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BAHIR DAR UNIVERSITY

College of Agriculture and Environmental Sciences

Department of Natural Resources Management

Potential of *Acacia decurrens*-based Agroforestry System in Improving Soil Properties, Carbon Stock and Crop performance in the Highlands of Northwestern Ethiopia

PhD Dissertation

By

Desalegn Tadele

May, 2025

Bahir Dar

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Potential of *Acacia decurrens*-based Agroforestry System in Improving Soil Properties, Carbon Stock and Crop Performance in the Highlands of Northwestern Ethiopia

PhD Dissertation

By

Desalegn Tadele Awoke

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy (PhD) in Soil Science

Advisory Board Members:

1. Prof. Enyew Adgo (Chairman)
2. Dr. Derege Tsegaye (Co-chairman)

May, 2025

Bahir Dar

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DECLARATION

This is to certify that the thesis entitled "**Potential of *Acacia decurrens*-based Agroforestry System in Improving Soil Properties, Carbon Stock and Crop performance in the Highlands of Northwestern Ethiopia**", submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Soil Science in the Department of Natural Resources Management, Bahir Dar University, is a record of original work carried out by me and has never been submitted to this or any other institution to get any other degree or certificates. The assistance and help I received during the course of this investigation have been duly acknowledged.

Desalegn Tadele		24/04/2025
Name of the candidate	Signature	Date

BAHIR DAR UNIVERSITY

College of Agriculture and Environmental Sciences

Department of Natural Resources Management

Approval of Dissertation for Defense

Approval of Dissertation/Thesis for Defense I hereby certify that I have supervised, read, and evaluated this dissertation entitled **"Potential of *Acacia decurrens*-based Agroforestry System in Improving Soil Properties, Carbon Stock and Crop Performance in the Highlands of Northwestern Ethiopia**" by Desalegn Tadele, prepared under my guidance. I recommend the thesis/dissertation be submitted for oral defense.

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Principal advisor's name	Signature	Date
Dr. Derege Tsegaye (PhD)		24/05/2025
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BAHIR DAR UNIVERSITY

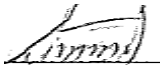
College of Agriculture and Environmental Sciences

Department of Natural Resources Management

Approval of Dissertation for Defense Result

As members of the board of examiners, we examined this dissertation entitled "**Potential of *Acacia decurrens*-based Agroforestry System in Improving Soil Properties, Carbon Stock and Crop Performance in the Highlands of Northwestern Ethiopia**" by Desalegn Tadele. We hereby certify that the dissertation is accepted for fulfilling the requirements for the award of the degree "Doctor of Philosophy in Soil Science".

Board of Examiners

Getachew Agegnehu (PhD)		17/06/2025
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DEDICATION

In the loving memory of my uncle Eyasu Mesfin Asress and elder brother Habtamu Tadele Awoke.

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ABBREVIATIONS AND ACRONYMS

AGB	Aboveground Biomass
ANOVA	Analysis Of Variance
BGB	Below-Ground Biomass
CSA	Central Statistics Agency
CEC	Cation Exchange Capacity
CSF	Charcoal-amended Soil at Full Fertilizer Addition
CSH	Charcoal-amended Soil at Half Fertilizer Addition
DAP	Diammonium Phosphate
DBH	Diameter at Breast Height
FAO	Food and Agriculture Organization
ha	Hectare
HSD	Honestly Significant Difference
n	Sample size
P_{av}	Available Phosphorus
RSF	Reference Soil at Full Fertilizer Addition
SE	Standard Error
SOC	Soil Organic Carbon
ST	Sole *Teff* cropping system
t	Ton
TN	Total Nitrogen
WB	Wood Biochar
yr	Year

LIST OF PUBLICATIONS

This dissertation consists of four manuscripts, out of which two have been published as articles.

I. Tadele, D., & Adgo, E. (2024). In situ charcoal production in *Acacia decurrens*-based Taungya system improved soil properties and productivity of three agricultural crops in the highlands of Northwestern Ethiopia. Soil Use and Management. 40:e13032. https://doi.org/10.1111/sum.13032.

II. Tadele, D., Adgo, E., & Meshesha, D. T. (2024). Improving soil chemical properties and *teff* (*Eragrostis tef*) productivity with *Acacia decurrens*-based fallow in the highlands of Northwestern Ethiopia. Soil Use and Management. 2024;40:e70002. https://doi.org/10.1111/sum.70002

III. Tadele, D., Adgo, E., & Meshesha, D. T. (2025). Amending degraded agricultural soil with Acacia decurrens wood biochar improved soil properties and sustained higher crop yields over two years in Northwestern Ethiopia (submitted to **Journal of Environmental Quality**).

IV. Tadele, D., Adgo, E., & Meshesha, D. T. (2025). Biomass and soil carbon stocks of *Acacia decurrens* and *Eucalyptus camaldulensis* woodlot systems in the highlands of Northwestern Ethiopia (manuscript under preparation for submission).

POTENTIAL OF *ACACIA DECURRENS*-BASED AGROFORESTRY SYSTEM IN IMPROVING SOIL PROPERTIES, CARBON STOCK AND CROP PERFORMANCE IN THE HIGHLANDS OF NORTHWESTERN ETHIOPIA

Abstract

Smallholder farmers in Fagita Lekoma district of Northwestern Ethiopia have introduced *Acacia decurrens*-based agroforestry system following land degradation and the associated reduction in land productivity and crop yield. Despite the rapid expansion of this agroforestry system, its effect on soil properties, carbon storage and crop performance of acidic agricultural soil largely remains unexplored. The present study therefore assessed: (i) short-term *in situ* charcoal production induced changes in soil properties and *teff* (*Eragrostis tef* (Zucc.) Trotter), barley (*Hordeum vulgare* L.) and wheat (*Triticum aestivum* L.) performance; (ii) dynamics of soil properties and *teff* performance on fallowed lands and at croplands adjacent to a four-year-old acacia woodlot; (iii) effects of *A. decurrens* wood-derived biochar application on acid soil properties and *teff* and barley performance; and (iv) carbon storage under *A. decurrens* and *Eucalyptus camaldulensis* woodlot systems. A total of 68 representative fields under various land uses were surveyed. A pot experiment was conducted with wheat using kiln soils and control soils. Acidic soil amendment with *A. decurrens* wood biochar was evaluated using four rates (0, 5, 10 and 20 t ha^{-1}) for two consecutive seasons in 12 permanent plots. Thirty farmers were interviewed for their observations and management of the new cropping system. The results were analyzed using ANOVA and a paired t-test. Descriptive statistics was employed to analyze the socioeconomic data. The relationships among the various parameters were tested using regression and correlation analysis. Compared to the non-kiln sites, charcoal production at kiln sites significantly increased sand fraction, pH, soil organic carbon (SOC), available phosphorus (P_{av}), exchangeable bases (Mg^{2+} and K^{+}), but decreased exchangeable acidity and exchangeable Al^{3+}. Aboveground biomass and grain yield of *teff*, barley, and wheat at kiln sites were, on average, increased by 135% as compared to the non-kiln sites. The results from wheat plants grown in pots demonstrated better crop performance and less inorganic fertilizer

needs in charcoal-amended soils. Soils after *A. decurrens* plantation had improved chemical properties and *teff* yield as compared to the conventional practice with greater effects in the second rotation than in the first rotation. The fallow system maintained two crop harvests in two years. Soil moisture, pH, SOC, P_{av}, total nitrogen (TN) and cation exchange capacity (CEC) were higher at croplands adjacent to the acacia woodlot. However, significant *teff* yield reductions (36 – 96%) were recorded up to 10 m distance from the acacia woodlot. According to the farmers, *in situ* charcoal production and fallowing with *A. decurrens* can improve soil properties and crop performance and reduce the need for inorganic fertilizer by 50%. A single addition of *A. decurrens* wood biochar persistently improved soil properties and crop performance over two years, and the effects were greater at higher application rates. Soil OC stocks were significantly higher in five-year-old woodlots of *A. decurrens* and *E. camaldulensi*s than in the croplands. Carbon storage both in the soil and biomass was higher in woodlots of *A. decurrens* than in *E. camaldulensis*. Overall, the results of this study suggested the significance of *A. decurrens*-based agroforestry system in reducing soil acidity and restoring nutrients for sustainable crop production and mitigating climate change through increased carbon storage of degraded acidic agricultural lands in smallholder farming systems. Further investigations based on multiple rotations and production seasons and combined application of biochar and inorganic fertilizer are required to ascertain the sustainability of the system on a long-term basis and improve nutrient management.

***Keywords*:** Acacia fallows, barley, biochar, *in situ* charcoal production, short-rotation woodlots, *teff*, wheat

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CHAPTER 1: GENERAL INTRODUCTION

1.1 Background and Justification

The dwindling of forest cover, coupled with the ever-increasing demand from the fast-growing human population for various forest products and agricultural land, has resulted in the expansion of tree plantations of fast-growing species (Bayle, 2019; FAO, 2020). The establishment of tree plantations in the highlands of Ethiopia has become an alternative management option to reduce the pressure on the remaining patches of natural forest, fulfill the demand for wood (Lemenih & Bongers, 2010; Pohjonen & Pukkala, 1990; Zerga et al., 2021) and reclaim acid soils (Amare et al., 2022; Belete, 2015). Previously, large tree plantations consisting of mainly *Eucalyptus* species were established on degraded agricultural lands (Pohjonen & Pukkala, 1990). To date, the inclusion of short-rotation woodlots in the cropping system has become a common agroforestry practice, especially in the highlands of the country (Abiyu et al., 2016; Alemayehu & Melka, 2022; Belayneh et al., 2018; Dessie et al., 2022).

In agroforestry systems, woody plants are grown along with crops, pasture, or livestock. Agroforestry has been practiced throughout the tropical regions and widely promoted as a sustainable food production system (Kumar & Nair, 2006). It is considered to be a viable option to improve soil properties, enhance crop performance, and increase carbon storage (Kuyah et al., 2019; Ngaba et al., 2024). Through the processes of litter or fine root production, reduced nutrient losses by leaching and erosion, low level of disturbance primarily by tillage, nutrient cycling and nutrient pumping, agroforestry systems can increase nutrient contents and improve soil properties on degraded lands (Fahad et al., 2022; Ketema & Yimer, 2014; Kim & Isaac, 2022; Ngaba et al., 2024). Soil fertility restoration and increased carbon accumulation through agroforestry systems can be influenced by many site-related factors and attributes associated with planted species, such as plantation density, stand age, planted species, intercrop, climate, and soil conditions (Gota et al., 2024; Lorenz & Lal, 2014; Syano et al., 2023; Yimam et al., 2024).

In the Ethiopian highlands, a short-rotation agroforestry system, which generally involves planting fast-growing trees, has become more common (Abiyu et al., 2016; Alemayehu et al., 2024; Worku et al., 2021). In the Fagita Lekoma district of Northwestern Ethiopia, the agroforestry system primarily consists of woodlots of *Acacia decurrens* and *Eucalyptus* species. Smallholder farmers in the district introduced planting of *A. decurrens* in response to soil acidity development and as a land management mechanism of the exhausted agricultural land. Nowadays, *A. decurrens* has become the principal exotic tree species planted by the smallholder farmers due to enhanced economic and livelihood benefits and improved soil conditions (Amare et al., 2022; Bazie et al., 2021; Nigussie et al., 2020, 2021). The increase in the extent of short-rotation woodlot systems on agricultural lands calls for the need to explore changes in (i) soil properties and crop performance after afforestation, and (ii) carbon stock and allocation both in the biomass and soil under the woodlot systems.

1.2 Statement of the Problem

In the Fagita Lekoma district of Northwestern Ethiopia, farmers have commonly practiced planting of *A. decurrens* on their farmlands. The inclusion of *A. decurrens* in the cropping system is a relatively new development in which *A. decurrens* is harvested at the age of five years and the cycle continues through replanting (Belete 2015; Nigussie et al., 2017). In the first year, *A. decurrens* is planted along with cereals. In the second year, grasses growing between the trees are used as fodder through cut and carry system. During the subsequent years, the tree canopy is too dense to allow understory growth. In the fifth year, the trees are harvested for making charcoal. After tree harvesting and charcoal production, the farmers cultivate the fallowed lands with annual crops for one or two successive years. Oral testimonies of farmers indicated that this new cropping system started about 30 years ago and the practice expanded tremendously during the previous decade. Belete (2015) indicated that about 50% of the cultivated land has been converted into *A. decurrens* stands in the first 15 years since it was introduced into the district (1990-2015). A study by Wondie and Mekuria (2018) showed an annual decline of cultivated land by 1% while area covered by forest, mainly attributed to the expansion of

A. decurrens, increased by 1.2% annually during the period 1995-2015. In 2017, *A. decurrens* woodlot system was the main land use type, covering 35.4% of the land area in the Guder watershed (Berihun et al., 2019). In 2022, *A. decurrens* plantations covered 22.4% of the land area in Fagita Lekoma district (Alemayehu et al., 2024). Despite the considerable increase of areas covered with *A. decurrens* and the advantages that resulted from establishing the system, there exists limited scientific evidence on its merits in terms of changes in soil fertility, carbon storage, and crop performance.

The inclusion of *A. decurrens* in the cropping system shows how farmers' innovations can lead to potentially positive effects on the land-use system. Understanding the effects of integrating this leguminous, nitrogen-fixing tree species on soil fertility and crop performance is important to assess the sustainability of this innovative cropping system. In the new cropping system, farmers also produce charcoal from *A. decurrens* stem wood using charcoal kilns. Farmers make the kilns *in situ* and a large amount of charcoal fines (biochar) can be obtained from charcoal production (Kim et al., 2022; Tazebew et al., 2023). Inevitably, it means that the soil in the kiln sites is altered by the addition of ashes, by the remaining charcoal fragments, and also by the high temperature (Emrich, 1985; Wahabu et al., 2015). During the rainy season, farmers usually cultivate these kiln sites with annual crops immediately after charcoal production. Yet the consequence of *in situ* charcoal production and application of biochar formed from *A. decurrens* wood to soils on soil properties is not exhaustively investigated (Amare et al., 2022; Kim et al., 2022) and there appears to be no report in relation to crop performance and tree-crop interactions in this new cropping system. Besides, the extent to which carbon storage and allocation both within the biomass and soil of the woodlot systems, which could vary with planted species and soil depth (Zhang et al., 2018), is not reported. Having these contexts in mind, this study was designed to evaluate the effects of converting degraded agricultural land into short-rotation woodlot systems on soil properties, carbon stock and crop performance in the highlands of Northwestern Ethiopia. The results of this study are important for the selection and management of trees and integration of charcoal production in agroforestry systems for improved crop performance, carbon sequesteration and nutrient restoration.

