depth of 0–20 and 20–40 cm. Total soil mineral N accumulation inside and outside PVC tubes in April showed an increasing trend compared to December and March sampling, under both land preparation methods and over the years. The average soil mineral N values obtained from inside PVC tubes ranged from 91 to 107.5 kg^{-1} in Expts I, II, III, and IV, respectively. There was no clear trend observed for the higher accumulation of mineral N between land preparation methods and legume species, while lower mineral N accumulation was detected for previous tef plots inside the PVC tubes. The accumulation of soil mineral N outside the PVC tubes was lower than inside the PVC tubes and on average decreased by 31, 67, 30, and 28% for Expts I, II, III, and IV, respectively. The total soil mineral N levels in June consistently decreased over time, regardless of the legume residue placement treatments and land preparation methods employed in all the experiments.

An increase in legume residue N applied was associated with an increase in soil mineralization inside and outside the PVC tubes in June. The relationship between the soil mineral N inside the PVC tubes and field plots showed a close relationship in at least two experiments out of four. The Camber Bed experiment found a stronger relationship between legume residue N and soil mineralization accumulation. The relationship between the soil mineral N inside the PVC tubes and outside was highly correlated in three out of four experiments. The study also found that the presence of legume residue in soil layers persisted in the absence of legume residue, while higher soil mineral N was detected under legume residue-retained plots. The soil mineral N increase due to legume residue retention was highly variable between treatments, land preparation methods, and seasons. Higher levels of inorganic nitrogen were observed in Experiments III and IV compared to Experiments I and II, showing that the season has a significant influence on N mineralization.

The last experiment studied the transfer of legume residue N and the fertilizer replacement values of legume residue N to subsequent wheat crops. The N fertilizer replacement value was studied to estimate the N contribution of legume residue nitrogen to a succeeding wheat crop. The findings indicated that the average nitrogen fertilizer replacement value resulting from the rotation of legumes ranged from 18 to 46 kg ha^{-1}. The study demonstrated that implementing a one-year legume-in-biannual wheat rotation is preferable to leaving the land fallow during the cropping season. However, it is important to ensure proper drainage during both legume and wheat cultivation for optimal positive impacts. Among the different tillage practices, camber beds exhibited the highest fertilizer replacement value for legumes, with an approximate grain yield of 25 kg per kg of N. On the other hand, when utilizing bare fallow (BBF), the fertilizer replacement value ranged from 19 to 23 kg per kg of N, varying across seasons and tillage practices. The value is nearly equal to the half-N recommended fertilizer rate for wheat in Ethiopia (Dargie et al., 2022). However, an actual yield increase of 30 kg N ha^{-1} may not be achievable due to differences in the N sources and some external factors governing the sources. Field conditions are influenced by multiple factors that can counteract the estimation process (Sainju, 2017) for this cropping system since several factors counteract field conditions. Several factors can affect the decomposition and mineralization of legume residue, making it challenging to estimate the N balance. The study showed that optimal fertilizer savings were recorded for all treatments, justifying legume residue incorporation as having an advantage.

7.3 Significance and implication of the study

One of the important characteristics of Vertisols is their sensitivity to changes in environmental conditions. The behavior of Vertisols can vary based on different environmental factors, making it challenging to generalize findings or outcomes from one location to another. This variability underscores the need for site-specific studies and tailored management approaches when dealing with Vertisols in diverse geographical settings. The diverse nature of Vertisols arises from their presence in various agroecological settings characterized by differences in temperature, rainfall patterns, clay content, slope gradients, cropping systems, and management practices. This variability emphasizes the importance of considering local environmental conditions and agricultural practices when studying or working with Vertisols. Understanding these variations is crucial for developing tailored solutions and management strategies that account for the specific characteristics of Vertisols in different agroecological contexts.

Despite the importance of Vertisols in the Ethiopian highlands, there is a lack of comprehensive research on the combined effects of rainfall variability, soil and water erosion, drainage improvement, and nutrient management on these soils. The results of this study imply that the identified planting window from the last week of May to mid-June for main-season cropping can help farmers maximize crop yields by aligning planting with the onset of reliable rainfall. This timing can enhance crop growth and overall agricultural productivity. Understanding the limitations of the short rainy season and the potential for double cropping in years with optimal rainfall can inform crop selection and rotation strategies. Farmers can consider cultivating wheat in June, followed by pulse crops in October, to diversify their crops and optimize land use.

Furthermore, the study highlights the importance of improving drainage, protecting erosion, and managing nutrients on Vertisols to enable early planting, which contrasts with the common practice of late planting and growing on residual moisture. Late planting of Vertisols can exacerbate soil erosion and have detrimental environmental effects on the soil. Therefore, applying suitable erosion measures is crucial to protecting the soil and preserving its productivity. Effective drainage systems and early sowing practices can reduce water accumulation and prevent waterlogging, benefiting crop growth. In high-intensity rainfall years, strategies like soil conservation, sowing dates, and drainage system improvements are needed to mitigate runoff and soil loss.