1.3 Objectives of the Dissertation

The general objective of this study was to evaluate the potential use of *A. decurrens*-based agroforestry system in improving soil properties, carbon stock and crop performance in the Highlands of Northwestern Ethiopia. The specific objectives of this study were to:

- Evaluate the effects of charcoal production from *A. decurrens* wood stem on soil properties and crop performance in kiln sites (Chapter 3)
- Examine acidic soil reclamation and crop performance in *A. decurrens* fallow system (Chapter 4)
- Investigate the effects of *A. decurrens* wood biochar application to acidic agricultural soil on soil properties and crop performance (Chapter 5)
- Assess carbon storage and allocation in short-rotation woodlot systems established on acidic agricultural lands (Chapter 6)

1.4 Research Questions and Hypotheses

Based on the specific objectives mentioned above, this study addressed the following research questions:

- Does charcoal production from *A. decurrens* wood improve soil quality and crop performance in kiln sites?
- Can the integration of *A. decurrens* in the cropping system help to reclaim acidic agricultural soil and improve crop performance?
- Does the addition of *A. decurrens* wood biochar to acidic soil increase crop performance by improving soil acidity and nutrient availability?
- Can carbon storage on degraded agricultural land be increased through the establishment of short-rotation woodlot systems?

In this study, we set the following hypotheses:

- Charcoal production would increase crop performance at kiln sites by remediation of soil acidity and improving soil nutrient availability.

- Soil properties and *teff* performance would be influenced by fallow duration and distance from *A. decurrens* woodlots.
- A single application of *A. decurrens* wood biochar to acidic agricultural soil would improve soil properties and crop performance for two successive production years.
- Organic carbon storage on a degraded agricultural land would be increased by the establishment of woodlot systems using fast growing species.

1.5 Organization of the Dissertation

The thesis consists of seven chapters. In Chapter 1, the introductory portion of the thesis is addressed. It highlights the general background and justification regarding short-rotation agroforestry systems, research objectives and questions, and the underlying hypotheses of the study. Chapter 2 describes the general materials and methods, including study site description, data collection and analysis. Chapter 3 focuses on how farmers' practice of on-site charcoal production impacts soil properties and performance of three crops. In Chapter 4, we look at soil properties and *teff* performance on fallowed lands in two rotations that represent 5 and 10 years of fallow duration, over two successive production years and at crop fields adjacent to a four-year-old *A. decurrens* woodlot. The effect of amending acidic soil with *A. decurrens* wood biochar, based on application rates and for two production years, on soil properties and crop performance is presented in Chapter 5. Chapter 6 examines the changes in organic carbon storage following the conversion of degraded agricultural lands into a woodlot system consisting of fast-growing species. In Chapter 7, broad conclusions and recommendations are drawn based on the main findings of the study (Chapters 3 – 6).

CHAPTER 2: GENERAL MATERIALS AND METHODS

2.1 Description of the Study Area

2.1.1 Location and climate of the study area

The study was conducted in the Guder watershed situated in Fagita Lekoma district of Amhara Region, Northwestern Ethiopia (Figure 2.1). Guder watershed, which lies between $10^{o}59'30''–11^{o}1'0''N$, $36^{o}54'0''–36^{o}56'0''E$, has a rugged and undulating topography with altitude ranging between 2492 and 2882 m above sea level (Yibeltal et al., 2019). Climatic data were collected from the Ethiopian Meteorological Agency, Bahir Dar District. Based on the climatic records from 2000 to 2020 at Injibara station (Figure 2.2), the watershed has a mean annual rainfall of 2393 mm and a mean monthly temperature ranging between 13 and 20 $^{\circ}C$, with a dry season extending from November to April and a wet season from May to October.

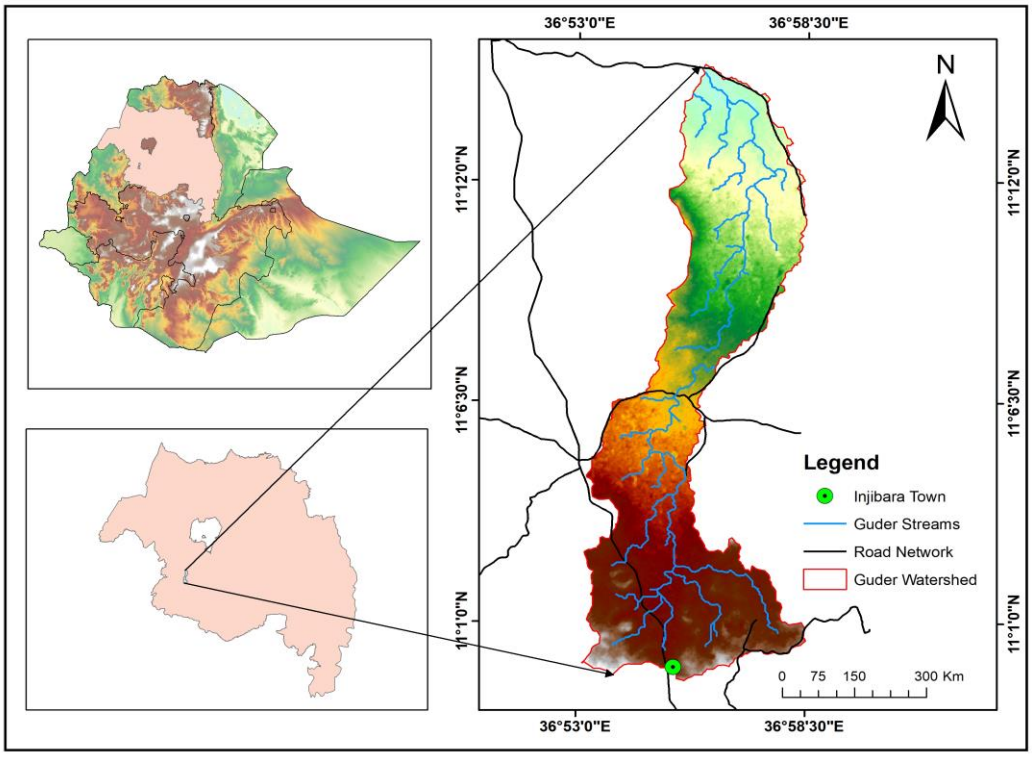

Figure 2.1 Map of the study area

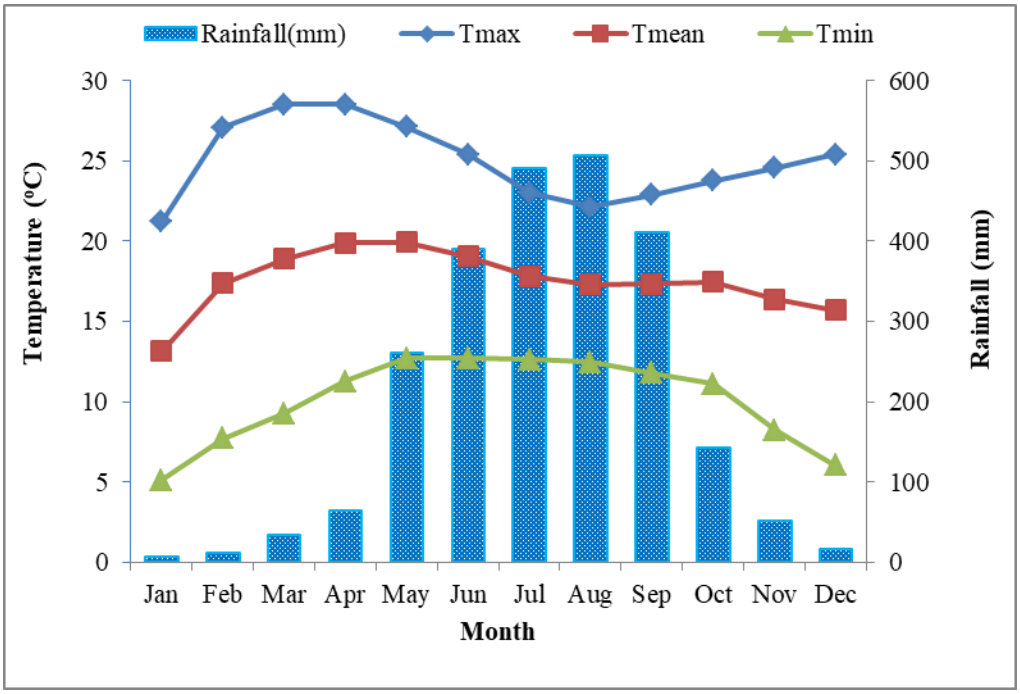

Figure 2.2 Mean monthly rainfall and temperature records of the study area from 2000 to 2020

2.1.2 Soil characteristics and farming systems

The watershed had a pH that varied between 4.2 and 6.5 (Abebe et al., 2020), CEC between 21 and 66 $cmol_+ kg^{-1}$, and clay loam as the primary textural class (Mekonnen, 2016). Luvisols and Leptosols represent the major soil groups for our sampling sites (Mekonnen, 2016). The major farming system in the watershed is mixed rain-fed subsistence agriculture with an increasing shift towards agroforestry systems dominated by *A. decurrens* plantation. The development of soil acidity and the associated low crop performance have been the major challenges to agricultural production and food security (Amare et al., 2022; Nigussie et al., 2020). The dominant crops cultivated consist of *teff* (*Eragrostis tef* (Zucc.) Trotter), barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.) and potato (*Solanum tuberosum* L.).

2.2 Data Collection and Laboratory Analysis

To assess the effects of fallow duration, *in situ* charcoal production practice and soil amendment with locally produced wood biochar on soil properties and crop performance, the present study employed a survey of farmlands under *A. decurrens*-based agroforestry system and the establishment of permanent plots treated with various rates of *A. decurrens* wood biochar. The general methodology for soil and crop data sampling and analysis is presented below.

2.2.1 Soil sampling and analysis

Soil samples were taken at 0 – 15 cm soil depth from selected farmlands which were converted into *A. decurrens*-based agroforestry system and from permanent plots established on farmlands that were not planted with acacia trees but amended with different biochar rates. The selected farmlands under the agroforestry system were in the first and second rotations and cultivated with annual crops for one or two production years between successive rotations after *A. decurrens* stand harvest, followed by *in situ* charcoal production.

Soil samples were analyzed for the selected soil physicochemical properties at the plant and soil laboratory of Amhara Design and Supervision Works Enterprise, and Bahir Dar University, Bahir Dar, Ethiopia. The soil samples were air-dried at room temperature and ground to pass through a 2 mm sieve. Bulk density was determined using undisturbed core sampling method, texture using the hydrometer method, soil pH in 1: 2.5 soil to water suspension, soil organic carbon (SOC) by Walkley-Black oxidation method (Walkley & Black, 1934), total nitrogen (TN) by Kjeldahl method and available phosphorus (P_{av}) by the Bray method (Bray & Kurtz, 1945). Exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}) and cation exchange capacity (CEC) were analyzed using the ammonium acetate method. Exchangeable acidity and exchangeable Al^{3+} were determined by KCl extraction and titration. Soil moisture was determined gravimetrically after soil samples were oven-dried at 105 ^{o}C for 24 h.

2.2.2 Crop performance

Crop performance was assessed using three annual crops: *teff*, barley and wheat under rain-fed conditions. The test crops were selected for the study as they are commonly integrated with *A. decurrens* seedlings during the early stage of the agroforestry system. Crop performance was evaluated by measuring vegetative growth and grain yield of the crops planted and managed under the existing farming practices. Plant height was measured with a scaled measuring tape from the base of the plant to the tip of the tallest leaf. Aboveground biomass and grain yields were determined by harvesting sample plots by hand close to the ground. The harvested samples were sun-dried till obtaining a constant weight. The samples were separated into grain and straw yields by manual threshing. The grain and straw yields were then measured using a standard digital scale (SF–400) to determine the aboveground biomass yield (grain + straw). Finally, aboveground biomass and grain yields were converted into t ha^{-1} for statistical analysis.

CHAPTER 3: IN SITU CHARCOAL PRODUCTION IN *ACACIA DECURRENS*-BASED TAUNGYA SYSTEM IMPROVED SOIL PROPERTIES AND PERFORMANCE OF THREE AGRICULTURAL CROPS IN THE HIGHLANDS OF NORTHWESTERN ETHIOPIA[1]

Abstract

Short-term *in situ* charcoal production-induced changes in soil properties and crop performance of acidic soil in *A. decurrens*-based Taungya system were assessed in the Guder watershed of Northwestern Ethiopia. Data were collected through a field survey, pot experiment and interviews with local farmers. A total of 36 paired charcoal production kiln sites and adjacent reference sites in 18 farmlands were surveyed to analyze soil physicochemical properties and performance of *teff*, barley and wheat. A pot experiment was undertaken with wheat to investigate seed germination and chemical fertilizer needs at charcoal production sites. Local farmers were interviewed for their perceptions and management practices. The production and short-term presence of charcoal in kiln sites significantly increased sand fraction, pH, SOC, P_{av}, exchangeable Mg^{2+} and exchangeable K^{+} compared to the reference sites. Charcoal production practice raised pH by 0.83 units, SOC, P_{av} and exchangeable K^{+} by 40, 92 and 303%, respectively. Exchangeable acidity and exchangeable Al^{3+} were lowered by over 80% at kiln sites. Both aboveground biomass and grain yield of *teff*, barley and wheat were, on average, 135% higher at kiln sites than at the reference sites. Furthermore, crops grown at kiln sites were taller and had greener and larger leaves. Farmers' responses indicated higher crop performance and reduced inorganic fertilizer application at kiln sites. Results from the pot experiment provided evidence of faster seed germination, enhanced crop yield and reduced inorganic fertilizer needs in charcoal-treated soils. The study suggests that the inclusion of charcoal remnants and heating can increase carbon storage, improve

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soil properties which promote crop production and reduce the need for inorganic fertilizer in degraded, acidic agricultural soil.

Keywords: Barley, acidic agricultural soil, charcoal-amended soil, kiln site, seed germination, *teff*, wheat

3.1 Introduction

Charcoal is primarily produced to generate income and energy (Afework et al., 2023; Smith et al., 2019). Over 53 million tons of charcoal is produced annually worldwide (FAO, 2017). The contribution of Africa to the world's charcoal production is nearly 65%, with Ethiopia in third position globally by producing over 4.4 million tons annually (Mensah et al., 2020). In developing countries, charcoal is mainly produced *in situ* using earthen mound kilns (Chidumayo & Gumbo, 2013; Tazebew et al., 2023). During charcoal production, a significant amount of biochar can be produced as a by-product and becomes incorporated into the soil at kiln sites (Coomes & Miltner, 2017; Lisboa et al., 2020). In Ethiopia, about 244,868 tons of biochar can be obtained annually as a waste product from charcoal production, considering annual charcoal production of 4.42 million tons (Mensah et al., 2020) and about 5.54% of the charcoal is non-marketable (Tazebew et al., 2023). This figure can be raised to a large extent as a result of the growing demand coupled with inefficient traditional charcoal production practices.

Charcoal production taking place *in situ* in agricultural fields can influence soil properties and crop production at kiln sites through heating effects and the introduction of charcoal remnants (biochar) into the soil (Abebe & Endalkachew, 2011; Coomes & Miltner, 2017; Leng et al., 2021; Oguntunde et al., 2004). In the Fagita Lekoma district of Northwestern Ethiopia, where this study was carried out, charcoal production is an integral part of a tree-based agroforestry system in which wood is taken from *A. decurrens* fallow forests established on acidic agricultural soil. Farmers in the study area practiced charcoal production from *A. decurrens* wood under several kiln sites in the farm field. Kiln sites are young, less than one year old, and farmers usually cultivate these kiln sites with annual crops immediately after charcoal production.

In the study area, integrating *A. decurrens* in the cropping system is a new development that has become the most popular agroforestry practice for farmers affecting large parts of the cropland (Belayneh et al., 2018; Wondie & Mekuria, 2018). This *A. decurrens*-based fallow system is typically a Taungya system (joint production of crops and trees on the same piece of land), allowing farmers to produce both annual crops and wood on the same area during a 5-year rotation scheme (Belete, 2015; Nigussie et al., 2017). The Taungya system, which involves *in situ* charcoal production, was developed through farmers' innovation following a significant reduction in crop performance (Nigussie et al., 2020; Wondie & Mekuria, 2018). Due to the deteriorating soil conditions, croplands can be cultivated with only one crop in two years. In contrast, introducing the new cropping system may help sustain crop yields for two consecutive years and influence crop performance at kiln sites. However, while the expansion of this innovative cropping system continues (Alemayehu et al., 2024; Worku et al., 2021), scientific evidence is scarce on its merits in terms of changes in soil acidity problems, soil fertility and crop performance.

Most studies conducted so far primarily addressed expansion, socioeconomic aspects and ecological sustainability of *A. decurrens* stands (Afework et al., 2023; Belayneh et al., 2018; Berihun et al., 2019; Nigussie et al., 2017, 2020; Teshome & Wondimu, 2019). Only a few studies reported changes in soil properties at charcoal production sites in *A. decurrens*-based Taungya system (Amare et al., 2022; Beshir et al., 2022; Kim et al., 2022) and there appears to be no report regarding the effects of this new cropping system on crop performance. The present study has practical significance as the innovative use of kiln sites for agricultural production (Coomes & Miltner, 2017; Miltner & Coomes, 2015) can be influenced by soil properties at the kiln sites that appear to vary depending on biochar type, site-specific soil and climatic conditions and management practices (Biederman & Harpole, 2013; Gezahegn et al., 2019; Glaser & Lehr, 2019; Singh et al., 2022; Ye et al., 2020). Furthermore, this study would provide valuable information on the short-term benefits of charcoal production on crop yield and soil properties as most studies addressed the long-term benefits using historical charcoal kilns mainly in forestlands (Bonhage et al., 2020; Carrari et al., 2018; Donovan et al., 2021; Hardy et al., 2016; Kerré et al., 2017; Mastrolonardo et al., 2019). It would hence be

worthwhile considering this cropping system to investigate the short-term effects of *in situ* charcoal production in the agricultural landscape on soil properties and crop performance. This study, therefore, aimed to test the management options available to farmers for soil acidity problems and low soil fertility status through the integration of charcoal production in *A. decurrens*-based Taungya system. We hypothesized that: (i) charcoal production would increase crop performance at kiln sites by remediation of soil acidity and improving soil nutrient availability; (ii) cultivating kiln sites can reduce inorganic fertilizer needs, which in turn would reduce crop production cost.

3.2 Materials and Methods

3.2.1 Study area description

The study was conducted in the Guder watershed situated in Fagita Lekoma district of Amhara Region, Northwestern Ethiopia (Figure 2.1). A detailed description of the study area can be found in section 2.1 of Chapter 2.

3.2.2 Characteristics and selection of kiln sites

Under the existing farmers' production circumstances, the effects of the inclusion of charcoal production in the *A. decurrens*-based Taungya system were evaluated in the study area during the cropping seasons of 2021. Charcoal production in the study area takes place using traditional earth mound kilns, and hence charcoal kiln sites were considered as field experimental sites to analyze the effects of *in situ* charcoal production on soil properties and crop performance. The charcoal kiln sites are round and easily recognized as black spots. They are formed *in situ* on the agricultural fields following charcoal production practices taking place right in the fallowed agricultural fields. Once formed, these kiln sites were managed under the existing farming practices for annual crop production.

Some features of kiln sites and biochar locally produced from *A. decurrens* wood are shown in Table S3.1. Charcoal production is the source of biochar, and farmers produce charcoal from *A. decurrens* wood in traditional earth mound charcoal kilns. *A.*

decurrens trees at the age of about five years are cut close to the ground, with the cut trunk and main branches chopped into 30-50 cm cutting logs (Tazebew et al., 2023). The logs are stacked around the kiln site into a mound (Figure 3.1b) and covered with crop residues and soil to heat wood in an oxygen-limited atmosphere for the carbonization process. When pyrolysis is complete, large pieces of harvested charcoal fragments are placed in sacks for marketing, whereas fine charcoal fragments are left at the charcoal production sites as a waste product (biochar) (Figure 3.1c).

Field survey was undertaken on 30 fallowed agricultural fields in the first rotation of *A. decurrens*-based Taungya system to characterize charcoal kiln sites and for the evaluation and comparison of soil properties and crop performance at charcoal kiln sites (plots on farmlands where charcoal production took place and had soil enriched with charcoal fragments, hereinafter referred to as kiln sites) with those of adjacent non-kiln sites (plots on farmlands that were not exposed to charcoal production and had soil not enriched with charcoal fragments, hereinafter referred to as reference sites). The farmlands had sizes ranging between 0.2 and 0.57 ha. The density of kiln sites was determined in the field by counting the number of kiln sites present in each farmland and finally reported as the number of kiln sites per hectare. The size of kiln sites was estimated by measuring the diameter of two randomly chosen kiln sites per farmland and their corresponding area was calculated using the circle formula. Soil properties and crop performance were assessed using 36 paired kiln sites and reference sites distributed over 18 fallowed agricultural fields. The kiln sites had ages ranging between 1 – 6 months since the sites were established to produce charcoal at the time of sowing. These kiln soils in this age range represent the most common kilns in the study area. Kiln sites were selected randomly, provided that each kiln site was paired with an adjacent reference site that lacked charcoal-enriched soils, subjected to identical management practices, and occurred at the same elevation and within 7 – 15 m to ensure that the soils for comparison had similar properties. Hence, we assume that charcoal production is the main discriminatory variable to induce changes in soil properties and crop performance between kiln sites and reference sites.

3.2.3 Soil sampling and analysis

Surface soil at 15 cm depth was sampled by taking three cores (composite) from ten randomly selected paired kiln sites and the reference sites planted with *teff* and distributed over five agricultural fields. The soil samples were analyzed for soil moisture, bulk density, texture, pH, SOC, TN, P_{av}, exchangeable bases (Ca^{2+}, Mg^{2+} and K^{+}), CEC, exchangeable acidity and exchangeable Al^{3+}. The details for the analysis of soil parameters can be found in section 2.2 of Chapter 2.

3.2.4 Crop growth and yield measurements

Crop performance at kiln sites and adjacent reference sites was assessed using three annual crops: *teff*, barley and wheat under rain-fed conditions. Crop performance was evaluated using 36 paired kiln sites and reference sites by measuring vegetative growth and grain yield of the crops planted and managed under the existing farming practice. Vegetative growth and grain yield of each crop were determined across six representative farmlands, each consisting of two paired kiln sites and reference sites. Growth in leaf area and height of the crops were measured using four randomly selected plants from a 1 m^2 plot in each paired kiln site and reference site (n = 48: 4 plants per plot x 2 plots per farmland x 6 farmlands). For all crops, leaf area was measured using a leaf area meter (AM350, UK) at the vegetative stage, whereas plant height, aboveground biomass yield and grain yield were determined at physiological maturity for *teff* plants (to reduce yield losses by shattering) and at crop maturity for barley and wheat plants. Aboveground biomass and grain yields were determined by harvesting a 1 m^2 plot in each site by hand close to the ground (n = 12: 2 harvested plots per farmland x 6 farmlands). Plant height, biomass and grain yields were determined as described in section 2.2 of Chapter 2

3.2.5 Pot experiment with wheat

To test whether charcoal production affects seed germination and reduces inorganic fertilizer needs, a pot experiment was undertaken with wheat as a test crop. Charcoal-enriched soil (kiln soil) and reference soil were sampled from agricultural land during a dry season to a depth of 15 cm at five paired kiln sites and reference sites. Soil samples were mixed and composited for each treatment site. The soil samples, consisting of three treatments (reference soil treated with full inorganic fertilizer rate (RSF); and charcoal-amended soil treated with half (CSH) and full (CSF) inorganic fertilizer rates) in four replications, were transferred to 12 plastic pots (17.5 cm in diameter at top and 20 cm in height), each filled with 1.8 kg soil and arranged in randomized complete block design. Inorganic fertilizer application rates were based on local farmers' practice (DAP and Urea, each 60 kg ha^{-1}). Pots were watered to 70% of field capacity once every three days. Pots filled with charcoal-amended soils and reference soils were watered to 70% field capacity, and then the weight of each pot was measured to determine the target weight. Changes in the weight of each pot occurred during the three-day intervals were considered as the amount of water lost from the soil, and the same volume of water was added to the respective treatments (Junker et al., 2015) to maintain soil moisture content corresponding to 70% field capacity. In each pot, 20 seeds were sown and the germinated seeds were counted each day from the first to the last day of seed germination after sowing. The daily germination rate was determined by dividing the number of seeds germinated each day by the total number of seeds sown. Wheat plants were thinned to 15 plants pot^{-1} 20 days after emergence. Chlorophyll content was measured using a chlorophyll meter (MC-100, USA) at the vegetative stage with triplicate readings on three young and fully expanded leaves per plant. Two plants per pot were chosen randomly to repeat the procedure. All plants in each pot were harvested at maturity for aboveground biomass production and grain yield estimation and converted into g pot^{-1}.

3.2.6 Farmers' perception and observation on the effects of *in situ* charcoal production on soil properties and crop performance

A socio-economic survey was conducted to investigate the agricultural use of kiln sites and their management through interviews with informant farmers. Thirty key informants were selected via purposive sampling. The sampling frame consisted of farmers who had converted their croplands into an acacia woodlot system, harvested acacia woodlots and cultivated fallowed lands with annual crops within two years prior to data collection. A semi-structured interview was employed to generate information related to the growth and grain yield of various crops under kiln sites, management of kiln sites for improved crop production, weed growth and changes in soil conditions at kiln sites.

3.2.7 Statistical analysis

We compared mean soil properties and crop performances between kiln sites and reference sites using a t-test. One-way ANOVA was employed to compare treatment means in the pot experiment. Mean differences were considered significant at $p < 0.05$ and 0.01. Tukey's honestly significant difference (HSD) test was used for mean separation. Socioeconomic data were analyzed using tables and percentages. Correlations between variables were calculated using Pearson's correlation coefficient at $p < 0.05$. The relationship between soil properties and crop performance was fitted to a simple linear model. The relative change in soil properties and crop performance induced by charcoal production was calculated.

$$\mathrm{RC}\ (\%) = \frac{(\mathrm{KS} - \mathrm{RS})}{\mathrm{RS}}\ \mathrm{x}\ 100$$

Where RC is the relative change in percent, KS is the soil property and crop performance measured at the kiln sites and RS is the soil property and crop performance measured at the reference sites.

3.3 Results

3.3.1 Inclusion of *A. decurrens* in the cropping system

The inclusion of *A. decurrens* in the cropping system, innovated by the local farmers, is a relatively new development that integrates charcoal production into a tree-based agroforestry system. This *A. decurrens*-based agroforestry system is a predominant agroforestry practice in the study area in which *A. decurrens* is integrated into a five-year rotation scheme. It is typically a Taungya system involving the joint production of woody plants and annual crops on the same plot of land followed by on-site charcoal production at the final stage. Farmers sow annual crops by broadcasting and they plant acacia seedlings in rows as intercrop (Figure 3.1). The *A. decurrens*-based Taungya system consists of three interrelated management phases (Table 3.1): mixed planting of *A. decurrens* and agricultural crops aimed at producing crops in the first year while establishing the woodlot; tree fallow phase to build up wood biomass and provide secondary benefits such as grass harvest in the second year and soil fertility restoration; and a final post fallow phase characterized by wood harvesting at the fifth year and on-site charcoal production. In this local farmers' innovative agricultural practice, reduced soil erosion, nitrogen fixation, nutrient recycling to surface soil by the root system, biochar by-product and farmers' practice of good residue management (leaving leaves, small branches, debris and charcoal fragments) can be factors for the restoration of soil fertility (Belete, 2015; Beshir et al., 2022; Tamirat & Wondimu, 2019).