Planting legumes in rotation with cereals improves agricultural practices, soil fertility management, and crop production. Legumes grow well on drained Vertisols and with the application of phosphorus fertilizer. Legume biomass production and nitrogen accumulation enhance soil nutrient levels and promote nutrient cycling. Farmers should choose legume species with a higher nitrogen concentration and accumulation potential for optimal benefits. The significant effects of residue placement and season on nitrogen mineralization suggest that the decomposition of legume residues plays a crucial role in nutrient cycling and soil fertility. Proper management of legume residues can enhance soil fertility, nutrient availability, and crop productivity through improved decomposition and mineralization processes.

7.4 Past Study on Vertisols

Research on Vertisols started some three decades ago. A lot of research work has been done and a substantial amount of information were gathered (Ababa 1993; Tekalign 1988). However, still, a large portion of the farmers residing on Vertisols practice traditional farming practices. To enhance Vertisols, researchers proposed drainage improvement and early planting. Challenges arose as the package of recommendations were proposed to overcome the management problems of Vertisols. However, farmers were unable to take up the technology due to poor socio-econoimic constraints. drainage system caused water flow from one farm to other farmer affecting neighboring farmers downstream. To mitigate this, a watershed approach and a water harvesting structure, such as a pond, could have been implemented alongside the drainage system.The farming system is low-input and low-output agriculture, relying on rainfed agriculture. The success of this type of agriculture largely depends on the amount, timing, and distribution of rainfall, which can vary greatly from place to place (Regassa et al., 2022). However, despite the development of various technologies aimed at improving agriculture, many of these innovations remain inaccessible to smallholder farmers. The adoption rates among farmers have been relatively low, with the majority still relying on traditional farming methods. Several underlying factors contribute to this discrepancy, including poor socio-economic conditions**,** land scarcity**,** and limited access to support and credit (Dercon, 2006)**.** These challenges collectively impact agricultural outcomes and necessitate targeted interventions to address them. Smallholder farmers often face significant socio-economic challenges, such as limited financial resources, a lack of education and training, and inadequate infrastructure. These constraints make it difficult for them to invest in and adopt expensive technologies that could enhance their rainfall agriculture practices. Additionally, land scarcity is a common issue among smallholder farmers, as they often have limited access to arable land (Knippenberg et al., 2020). This constraint further restricts their ability to implement advanced technologies that require larger land areas. Moreover, the lack of support and credit mechanisms exacerbates the problem of low technology adoption. Smallholder farmers often struggle to access appropriate financial services and agricultural extension services that could provide them with the necessary assistance and guidance to embrace new technologies. Additionally, the absence of supportive policies and inadequate market linkages further hinder the adoption of innovative practices. Addressing these challenges requires a coordinated approach involving various stakeholders, including governments, NGOs, and agricultural research institutions. Policy intervention is critically important to create an enabling environment for smallholder farmers to adopt advanced technologies. This can include providing subsidies or financial incentives for technology adoption, improving access to credit and extension services, and facilitating knowledge-sharing platforms. Furthermore, investments in rural infrastructure, such as irrigation systems and storage facilities, can enhance farmers' resilience to erratic rainfall patterns and improve their capacity to adopt new technologies. Strengthening farmer cooperatives and promoting collective action can also enable smallholders to pool resources and benefit from economies of scale. Overall, addressing the barriers to technology adoption in rainfall agriculture on Vertisols requires a holistic approach that encompasses policy reforms, financial support, capacity building, and improved market access. Only through concerted efforts can smallholder farmers overcome these challenges and unlock the potential of advanced technologies to improve their livelihoods and enhance agricultural productivity.

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7.5 Conclusion and recommendations

7.5.1 Conclusion

Vertisols are considered one of the major soil types in the highlands of Ethiopia. Rainfall variability greatly affects crop production and the environment through waterlogging and soil and water erosion. The rain-fed subsistence agriculture in the Ethiopian highlands is a victim of climate change and rainfall variability, resulting in food insecurity. Past rainfall probability studies showed that climate change is evident; the question is how to translate the results to farmers' needs so that farmers can adapt to the existing climatic conditions. Understanding rainfall variability helps farmers develop resilience and mitigation capacity. Agricultural production relies mainly on rainfall onset, cessation, intensity, amount, and distribution. As a result, it would be crucial to build development plans and programs, forecasts and early warning systems, and integrated adaptation strategies that consider local conditions. The present study tried to identify the onset, withdrawal, and length of the growing season for the Ghinchi area from the long-term rainfall data analysis. Dependable rainfall at a 75% probability level starts in June and extends until September. The planting time for main-season cropping may range from the last week of May to mid-June. The short rainy season is unreliable for planting crops due to its low amount and high variability. Double cropping can be exercised in years of optimal rain because Vertisols have a naturally high waterlogging capacity. Sowing wheat in June using an improved drainage system, followed by growing pulse crops in October, as opposed to traditional practice, is advantageous. Building a water harvesting structure is another promising venture for Vertisols to combat dry spells. Our findings show that the chances of receiving more than 50% of the predicted rainfall at a >20 mm (P(W/W)) threshold level begin on the 20th (14–20 May) and end on the 36th (3–9 September). Based on this calculation, the length of the growing period becomes four months, with 116, 201, 187, and 107 mm for June, July, August, and September, respectively. Forecasting the likely onset and cessation of precipitation on Vertisols helps farmers prepare their land, plant crops, and harvest on time before the soil becomes saturated or dries out, making farm operations difficult under the traditional farming system. During years of excess rain, improving the drainage system and constructing water harvesting structures become useful so that farmers can supplement their land if an early withdrawal of rainfall occurs at any time of the year.