Table 3.1 Management practice of short-rotation *A. decurrens*-based Taungya system in the study area

Steps	Description of management practices	Stand age
1	Mixed planting of *A. decurrens* and annual crops	1st year
2	Crop harvest in the first year	1st year
3	Grass harvest in the second year	2nd year
4	Clear cutting of *A. decurrens* at the fifth year	5th year
5	On-site charcoal production	5th year

The Taungya system was developed through farmers' innovation in response to severe land degradation that led to a significant reduction in crop production (Nigussie et al., 2017; Wondie & Mekuria, 2018). It is particularly over the last decade that the practice has expanded tremendously, both in the study area and to the neighboring districts, competing for annual cropping and grazing land. The report by Belete (2015) showed that about 50% of the cultivated land was converted into *A. decurrens* trees during 15 years since its introduction into the district (1990-2015). The area covered by *A. decurrens* reached 35.4% in 2017 in the Guder watershed (Berihun et al., 2019) and 22.4% in 2022 in the Fagita Lekoma district (Alemayehu et al., 2024). The Taungya system includes charcoal production, which takes place using earth mound kilns (Table S3.1) right in the field where *A. decurrens* wood biomass is burnt (Figure 3.1b & c). There were about 25 – 39 kiln sites ha^{-1} (averaged 33 ha^{-1}), having an average size of 7 m in diameter (38.5 m^2). Kiln sites had ages ranging between 1 – 12 months since their establishment, and they are being used only once for charcoaling (Table S3.1). Charcoal production often occurs during the dry season and the abandoned kiln sites are commonly cultivated with annual crops during the rainy season. Farmers reported that crops grown on these kiln sites perform better compared to the adjacent reference sites (Table 3.6). *Teff,* wheat and barley are commonly grown with *A. decurrens* seedlings intercropped during the first year of the Taungya system. In this innovative cropping system, there is also the practice of cultivating two crops in two years with annual crops grown in monoculture in the first year and intercropped with *A. decurrens* seedlings in the second year. Croplands, unless converted into this new cropping system, can sustain only one crop in two years.



Figure 3.1 Illustration of the *A. decurrens*-based cropping and charcoal production system: (a) 4th year growth of *A. decurrens*; (b) heap of wooden sticks forming a kiln; (c) bags of charcoal ready for the market; (d) sapling with remaining stalks of last season's harvested *teff*

3.3.2. Effects of *in situ* charcoal production on soil physical properties

The mean values of bulk density, texture and soil moisture content, measured at the surface layer for analysis of soil physical properties between kiln sites and reference sites, are presented in Table 3.2. The results showed that charcoal production had significant effects on the sand and clay fractions of the soils. At kiln sites, sand content (37.9%, $p < 0.01$) was raised by 23.6%, whereas the clay content (21.1%, $p < 0.05$) was reduced by 21.2%. In contrast, bulk density, silt fraction and soil moisture content were not different between the two sites ($p > 0.05$). The soil at the kiln site and reference site had different textural classes, i.e., loam and clay loam, respectively.

Table 3.2 Charcoal-induced changes in soil physical properties in *A. decurrens*-based Taungya system (mean + SE, n = 10)

Soil parameters	Unit	kiln site	Reference site	RC (%) †	t-statistics	*P*-value
Sand	%	37.9±1.84a	30.7±1.55b*	+23.6	9.74	< 0.0001
Silt	%	41.0±1.55	42.6±1.28	-3.7	-1.32	ns
Clay	%	21.1 ±1.45b	26.8±1.01a	-21.2	-4.76	0.00143
Textural class		Loam	Clay Loam			
Bulk density	g cm^{-3}	1.08±0.01	1.05±0.02	+2.9	2.35	ns
Soil moisture content	%	38.3 ±1.06	40.1±1.02	-4.5	3.14	ns

Values followed by different letters in a row are significantly different at $p < 0.05$; * significant at $p < 0.01$; †relative change.

3.3.3 Effects of *in situ* charcoal production on soil chemical properties

In this study, soil chemical properties exhibiting significant variations between kiln sites and reference sites include pH, SOC, P_{av}, exchangeable Mg^{2+}, exchangeable K^{+}, exchangeable acidity and exchangeable Al^{3+} (Table 3.3). The value of pH, averaged 5.58, was increased by 0.83 units at the kiln sites compared to the corresponding value at the reference sites with a mean pH value of 4.74. Charcoal production substantially reduced ($p < 0.01$) exchangeable acidity and exchangeable Al^{3+} contents at kiln sites by 82 and 86%, respectively. Contents of SOC and P_{av} at kiln sites were significantly higher ($p < 0.01$) and increased by 40 and 92%, respectively. Kiln sites also had higher contents of exchangeable Mg^{2+} and exchangeable K^{+} which were increased by 32 and 303%, respectively. In contrast, exchangeable Ca^{2+}, TN and CEC were not significantly affected by the charcoal production practice ($p > 0.05$).

Table 3.3 Charcoal-induced changes in soil chemical properties in *A. decurrens*-based Taungya system (mean + SE, n = 10)

Soil parameter	Unit	Site		RC (%) †	t-statistics	*P*-value
		Reference site	Kiln site			
pH (H_2O)		4.74 ± 0.03b	5.58 ± 0.09a	+17.7	5.42	0.00063
SOC	%	3.39 ± 0.13b	4.74 ± 0.14a*	+39.8	6.00	0.00032
Ex. Ca^{2+}	$cmol_+ kg^{-1}$	7.03 ± 0.48	7.93 ± 0.62	+12.8	1.48	ns
Ex. Mg^{2+}	$cmol_+ kg^{-1}$	0.59 ± 0.03b	0.78 ± 0.07a	+32.2	2.79	0.0236
Ex. K^+	$cmol_+ kg^{-1}$	1.21 ± 0.031b	4.88 ± 1.08a*	+303	4.90	0.0012
TN	%	0.47 ± 0.01	0.44 ± 0.02	-6.4	-1.77	ns
Pav	$mg\ kg^{-1}$	10.75 ± 0.63b	20.6 ± 2.18a*	+91.6	3.84	0.0049
CEC	$cmol_+ kg^{-1}$	46.82 ± 1.50	41.68 ± 1.55	-11.0	-2.43	ns
Ex. Acidity	$cmol_+ kg^{-1}$	3.87 ± 0.31a	0.69 ± 0.06b*	-82	-8.53	< 0.0001
Ex. Al^{3+}	$cmol_+ kg^{-1}$	3.42 ± 0.40a	0.48 ± 0.02b*	-86	8.14	< 0.0001

Values followed by different letters in a row are significantly different at $p < 0.05$; * significant at $p < 0.01$; †relative change; Ex., exchangeable; SOC, soil organic carbon; TN, total nitrogen; P_{av}, available phosphorus; CEC, cation exchange capacity.

3.3.4 Effects of *in situ* charcoal production on crop performance

Growth and grain yields of *teff*, barley and wheat under the existing farming system in the field are shown in Table 3.4 and Figure 3.2. Charcoal production significantly affected ($p < 0.01$) the growth of *teff*, barley and wheat. Kiln sites exhibited greater growth in height and leaf area of the crops than the reference sites. At kiln sites, heights of *teff*, barley and wheat were increased by 40, 23 and 39%, respectively. Similarly, leaf areas of *teff*, barley and wheat at kiln sites were remarkably increased by 185, 150 and 140%, respectively.

Table 3.4 Comparison of growth in height and leaf area and harvest index of annual crops (mean + SE) between paired kiln sites and reference sites (n = 48 for plant height and leaf area; n = 12 for harvest index)

Crop characteristics	Crop	Sites		RC (%) †		
		Kiln sites	Reference sites		t-statistics	*P*-value
Plant height (cm)	*Teff*	88±2.0a	63± 1.2b*	+40	10.9	< 0.0001
	Barley	122± 2.2a	99± 1.2b*	+23	10.2	< 0.0001
	Wheat	147±1.8a	106± 1.4b*	+39	20.3	< 0.0001
Leaf area (cm^2)	*Teff*	9.7±0.3a	3.4± 0.2b*	+185	20.1	< 0.0001
	Barley	55.3± 1.8a	22.1± 1.2b*	+150	17.2	< 0.0001
	Wheat	38.3±0.8a	16.0± 0.5b*	+140	27.1	< 0.0001
Harvest index (%)	*Teff*	18.0 ± 0.03b	22.0 ± 0.06a	-18.2	-5.34	< 0.0001
	Barley	47.8 ± 0.03	47.9 ± 0.05	-0.21	-0.17	ns
	Wheat	40.5 ± 0.04	42.0 ± 0.03	-3.6	-4.69	ns

Values followed by different letters in a row are significantly different at $p < 0.05$; * significant at $p < 0.01$; †Relative change.

There were clear dry matter yield differences between agricultural crops grown at kiln sites and reference sites. At harvest, total aboveground dry biomass and grain yields were significantly ($p < 0.01$) higher for the three crops grown at kiln sites than at the reference sites. Compared to the reference sites, charcoal production increased aboveground biomass and grain yields of *teff*, barley and wheat by 69, 168 and 158 and 46, 167, 142%, respectively. The harvest index of *teff* was significantly reduced at kiln sites ($p < 0.01$), whereas for barley and wheat harvest index was not affected by charcoal production (Table 3.4).

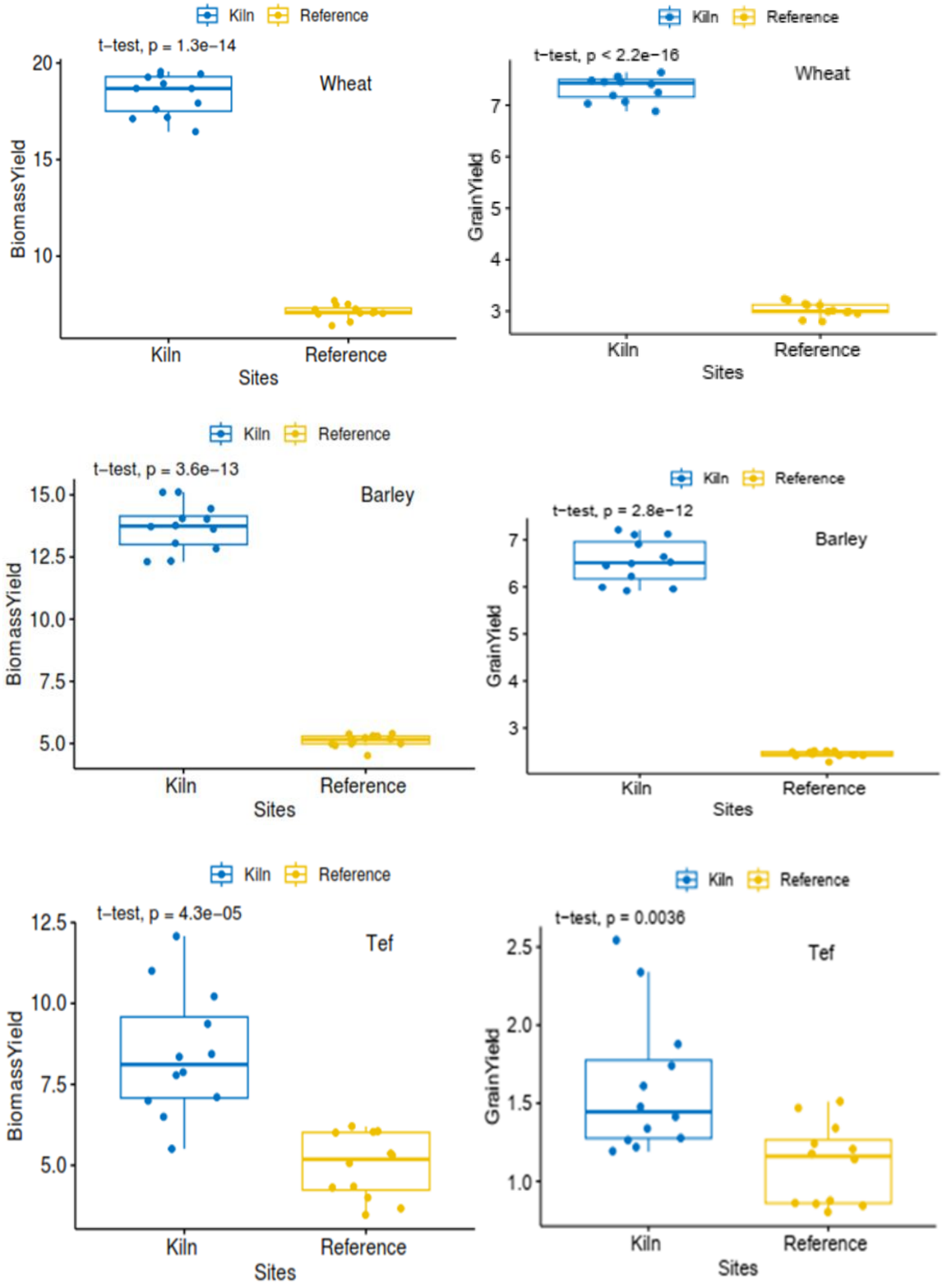

Figure 3.2 Total aboveground biomass yield and grain yield (t ha^{-1}) of crops grown at kiln sites and adjacent reference sites in the highlands of Northwestern Ethiopia (n = 12).

Results of the pot experiment showed that charcoal-amended soil at half (CSH) and full (CSF) inorganic fertilizer application rates significantly increased ($p < 0.01$) wheat performance compared to the reference soil at full inorganic fertilizer application rate (RSF). However, there was no significant difference in wheat performance between CSH and CSF. Compared to RSF, wheat biomass yield was increased by 180 and 205% in CSH and CSF, respectively. Grain yield was also increased by 171 and 200% in CSH and CSF, respectively (Table 3.5). Charcoal production significantly increased the chlorophyll content of wheat plants. The highest chlorophyll content was recorded in wheat plants grown on CSF.

Table 3.5 The effects of charcoal production on total aboveground biomass yield, grain yield and chlorophyll content of wheat using a pot experiment (n = 4 for biomass and grain yields; n = 8 for chlorophyll content)

Crop characteristics	Treatments		
	CSF	CSH	RSF
Aboveground biomass yield (g pot^{-1})	37.5 $\pm$ 0.65a	34.5 $\pm$ 0.65a	12.3 $\pm$ 0.45b*
Grain yield (g pot^{-1})	18 $\pm$ 0.91a	16.3 $\pm$ 0.49a	6.0 $\pm$ 0.48b*
Chlorophyll content (SPAD-unit)	40.0 $\pm$ 0.78a	35.9 $\pm$ 0.45a	20.0 $\pm$ 0.30b*

Values followed by different letters in a row are significantly different at $p < 0.05$; * significant at $p < 0.01$. CSF, charcoal-amended soil at full fertilizer addition; CSH, charcoal-amended soil at half fertilizer addition; RSF, reference soil at full fertilizer addition.

For all treatments, wheat seed germination commenced on the fourth day and culminated on the 8th day (Figure 3.3). Charcoal production stimulated wheat seed germination which reached the peak on day 5, one day faster than the control. On day 5 (peak germination), CSH and CSF had significantly higher ($p < 0.05$) seed germination rates (45%) than the RSF (20%). The germination capacity of wheat seeds reached 100% on the 8th day and was not influenced by charcoal production or fertilizer addition.

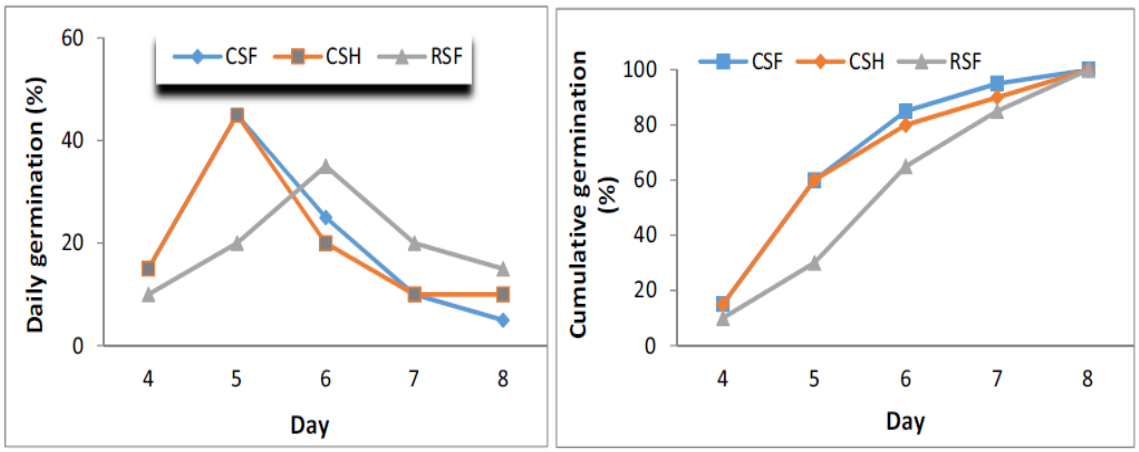

Figure 3.3 The response of wheat seed germination to charcoal production using a pot experiment. CSF, charcoal-treated soil at full fertilizer addition; CSH, charcoal-treated soil at half fertilizer addition; RSF, reference soil at full fertilizer addition (n = 4).

3.3.5 Farmers' observation, perception and management of the new cropping system

All the respondent farmers witnessed faster seed germination and early growth and greater vegetative and grain yields of *teff*, barley and wheat in the kiln sites than in the reference sites (Table 3.6). Farmers' estimation of the increase in grain yield of crops at the kiln sites was over 100% compared to the reference sites. All the farmers perceived that the soil becomes more fertile at kiln sites than at reference sites and considered improved soil fertility as a major factor for enhanced performance of annual crops at the kiln sites. Over 80% of the farmers replied reduced weed establishment and practiced the removal or spread of some charcoal fragments from kiln sites. About 77% of the farmers reduced inorganic fertilizer application at kiln sites by half, and the rest applied equal amounts of inorganic fertilizer at kiln sites and reference sites. Furthermore, farmers observed that *teff* plants at kiln sites were subject to lodging and therefore all of them perceived a reduction in *teff* grain yield due to lodging effects.

Table 3.6 Farmers' perception, observation and management practices about the effects of in situ charcoal production at the kiln sites on soil properties and crop performance, compared to the reference sites, as stated by the informants in the study area (n = 30)

Characteristics	Respondents' responses	Respondents' proportion (%)
Soil fertility	Improved	100
Inorganic fertilizer application	Reduced by half	77
Germination and early growth of crops	Fast	100
Weed cover	Reduced	83
Crop growth and grain yield	Increased	100
Crop leaf	Broad and deep green	100
Lodging effect on *teff* production	Grain yield loss	100
Residue management (charcoal fragments)	Spread or some amount removed for offsite use	83

3.4 Discussion

3.4.1 Effects of *in situ* charcoal production on soil physical properties

The inclusion of charcoal production in *A. decurrens*-based Taungya system significantly affected the sand and clay fraction of acidic agricultural soil, whereas silt content was not affected. Heating effects during charcoal production (Emrich, 1985) may cause the fusion of silt and clay-sized particles into sand-sized particles leading to greater sand fraction at kiln sites (Abebe & Endalkachew, 2011; Oguntunde et al., 2008; Wahabu et al., 2015). Bulk density was slightly and insignificantly higher at the kiln sites than at the reference sites, despite the presence of charcoal at the kiln sites (Beshir et al., 2022; Mastrolonardo et al., 2019). Soil moisture content was insignificant but lower in the kiln sites than in the reference sites, which may be due to coarsening of heated soil (Abebe & Endalkachew, 2011). For both kiln sites and reference sites, soil bulk density values were at optimal levels for plants to grow (Hazelton & Murphy, 2016). Some studies have shown similar values of bulk density and moisture content between charcoal-amended soils and the reference soils (Glaser et al., 2002; Jeffery et al., 2011; Mastrolonardo et al., 2019).

3.4.2 Effects of *in situ* charcoal production on soil chemical properties

Charcoal production in the *A. decurrens-based* Taungya system significantly increased soil pH at kiln sites compared to the reference sites. Similar results were reported at kiln sites soon after charcoal production (Abebe & Endalkachew, 2011; Amare et al., 2022; Hardy et al., 2016; Ogundele et al., 2011) and in historical charcoal production sites that had been used multiple times and after long-time abandonment (Bonhage et al., 2020; Carrari et al., 2018; Faghih et al., 2018). Soil pH was raised by 0.83 unit at kiln sites. This is comparable to a 0.71 - 0.98 unit change in Coomes & Miltner (2017), a 0.9 unit change in Kim et al. (2022) and a 1.0 unit change in Amare et al. (2022). In contrast, charcoal-amended soils showed no change (Beshir et al., 2022; Mastrolonardo et al., 2019) or a significant decrease (Donovan et al., 2021; Kerré et al., 2017) in pH, compared to the adjacent reference sites. The increased pH at kiln sites could be attributed to the high pH of biochar used (Li et al., 2021; Mulualem et al., 2021; Zhu et al., 2014) and the addition of ashes formed from burnt materials during the carbonization process which release basic cations in oxide or carbonate forms (Domingues et al., 2017; Glaser et al., 2002; Goulding, 2016). *A. decurrens* wood biochar had a pH of 9.63 (Table S3.1) exhibiting its alkalinity nature which reflects the positive effect of its application to ameliorate soil acidity by raising the pH of acidic soils (Elias et al., 2020; Zhu et al., 2014). The accumulation of basic cations released from ashes at kiln sites (Gómez-Luna et al., 2009; Thomaz, 2017) will alter soil pH. The correlation analysis in this study showed that increased pH was strongly and positively correlated (data not shown) with the contents of exchangeable Mg^{2+} ($r = 0.702$, $p < 0.01$) and exchangeable K^{+} ($r = 0.946$, $p = 0.000$). Overall, *in situ* charcoal production improved soil pH to a level (pH = 5.6) that lies within the range of promoting plant performance and nutrient availability (Weil & Brady, 2017).

Kiln sites also had significantly lower amounts of exchangeable acidity and exchangeable Al^{3+} compared to the reference sites. The results showed that the decline in exchangeable acidity and exchangeable Al^{3+} followed the same order with the change in pH of the soil. There were significant negative correlations of pH (data not shown) with exchangeable acidity ($r = -0.924$, $p = 0.000$) and exchangeable Al^{3+} ($r = -0.906$, $p =$

0.000). Charcoal production could lower Al^{3+} contents in kiln site soils through complexation (Butnan et al., 2015; Haynes & Mokolobate, 2001; Nziguheba et al., 1998). In acid mineral soils, exchangeable Al^{3+} is the principal factor in the development of soil acidity. The pH at the reference sites is below 5.0, and aluminum toxicity is expected in the study area (Singh et al., 2017; van Zwieten et al., 2010); whereas at the kiln sites the pH value is above the threshold level below which Al^{3+} toxicity will occur. A higher soil pH at kiln sites with a subsequent decrease in exchangeable Al^{3+} would help improve nutrient availability, especially P, and reduce reducing the potential Al^{3+} toxicity to crops in acidic soils. This indicates of the advantages of *in situ* charcoal production in highly weathered, acidic tropical soils (Abate et al., 2017; Agegnehu et al., 2021; Thomaz, 2017; Zhu et al., 2014).

Our results showed that kiln sites stored more organic carbon in the soil than the reference sites. Charcoal production increased SOC by 40% at kiln sites compared to the reference sites (Table 3.3). The increased SOC at kiln sites can be related to the presence of charcoal which can influence soil properties. In the same study area, Kim et al. (2022) reported that around 8 kg of charcoal debris remained at the charcoal production spot which is equivalent to 11 t ha^{-1} charcoal incorporated into the soil. Coomes and Miltner (2017) found a substantial amount of biochar added into the soil, close to 37.5 t ha^{-1} each year, at kiln sites. Increased contents of SOC were found in many studies at kiln sites (Amare et al., 2022; Coomes & Miltner, 2017; Kerré et al., 2017; Kim et al., 2022). Improvement in the contents of SOC can be resulted from the high content and recalcitrant nature of carbon present in biochar (Goulding, 2016; Herath et al., 2015; Lorenz & Lal, 2014) and the retarded native soil organic matter decomposition (Jiang et al., 2016; Wang et al., 2016). Kim et al. (2022) found stable black carbon increased by 164% at kiln sites where *A. decurrens* wood was burnt. High SOC content at kiln sites can also be attributed to an increase in crop performance which might have raised organic matter accumulation in the soil (Cai et al., 2019; Jeffery et al., 2011). The increased carbon content at kiln sites demonstrates the role of the inclusion of charcoal production in the cropping system in achieving more stable SOC to enhance carbon sequestration.

Charcoal production increased the content of P_{av} by 92%. In contrast, the content of TN was not affected by charcoal production practice at kiln sites. This increase in P_{av}

could result from direct addition from the charcoal itself and the increase in soil pH (Hong & Lu, 2018; Xu et al., 2013; Zhou et al., 2020). Biochar contains nutrients that can be directly returned to the soil by biochar addition (Glaser et al., 2002; Xu et al., 2013; Zhou et al., 2020). *A. decurrens*-derived charcoal containing 38 g kg^{-1} total P (Kim et al., 2022) and 278 mg kg^{-1} P_{av} (Mulualem et al., 2021) suggests that the increased P_{av} at kiln sites could be attributed to the direct supply from the charcoal itself. Improved soil pH at kiln sites would cause an increase in P_{av} in the soil (Amare et al., 2022). In acidic soils, soil pH can alter P_{av} present in the soil through its influence on P fixation by Al and Fe. Whenever the pH of acid soils increases P_{av} content increases through the release of more phosphate in the soil as P becomes free from fixation by Al and other elements (Chintala et al., 2014; Hong & Lu, 2018; Xu et al., 2014). Change in P_{av} affected by soil pH was evident in the present study as higher contents of P_{av} followed the reduction in exchangeable acidity and exchangeable Al^{3+} resulting from increased pH. Results of correlation analysis indicate a strong relationship of P_{av} (data not shown) with pH ($r = 0.946$, $p = 0.000$), exchangeable acidity ($r = -0.865$, $p = 0.000$) and exchangeable Al^{3+} ($r = -0.850$, $p = 0.000$). Consistent with our study, earlier studies have shown increased concentration of P owing to charcoal production (Faghih et al., 2018; Glaser & Lehr, 2019). The lack of variation in TN between kiln sites and the reference sites is in line with the result reported by Beshir et al. (2022). Reduced TN at kiln sites could be due to increased plant uptake resulting from enhanced crop performance (Bista et al., 2019; Huang et al., 2014; Liu et al., 2018). Increased wheat growth and grain yield positively correlated with leaf chlorophyll content (Figure 3.5), high leaf chlorophyll content of wheat in charcoal-treated soils (Table 3.5) and farmers' observation of deep green leaves of crops at kiln sites (Table 3.6) highlight increased nitrogen uptake as a plausible factor that may lead to a reduction in soil nitrogen. Li et al. (2021) mentioned improved nitrogen utilization by plants as a possible factor for the decrease of soil total and available nitrogen in biochar-amended soils.

Charcoal production induced significant changes in the concentration of exchangeable Mg^{2+} and K^{+} while the concentrations of exchangeable Ca^{2+} and CEC remained unaffected by charcoal production practice. Charcoal production raised the concentration of exchangeable Mg^{2+} by 32%, whereas the concentration of exchangeable

K^+ was increased by more than threefold at the kiln sites. The burned materials during carbonization release these basic cations which are dominant components of the ash (Goulding, 2016; Thomaz, 2017). *Acacia decurrens*-derived charcoal with a total K content of 380 g kg^{-1} (Table S3.1) shows the contribution of direct supply from ash deposited for the increased contents of basic cations at the kiln sites (Table 3.3). Oguntunde et al. (2004) reported an increase in the concentration of exchangeable bases that ranged 14 – 329% at the charcoal production site compared to the adjacent control site. The study by Gómez-Luna et al. (2009) showed increased concentrations of exchangeable Ca^{2+}, $Mg^{2+,}$ and K^+ by more than 1.6 times at kiln sites. In many studies at historical charcoal kilns, concentrations of basic cations, mostly Ca^{2+} and Mg^{2+}, were significantly raised by the long-term presence of charcoal (Donovan et al., 2021; Faghih et al., 2018; Hardy et al., 2016). A slight decrease of CEC at the kiln site might relate to lower clay fraction (Table 3) and ageing effects. Kiln sites considered in this study were young, less than one year old, and thus enriched with fresh charcoal fragments (Table S3.1). Fresh charcoals have small negative charges that would be raised over time and eventually lead to an increase in CEC with ageing (Cheng et al., 2006; Lehmann, 2007). Compared to the reference sites, small and insignificant CEC values were reported at kiln sites (Abebe & Endalkachew, 2011; Ogundele et al., 2011).

3.4.3 Effects of *in situ* charcoal production on crop performance

Acid soils generally have low fertility and productivity, and amending these soils with charcoal can improve soil properties and crop performance (Jeffery et al., 2017; van Zwieten et al., 2010). Results from field plots under the existing farming system reveal enhanced performance of *teff*, barley and wheat in charcoal-amended soils. As shown in Figure 3.2, charcoal production increased the performance of the three crops at kiln sites ranging from 69 to 168% and 46 to 167% based on aboveground dry biomass and grain yield, respectively. The average grain yield of the three crops was 136% higher at kiln sites indicating that much less than half the farmland can be sufficient to meet the current crop production, which is a significant reduction. Interestingly, improved performance of wheat at kiln sites in the field study was comparable to that obtained through the addition

of soil with *A. decurrens* charcoal in the pot experiment (Table 3.5), in contrast to our expectation that the effects of charcoal production on crop performance would be greater for pot experiment than for field study due to dilution of charcoal by tillage in field condition (Schlatter et al., 2018). Consistent with the present study, improvements in crop performance in charcoal-amended soils were reported. Oguntunde et al. (2004) found that maize grain and biomass yield increased by 91 and 44%, respectively in charcoal sites compared to the reference adjacent farmland. Kerré et al. (2017) reported a 23% higher maize yield at historical charcoal kilns. A crop yield increment of 55% was obtained through the addition of charcoal to acidic soil in a pot experiment (Subedi et al., 2023). Our result of crop yield increment (136%) by charcoal production is greater compared to meta-analysis for biochar that can increase crop yield by 17% (Singh et al., 2022), 25% (Jeffery et al., 2017) and 17.1 % (Biederman & Harpole, 2013). The enhanced crop performance by charcoal production lies within the review for biochar that can stimulate crop performance in acid soils, ranging from 28 to 363% (Yu et al., 2019).