Rainfall variability also affects the environment through soil and water erosion and land degradation. Early planting of crops accompanied with drainage improvement on vertisols can minimize soil erosion. The copping system study showed that growing legumes followed by wheat crop can minimize the use of synthetic fertilizer at least by 50%. Mineralization of legume residue N can contribute the N accumulation in the soil which can be taken by the following crops. For poor resource farmers a one year legume growing can improve the soil structure and fertility.

Despite the importance of Vertisols in the Ethiopian highlands, there is a lack of comprehensive research on the combined effects of rainfall variability, soil and water erosion, drainage improvement, and nutrient management on these soils. From the results of this study, we can conclude that the identified planting window from the last week of May to mid-June for main-season cropping can help farmers maximize crop yields by aligning planting with the onset of reliable rainfall. This timing can enhance crop growth and overall agricultural productivity. Understanding the limitations of the short rainy season and the potential for double cropping in years with optimal rainfall can inform crop selection and rotation strategies. Farmers can consider double cropping and water harvesting in years of dependable rainfall. For this purpose, the study of rainfall variability is of paramount importance. Furthermore, the study highlights the importance of improving drainage to enable early planting and managing nutrients on Vertisols as opposed to the traditional farming practices of planting crops on residual moisture. Late planting of Vertisols can exacerbate soil erosion and have detrimental environmental effects on the soil. The study revealed that planting legumes in rotation with cereals improves agricultural practices, soil fertility management, and increased crop production.

The study also showed that drainage improvement and phosphorus application can increase legume biomass production and nitrogen accumulation, enhance soil nutrient levels, and promote nutrient cycling. The significant effects of residue placement and season on nitrogen mineralization suggest that the decomposition of legume residues plays a crucial role in nutrient cycling and soil fertility. Proper management of legume residues can enhance soil fertility, nutrient availability, and crop productivity through improved decomposition and mineralization processes. The significance of the research on Vertisols in the Ethiopian highlands lies in addressing the challenges faced by farmers who still rely on traditional farming practices. Despite several decades of research and the accumulation of valuable information, a large portion of farmers in these regions continue to practice low-input and low-output agriculture, which not only hampers their productivity but also has detrimental environmental consequences. Research on Vertisols in this context holds significant importance. It offers valuable insights into sustainable Vertisol management and environmentally friendly farming practices that farmers can adopt.

7.5.2 Recommendations

Future studies can explore modifications to the BBF practice or the integration of additional erosion control measures to minimize runoff and soil loss. Additionally, research can focus on identifying and evaluating the effectiveness of other practices that balance agricultural productivity with erosion control, taking into account local conditions and specific cropping systems. By incorporating these findings into farming practices and conservation strategies, farmers can enhance productivity while minimizing erosion risks and promoting sustainable land management. By studying the specific characteristics and challenges of Vertisols in the Ethiopian highlands, researchers can identify effective strategies for mitigating erosion, improving soil conservation, and enhancing agricultural productivity. Farmers should choose legume species with a higher nitrogen concentration and accumulation potential for optimal benefits.

The future implications of this research are multi-faceted. Firstly, the findings can contribute to the development of tailored interventions and extension programs that promote sustainable farming practices for farmers residing on Vertisols. This can lead to increased agricultural productivity, improved livelihoods, and reduced environmental degradation. Secondly, the research can inform policy decisions and guide the allocation of resources towards addressing the pressing issues of erosion and food insecurity in the highlands of Ethiopia. By highlighting the importance of sustainable land management practices, policymakers can prioritize investments in infrastructure, agricultural extension services, and capacity-building initiatives to support farmers in adopting more resilient and environmentally friendly farming techniques. Furthermore, the research on Vertisols can contribute to the broader scientific knowledge and understanding of soil conservation, climate change adaptation, and sustainable agriculture. Researchers can develop innovative approaches by uncovering the specific interactions between soil properties, climatic factors, and agronomic practices. These approaches find application not only in the Ethiopian highlands but also in other regions with similar soil characteristics and environmental challenges. In conclusion, the research on Vertisols in the Ethiopian highlands is significant as it addresses the persistence of traditional farming practices, erosion, and food insecurity. By providing valuable insights and recommendations, this research can pave the way for sustainable land management, improved agricultural productivity, and ental stewardship in the region.

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