In Ethiopia, liming and chemical fertilizer application are commonly practiced to address soil acidity-related problems and low soil fertility. By applying lime in a range of sites, barley grain yield could increase in the range of 0.24–1.7 t ha^{-1} (Gurmessa, 2021), which is lower than the barley grain yield increase at kiln sites in the range of 3.43–4.6 t ha^{-1} observed in the present study. Grain yields of *teff*, barley and wheat at kiln sites as compared to their average national and regional yields are presented in Table 3.7. *Teff* grain yield produced at kiln sites in the present study is higher than the average national yield from 2001-2017 (Cochrane & Bekele, 2018) but close to that reported for 2020 (CSA, 2021). Similarly, the grain yield of barley and wheat at kiln sites is higher than the average national yield in 2018 and 2020 (CSA, 2019, 2021). Interestingly, charcoal production resulted in a 76 and 132% increase in grain yields of barley and wheat, respectively, as compared to their yields at the recommended inorganic fertilizer application rate in the highlands of central Ethiopia (Agegnehu et al., 2014, 2016).

Table 3.7 Comparison of *teff*, barley and wheat grain yields at kiln sites in the highlands of Northwestern Ethiopia with the average national and regional yields

Crops	Grain yield (t ha^{-1})			References
	Kiln sites	National	Central Ethiopian highlands	
Teff	1.61	1.20	2.06	Agegnehu et al. (2014); Cochrane & Bekele (2018)
Barley	6.55	2.18	3.72	Agegnehu et al. (2016); CSA (2019)
Wheat	7.33	2.77	3.16	Agegnehu et al. (2014); CSA (2019)

Inorganic fertilizer application rates: Kiln sites (DAP and Urea, 60 kg ha^{-1} each, for wheat and barley, only DAP applied for tef), central Ethiopian highlands (recommended NP rates: 46/20 kg ha^{-1} for barley; 60/20 kg ha^{-1} for tef and wheat).

Charcoal production resulted in a decrease in the harvest index of *teff* at kiln sites (Table 3.4) which implies that the crop remained more vegetative and seed setting is affected by lodging. Accordingly, a relatively higher grain yield of barley (167% increase) and wheat (142% increase) compared to *teff* (46% increase) was obtained at kiln sites. Farmers' observation also revealed that *teff* plants at kiln sites were subject to lodging which thereby caused a reduction in grain yield (Assefa et al., 2011). All farmers felt that a relatively higher grain yield of barley and wheat can be obtained at kiln sites than *teff* as these crops are more resistant to lodging. Compared to *teff*, Nigussie et al. (2021) reported improved grain yields of barley and wheat at kiln sites. Farmers tried to manage *teff* yield loss at kiln sites due to lodging by reducing inorganic fertilizer application and spreading charcoal fragments to adjacent non-kiln sites during tillage (Table 3.6).

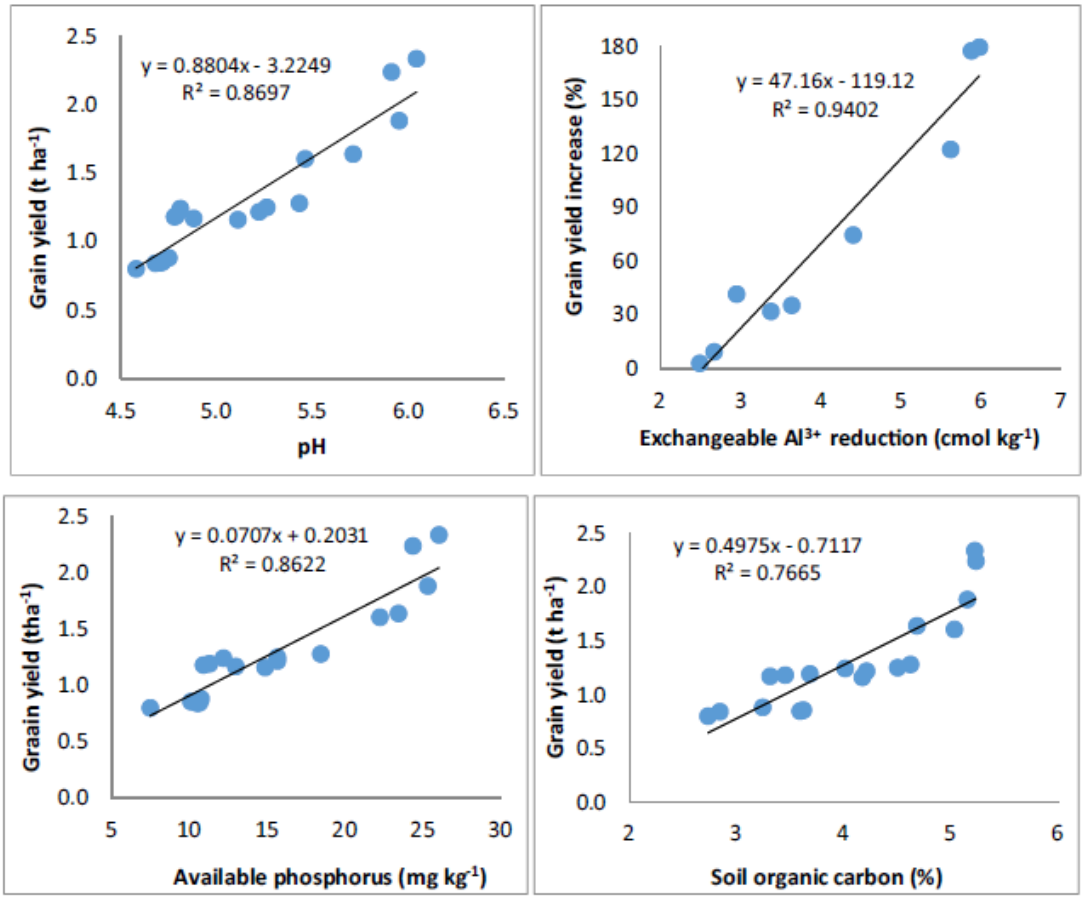

Figure 3.4 Relationship between grain yield and soil properties at kiln sites and adjacent reference sites

Biomass and grain yields of wheat in CSH under the pot experiment were increased by over 170% compared to RSF. The yield increase in CSH is greater compared to the yield increase by 17-54% following biochar addition at 15 and 30 t ha^{-1} with fertilizer (Elias et al., 2020), or meta-analysis for biochar combined with inorganic fertilizer that can increase crop yield by 15% (Ye et al., 2020). Maintaining higher wheat performance in charcoal-amended soil, even with a reduction in inorganic fertilizer application suggests that inclusion of charcoal production in the cropping system may reduce the need for inorganic fertilizer. Previous studies indicated that amending agricultural soils with charcoal can improve soil fertility and crop performance (Glaser et al., 2002; Ye et al., 2020) and reduce the amount of inorganic fertilizer needed for sustainable crop production (Agegnehu et al., 2016; Al-Wabel et al., 2018; Domingues et

al., 2017; Rafael et al., 2019). Regarding the local farmers' farming practices, the results of the pot experiment demonstrate that the amount of inorganic fertilizer needed could be reduced by half with the integration of charcoal production in a tree-based Taungya system, in agreement with farmers' practice of reduced inorganic fertilizer application at kiln sites (Table 3.6) that can be related to improved soil fertility by charcoal production practice (Table 3.3). The low rate of inorganic fertilizer required in this innovative farming practice has economic and environmental benefits through low cost of food production (Nigussie et al., 2021; Rafael et al., 2019), reduced acidification and climate change mitigation (Cai et al., 2019; Goulding, 2016; van Zwieten et al., 2010).

Improved crop performance could also be linked to an improvement in plant metabolic responses. In this study, increased leaf chlorophyll content was observed for wheat plants grown in charcoal-amended soils (Table 3.5), as reported by earlier studies (Agegnehu et al., 2015; Ali et al., 2021; Sun et al., 2017). And the increase in biomass and grain yield of wheat plants was positively correlated to leaf chlorophyll content (Figure 3.5). Supporting the results from the pot experiment, interviewed farmers reported enhanced performance and deep green leaves of annual crops grown at kiln sites (Table 3.6). Consistent with our results, Sun et al. (2017) found increased leaf chlorophyll contents following biochar application, which partly contributed to improved performance of maize plants. Agegnehu et al. (2015) also mentioned increased leaf chlorophyll content under biochar application which was significantly correlated with maize shoot growth and soil and plant contents of nitrogen. High leaf chlorophyll content of wheat in charcoal-amended soils reflects increased uptake of nitrogen and subsequently high leaf nitrogen (Agegnehu et al., 2015; Bista et al., 2019; Huang et al., 2014; Liu et al., 2018).

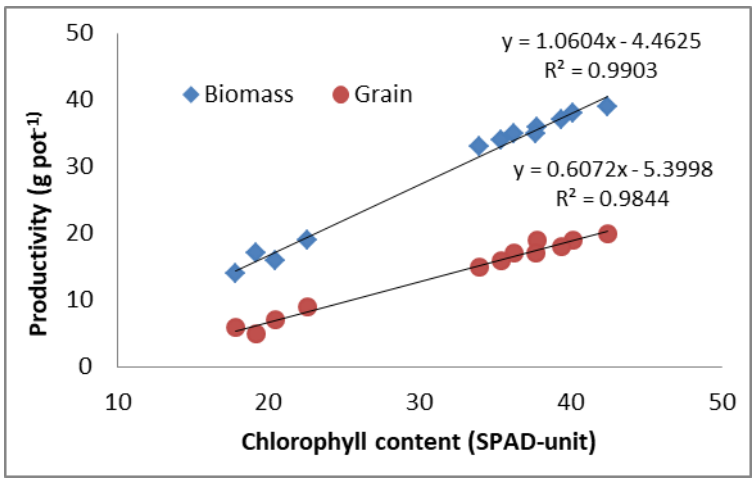

Figure 3.5 Effect of charcoal production on the relationship between wheat performance (aboveground biomass and grain yield) and leaf chlorophyll content

Overall, the benefits of *in situ* charcoal production on crop performance are mainly related to nutritional effects. Direct nutrient supply by the biochar itself and amelioration of soil acidity can be factors for improvements in soil nutrient availability. Charcoal-induced increase in pH and the reduction in exchangeable Al^{3+} will increase nutrient availability resulting in enhanced crop performance (Chan et al., 2007; Nziguheba et al., 1998). The reduction in exchangeable Al^{3+} concentration may provide a better condition for root growth which increases nutrient uptake and crop performance (Chan et al., 2007). The increase in aboveground biomass yield, grain yield, leaf area and height of annual crops was strongly related to soil pH, SOC, Pav, exchangeable Mg^{2+}, exchangeable K^{+}, exchangeable acidity and exchangeable Al^{3+} (Table S3.2 and Figure 3.4). These results are in agreement with the farmers' observation and recognition of increased soil fertility and crop production at kiln sites (Table 3.6). Considering soil fertility improvements, farmers even practiced spreading charcoal fragments from kiln sites leading to increased area coverage for off-site use and, thereby, positive effects for the economic return of smallholder farmers (Coomes & Miltner, 2017; Dubiez et al., 2019; Nigussie et al., 2021). These farmers further mentioned reduced weed cover at kiln sites as a factor for the increase in crop performance. Farmers' report of reduced weed cover at kiln sites when first sown with annual crops agrees with previous reports of remarkably weed-free kiln sites (Miltner & Coomes, 2015) and weed biomass reduction in biochar-treated soils (Agegnehu et al., 2016; Vaccari et al., 2011). The reduction of

weed cover could be attributed to the heating effects of high temperatures during the carbonization process (Miltner & Coomes, 2015).

3.4.4 Effect of charcoal production on seed germination and early growth of annual crops

Soon after the clear-felling of *A. decurrens* stands and charcoal production, farmers cultivate the fallowed land and the abandoned several kiln sites formed *in situ* with annual crops during the rainy season. Kiln sites covered a total area of 1270 m^2 (13% of a hectare of fallowed land); and during the field survey, we observed faster germination and enhanced early growth of annual crops in these kiln sites. Pot experiment with wheat (Figure 3.3) showed faster germination in charcoal production sites. Under field conditions in farmers' croplands, there was a clear differentiation of *teff* and barley early growth (at 17 and 45 days after sowing) between kiln sites and reference sites (Figure 3.6). In line with our field observation on farmlands and pot experiment, all interviewed farmers reported faster seed germination and seedling growth of annual crops in kiln sites than in reference sites. Biochar application to agricultural soils may cause faster seed germination and seedling emergence (Ali et al., 2021; Baronti et al., 2010). Boyd et al. (2017) demonstrated greater seedling establishment in darker soils. Through its dark color, soil temperature will increase in charcoal-amended soil (Baronti et al., 2010; Feng et al., 2021), which facilitates rapid germination and growth of crops. Enhanced early growth could also be due to improved soil fertility (Ali et al., 2021; Solaiman et al., 2012).

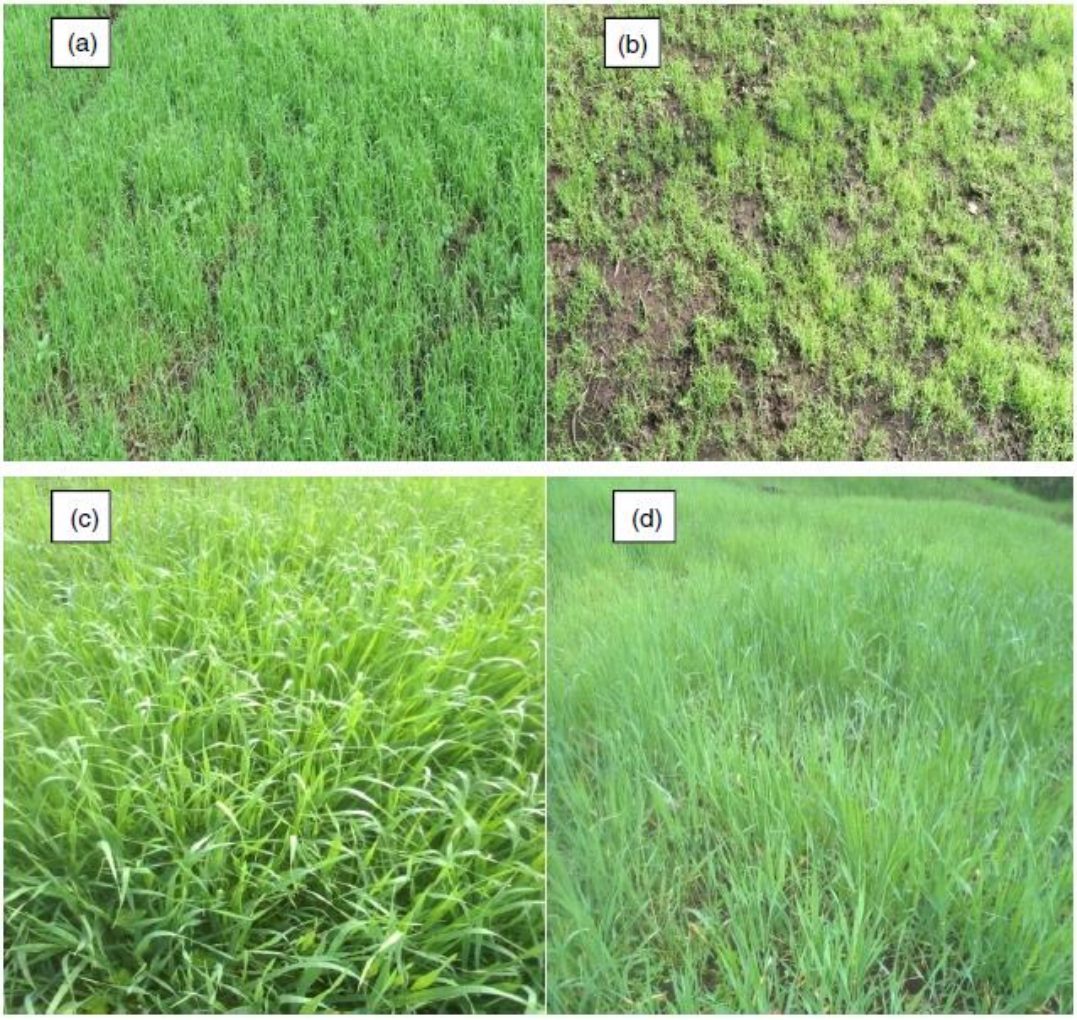

Figure 3.6 Growth of *teff* and barley at kiln sites and reference sites under the existing farming system in *A. decurrens*-based fallow system. Early growth of *teff* at the kiln site (a) and the reference site (b) at day 17 after planting; growth of barley at the kiln site (c) and the reference site (d) at day 45 after planting

3.5 Conclusion

In response to soil degradation, farmers in the study area have practiced *A. decurrens*-based Taungya system in which charcoal production is an integral part of the system. This study reports the effects of *in situ* charcoal production in the first rotation of *A. decurrens*-based Taungya system on soil properties and crop performance of acidic agricultural soil. At kiln sites, charcoal production resulted in an increase in SOC, exchangeable K^+, exchangeable Mg^{2+}, P_{av} and pH and a reduction in exchangeable acidity and exchangeable Al^{3+}. Charcoal production positively influenced the

performance of *teff*, barley and wheat at kiln sites resulting from improvements in soil nutrient contents and remediation of soil acidity. The crops had faster seed germination and better establishment in charcoal-amended soils. The results of the pot experiment and farmers' responses revealed that amending the soils with *A. decurrens*-derived charcoal can improve crop performance and reduce the need for inorganic fertilizer. Farmers practiced the removal of some amount of charcoal fragments from kiln sites to reduce *teff* yield loss due to lodging and for off-site use to enhance crop yields beyond the charcoal production spots.

Overall, the results provide new insights into the benefits of a tree-based agroforestry system that integrates charcoal production as a management strategy for maintaining agricultural use of degraded acidic agricultural soils. Future studies on a long-term basis, for example, after the second and third rotation cycles of the *A. decurrens*-based Taungya system, are required to further understand the sustainability of this practice innovated by the local farmers. The extent to which charcoal production can reduce inorganic fertilizer application rate also needs to be evaluated, as the reduction in fertilizer requirements has both economic and environmental benefits. Moreover, characterizing *A. decurrens*-derived wood biochar, introducing efficient methods of biomass carbonization for efficient charcoal production process and for reducing health and environmental hazards and evaluating the economics of biochar application are required.

CHAPTER 4: IMPROVING SOIL CHEMICAL PROPERTIES AND *TEFF* (*ERAGROSTIS TEF*) PERFORMANCE WITH *ACACIA DECURRENS*-BASED FALLOW IN THE HIGHLANDS OF NORTHWESTERN ETHIOPIA[2]

Abstract

Following land degradation and the associated reduction in crop production, smallholder farmers in the highlands of Northwestern Ethiopia have recently practiced the *A. decurrens*-based fallow system. Despite the rapid expansion of this new cropping system, its impact on soil properties and crop performance has never been exhaustively studied. We assessed the effect of *A. decurrens*-based fallow system on soil properties and *teff* performance under the existing production environment on farmers' fields using: (i) *teff* cultivation under the fallow system in two rotations which represent 5 and 10 years of continuous fallow period (fallowed lands); (ii) sole *teff* cultivation system (ST system); (iii) *teff* cultivation on fallowed lands in the first rotation for two consecutive years; (iv) ST system adjoining a-4-year-old acacia woodlot; and (v) interview with local farmers. The results showed that fallowed lands in the first and second rotations improved soil properties and *teff* performance with greater effects in the second rotation. Compared to the ST system, fallowed lands in both rotations significantly increased soil pH, SOC, P_{av}, TN and CEC, but decreased exchangeable Al^{3+}. *Teff* aboveground biomass and grain yields were increased by 41–64% in two rotations. Fallowed lands sustained positive effects on soil fertility and *teff* performance over two successive production years highlighting that the fallow system can benefit farmers through the cultivation of two annual crops in two years. Significant *teff* yield reductions occurred over the first 10 m distance from the acacia woodlot. Soil moisture, pH, SOC, P_{av}, TN and CEC were higher at croplands close to the acacia woodlot. According to the farmers, the fallow system can

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improve *teff* performance and reduce the need for inorganic fertilizer by 50%. Overall, the results demonstrated that fallowing with *A. decurrens* can reduce soil acidity and restore nutrients for sustainable crop production; and the shading effect could be the limiting factor for *teff* production on croplands adjacent to the acacia woodlots.

***Keywords*:** Acacia woodlot, crop performance, fallowing, shading effects, soil fertility

4.1 Introduction

Globally, land degradation affects about 30% of the total land area, with 2.2 billion ha of degraded land being considered potentially to be restored using systems and practices like forest plantations (Sileshi et al., 2020). According to FAO (2020), the area under forest plantations, which were produced at large and small scales, was about 131 million ha, and has increased at a rate of 3% annually during the last decade. Nowadays, small-scale plantations in particular agroforestry systems have been receiving positive attention following their social, economic and environmental benefits such as increases in crop yields, wood extraction, enhanced soil fertility, nutrient cycling, reduced soil erosion and climate change adaptation (Kuyah et al., 2019; Ngaba et al., 2024) In Sub-Saharan Africa, agroforestry is a major land use with 30% of the agricultural land having at least 10% tree cover and nearly 40% of the population residing in such areas (Zomer et al., 2014).

In the highlands of Ethiopia, land degradation coupled with the rapidly growing population resulted in low agricultural productivity and food insecurity (Agegnehu & Amede, 2017; Ebabu et al., 2019; Schmidt & Tadesse, 2019). Previously, when population density was low, the land was left fallow for years as a management option to low productivity. Rapid population growth in the country has pressured farmers to reduce or abandon fallowing practices, which has lowered agricultural productivity (Tesfahunegn, 2013). Consequently, many highland farmers have shifted from growing cereal crops to planting tree species such as acacia and eucalypts (Abiyu et al., 2016; Dessie et al., 2022; Lemenih & Kassa, 2014; Wondie & Mekuria, 2018). In developing countries such as Ethiopia, agroforestry systems are crucial for mitigating land degradation and meeting food and wood demands, particularly within smallholder

farming systems that dominate agricultural production (Afework et al., 2023; Alemayehu & Melka, 2022; Kuyah et al., 2019). Trees in agroforestry systems are widely acknowledged to increase agricultural productivity (Kuyah et al., 2019) owing to their positive effects on soil properties (Fahad et al., 2022; Ngaba et al., 2024). However, the effects of agroforestry systems on soil properties can vary depending on multiple factors, including climatic conditions (Ngaba et al., 2024), species selection (Gota et al., 2024; Vyamana et al., 2021), stand age (Kinyili et al., 2024; Yimam et al., 2024) and planting density (Syano et al., 2023).

Agroforestry has a long history in Ethiopia, and numerous studies have demonstrated its positive impacts on soil properties and crop yields across various contexts, utilizing both exotic and native species (Abiyu et al., 2016; Dessie et al., 2022; Desta et al., 2021). In recent decades, owing to land degradation and the associated reduction in crop production, smallholder farmers in the Guder watershed have been adapting their cropping system dominated by cereals to a tree-based fallow system in which *A. decurrens*, a nitrogen-fixing leguminous tree species, is integrated. The incorporation of *A. decurrens* into cropping systems is a relatively recent advancement that has been implemented over the past three decades (Nigussie et al., 2017). This system operates on a five-year rotation scheme, with annual crops—primarily *teff*—cultivated between rotations. While annual crop production under the sole cropping system is constrained by severe land degradation (Schmidt & Tadesse, 2019; Tamirat & Wondimu, 2019), the fallow system, however, contributes to the restoration of degraded agricultural land and hence has been widely used by smallholder farmers for improving soil fertility and economic gains (Amare et al., 2022; Nigussie et al., 2017, 2020; Worku et al., 2021).

The practice of *A. decurrens*-based fallow (referred to as acacia fallow) influences soil quality and is expected to impact crop yields due to the cultivation of annual crops between rotations and their proximity to acacia woodlots. In this system, annual crops can be grown on fallowed land for two consecutive years: as a sole crop in the first year and intercropped with *A. decurrens* seedlings in the second year. Additionally, crop production is affected by the distance from acacia woodlots, as small fields and woodlots are interspersed in a mosaic pattern. This arrangement can lead to tree-crop interactions,

where trees may benefit crops (Hadgu et al., 2009; Hailu et al., 2000) or compete with them, potentially reducing productivity (Desta et al., 2023; Kidanu et al., 2004; Mugunga et al., 2017). Although the acacia fallow system has shown profitability and rapid expansion in agricultural lands (Alemayehu et al., 2024; Nigussie et al., 2020; Worku et al., 2021), information regarding its sustainability is scarce (Beshir et al., 2022; Kim et al., 2022). Moreover, there are no existing studies on the effects of this system on crop performance or the dynamics of tree-crop interactions. The objectives of this study were therefore to: (i) evaluate soil properties and *teff* performance on croplands under the acacia fallow system in two successive rotations which represent 5 and 10 years of continuous fallow period (fallowed lands); (ii) examine whether fallowed lands can sustain harvesting of two annual crops in two successive crop production years; (iii) assess soil properties and *teff* performance on adjacent croplands along distance from a 4-year-old acacia woodlot; and (iv) explore farmers' observations and management practices on the effects of acacia fallows on soil properties and *teff* performance. This study provides preliminary data on the interactions between trees and crops within this agroforestry system in acidic and degraded soil.

4.2 Materials and Methods

4.2.1 Study area description

The study was conducted in the Guder watershed, a highland area located in the Fagita Lekoma district of Amhara Region, Northwestern Ethiopia (the description of the study area is presented in section 2.1 of Chapter 2). In the Guder watershed, *A. decurrens* is commonly grown in agricultural fields along with crops like *teff*, wheat and barley during the first year of its establishment and harvested at a short rotation age of five years. After harvesting acacia woodlots and on-site charcoal production, farmers cultivate annual crops between rotations for one or two consecutive years (Figures 4.1 and S4.1). Farmers also grow crops on farmlands adjacent to acacia woodlots.

4.2.2 Measurement design and chronosequence

Twelve farmlands planted with *A. decurrens* trees were selected. The farmlands had sizes ranging from 0.18 to 0.45 ha (Table 4.1). Nine of the farmlands were under acacia fallows in the first rotation and managed for 5 years and the remaining three farmlands were in the second rotation and managed for 10 years (hereafter referred to as fallowed lands). Six fallowed lands, three in the first rotation and another three in the second rotation which represent a fallow period of 5 and 10 years, respectively, were identified to analyze agricultural sustainability under the acacia fallows by assessing soil properties and crop performance in two rotations. After harvesting five-year-old acacia woodlots, the fallowed lands were cultivated during the rainy season for two consecutive years with *teff* monocropping in the first year and intercropped with acacia seedlings and *teff* plants in the second year (Figure 4.1). For comparison purposes, three farmlands that were not planted with acacia trees, laid adjacent to fallowed lands and sole cropped with *teff* crop (ST system) were included. The rest six fallowed lands in the first rotation were used to evaluate the persistence of soil properties and *teff* performance over two consecutive crop production years. The comparison was made between the fallowed lands in the first and second crop production years in reference to the ST system. Three of the fallowed lands were in the first crop production year and the remaining three were in the second production year. Except for the rotation cycles, the fallowed lands were under uniform management interventions and laid close to each other and in similar topographic features. We assumed that the rotation cycle (fallow duration) and conversion into the acacia fallow (land use change) are the main differentiating factors inducing changes in soil properties and crop performance amongst the fallowed lands and the ST system.

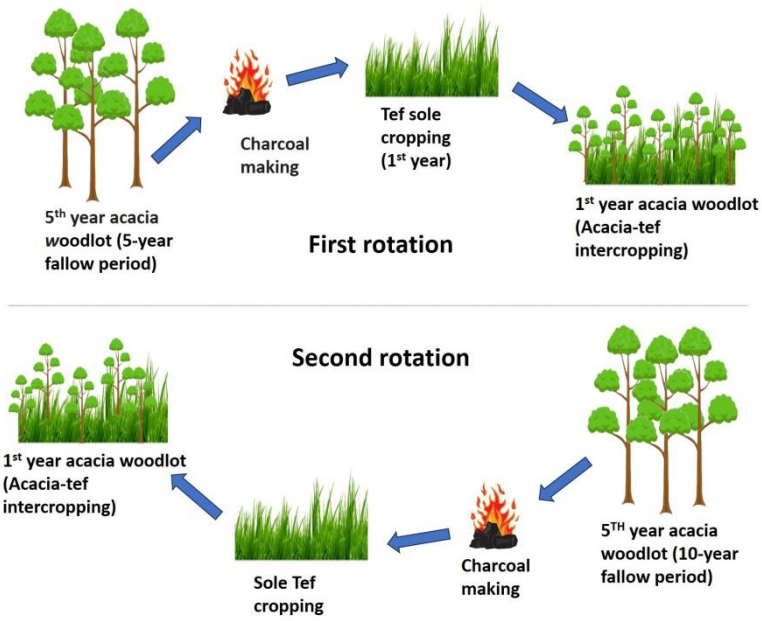

Figure 4.1 Pictorial representation of acacia fallows in the first and second rotation. The sequence in the first rotation represents land management under acacia fallow for 5 years in the first rotation (a total of 5-year fallow period). After harvesting of five-year old acacia woodlots, on-site charcoal production took place. Then, fallowed lands were cultivated with sole *teff* crop in the first year and intercropped with *teff* and acacia seedlings in the second year. The sequence in the second rotation represents land management under acacia fallow for two successive rotations, each 5-year (a total of 10-year fallow period). Similar to the first rotation, after harvesting of 5-year old acacia woodlots in the second rotation and on-site charcoal production, fallowed lands were cultivated with sole *teff* crop in the first year and intercropped with *teff* and acacia seedlings in the second year.

Table 4.1 Characteristics of farmlands (under acacia fallow and ST system) sampled for this study

Rotation	Stand age (year)	Fallow duration (year)	Total number of farmlands	Purpose
First	5*	5	9	Fallowed lands to analyze soil properties and *teff* performance under acacia fallow for 5 years in the first rotation
Second	5*	10	3	Fallowed lands to analyze soil properties and *teff* performance under acacia fallow for 10 years in two rotations
First	4**	-	2	Croplands to evaluate the effect of acacia woodlot on *teff* performance at the adjacent ST system

*age when acacia woodlots were harvested; **age of acacia woodlots at the time of soil and crop data sampling for the effects on adjacent croplands

To quantify the bordering effects of acacia woodlots on soil properties and crop performance at the adjacent crop fields, acacia woodlots of 4-year-old casting shade on the east and west sides at adjacent ST systems were considered. Only woodlots that divide ST systems into east-west aspects were selected assuming higher intensity and duration of shading on east-west facing plots than on north-south facing plots (Kidanu et al., 2005). The woodlot consisted of *A. decurrens* trees planted at a spacing of 50 cm x 75 cm and attaining an average height of 9.8 m and DBH of 7.5 cm. Samples for soil chemical properties and *teff* performance analysis were taken on plots located at seven distances of 1, 3, 6, 10, 14, 18 and 25 m from the acacia woodlot in both aspects (Mugunga et al., 2017). It is assumed that the effect of woodlots will not extend beyond 25 m from the woodlot-crop interface; thus, the plot located at 25 m from the acacia woodlot was taken as a control.

The effect of acacia fallow on crop performance was evaluated using *teff* as a test crop under the actual production environment during the rainy season. *Teff* was sown in broadcasting on farmlands under the acacia fallow system and ST system and managed, including chemical fertilizer application, based on local farmers' experience. *Teff* was sown in the second week of August and harvested in the third week of December. Plant parameters were assessed at physiological maturity. Plant height was measured using five randomly selected *teff* plants from a 1 x 1 m subplot in each plot. Aboveground biomass and grain yields were estimated by harvesting a 1 m^2 area close to the soil surface at the center of each plot. The details for measuring plant parameters can be found in section 2.2 of Chapter 2.

4.2.3 Soil sampling and analysis

Soil samples from three random plots per farmland were taken for soil analysis (n = 9). From the top (0 – 15 cm) soil depth, samples were taken at the center of the plots using a soil auger after crop harvest. For the bordering effects of the acacia woodlot, soil samples were taken from 8 m^2 observation plots in triplicate at each distance considered. Soil samples were analyzed for soil moisture, pH, SOC, TN, P_{av}, exchangeable Al^{3+} and CEC following the methods described in section 2.2 of Chapter 2.

4.2.4 Farmers' perceptions and management practices

A total of thirty farmers were chosen for interview through purposive sampling. Farmers were sampled based on their involvement in establishing acacia woodlots on croplands, harvesting the acacia woodlots and cultivating acacia fallows with annual crops within two years before data collection. A semi-structured interview was used to gather information regarding farmers' perceptions and management practices on the effects of acacia fallow on soil properties and *teff* performance. Specifically, issues related to changes in soil properties and *teff* performance between repeated rotations and over two successive production years under the fallow system, inorganic fertilizer use on fallowed lands and tree-crop interaction in *teff*-acacia woodlot system were considered for a socio-economic survey.

4.2.5 Statistical analysis

One-way ANOVA was used to test the differences in soil properties and *teff* performance among the treatment groups with respect to fallow duration, production year and distance from acacia woodlots. Correlation between selected soil properties and *teff* growth and grain yield was done using Pearson correlation. Descriptive statistics were employed to analyze the socioeconomic data. The significant differences between treatment means were separated using Tukey's HSD test at 1% and 5 % levels of significance.

4.3 Results

4.3.1 Effects of acacia fallows on soil chemical properties and *teff* performance

Soil pH, SOC, TN, P_{av}, CEC and exchangeable Al^{3+} exhibited significant differences between acacia fallows and the ST system (Table 4.2). Compared to the ST system, all the soil chemical properties were considerably improved by the acacia fallows. The values of pH, TN, Pav and CEC were higher in the second rotation than in the first rotation. However, there were no significant differences ($p > 0.05$) in the values of SOC and exchangeable Al^{3+} between rotations. The results for soil chemical properties showed

an increase of pH by 14 and 22%, Pav by 93 and 200%, and a decrease of exchangeable Al^{3+} by 77 and 81% on fallowed lands in the first and second rotations compared to the ST system, respectively. Mean values of SOC and TN on fallowed lands ranged between 3.90 and 4.48% and 0.35 and 0.44%, respectively. The values of SOC and TN were enhanced by 70 and 95% and 21 and 52% over the ST system in the first and second rotations, respectively. Compared to the ST system, the values of CEC were increased by 41% in the first rotation and 78% in the second rotation.

Table 4.2 Effect of acacia fallow on soil chemical properties (mean + SE) in two rotations (first and second rotations) (n = 9)

Soil parameters	Land use					
	ST system	FR1	FR2	$LSD_{0.05}$	*P*-value	CV (%)
pH (H_2O)	4.56 ± 0.02c	5.2 ± 0.04b	5.56 ± 0.04a*	0.1277	< 0.0001	1.67
SOC (%)	2.30 ± 0.08b	3.90 ± 0.14a	4.48 ± 0.1a*	0.401	< 0.0001	7.17
TN (%)	0.29 ± 0.01c	0.35 ± 0.03b	0.44 ± 0.02a	0.0692	0.0003	12.7
Pav (mg kg^{-1})	8.67 ± 0.4c	16.74 ± 0.38b*	25.95 ± 0.74a*	1.9597	< 0.0001	7.63
CEC ($cmol_+ kg^{-1}$)	24.9 ± 1.21c	35.03 ± 1.21b*	44.25 ± 0.92a*	4.1173	< 0.0001	7.91
Ex. Al^{3+} ($cmol_+ kg^{-1}$)	3.77 ± 0.4a	0.87 ± 0.02b*	0.72 ± 0.01b*	0.3166	< 0.0001	11.7

Values followed by different letters in a row are significantly different at $p < 0.05$; * significant at $p < 0.01$. SOC, soil organic carbon; TN, total nitrogen; P_{av}, available phosphorus; CEC, cation exchange capacity; Ex. Al^{3+}, exchangeable Al^{3+}; FR1, acacia fallow in the first rotation; FR2, acacia fallow in the second rotation; ST system, sole *teff* cropping system

Plant height, total aboveground biomass yield, grain yield and harvest index of *teff* averaged over three farms in the ST system and fallow system in two rotations are presented in Figure 4.2. Aboveground biomass and grain yield of *teff* varied between fallowed lands and the ST system ($p < 0.01$). Biomass and grain yield of *teff* grown on fallowed lands in the first rotation were 93 and 74% higher than those obtained from the ST system, respectively. Similarly, 167 and 103% higher biomass and grain yield of *teff* were recorded on fallowed lands in the second rotation, respectively, compared to the ST system. Tef plants growing at the ST system had a significantly higher harvest index than those on fallowed lands. *Teff* plants were significantly ($p < 0.05$) taller and increased by 9 and 17% on fallowed lands in the first and second rotations, respectively, compared to the ST system. The results showed that the *teff* performance was greater in the second

rotation than in the first rotation. There were significantly strong correlations between the growth and yield of *teff* with soil pH, OC, TN, Pav, CEC and exchangeable Al^{3+} (Figure 4.4).

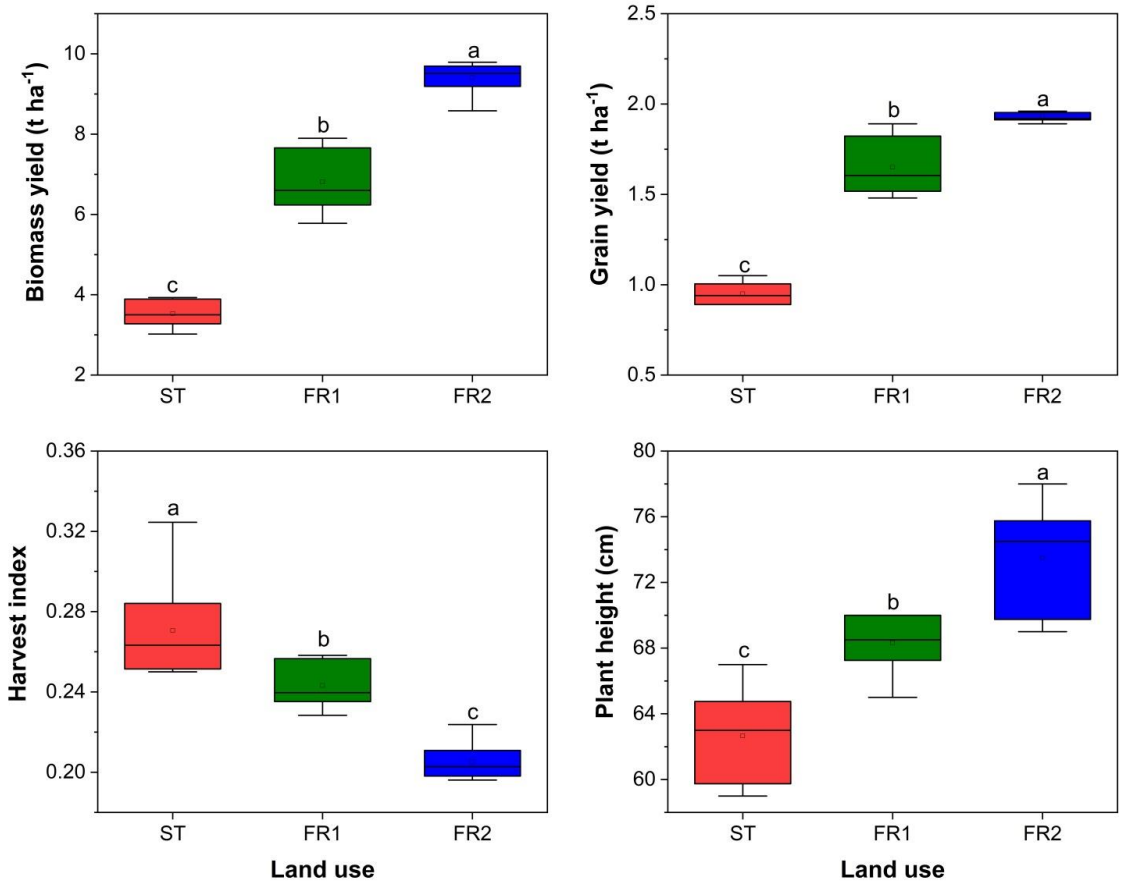

Figure 4.2 Effect of acacia fallow on *teff* performance in two rotations at the Guder watershed in Northwestern Ethiopia. Different letters indicate significant differences at $p < 0.01$; FR1, fallowed land in the first rotation; FR2, fallowed land in the second rotation; ST, sole *teff* cropping system

For the effects of the acacia fallow system during two successive crop production years on soil chemical properties, statistical analysis showed that there were significant effects of the fallow system on the assessed soil chemical properties (Table 4.3). The fallow system during both production years maintained higher values of pH, SOC, Pav, TN and CEC, but lower values of exchangeable Al^{3+} than the ST system. The fallow system significantly increased ($p < 0.05$) soil pH by 12 and 11%, SOC by 69 and 61%, TN by 58 and 54%, Pav by 83 and 77% and CEC by 52 and 43%, but decreased

exchangeable Al^{3+} by 78 and 77% over the ST system in year 1 and year 2 of *teff* production, respectively. Soil chemical properties exhibited a small but insignificant increase in the first year of *teff* production compared to the second production year.

Table 4.3 Soil chemical properties (mean + SE) under the acacia fallow over two consecutive *teff* production years (n = 9)

Soil parameters	**Land use**					
	ST system	**FY1**	**FY2**	**$LSD_{0.05}$**	***P*-value**	**CV (%)**
pH (H_2O)	4.56 ± 0.02b	5.11 ± 0.04a	5.06 ± 0.04a	0.1389	< 0.0001	1.89
SOC (%)	2.31 ± 0.18b	3.9 ± 0.09a	3.72 ± 0.29ab	0.7474	0.0165	14.1
TN (%)	0.26 ± 0.01b	0.41 ± 0.01a	0.40 ± 0.02a	0.0432	< 0.0001	8.1
Pav (mg kg^{-1})	9.61 ± 0.63b	17.56 ± 0.6a*	16.99 ± 0.39a	2.0183	< 0.0001	9.14
CEC ($cmol_+ kg^{-1}$)	27.0 ± 1.02b	41.1 ± 1.24a	38.5 ± 1.09a	4.1138	< 0.0001	7.72

Values followed by different letters in a row are significantly different at $p < 0.05$; *significant at $p < 0.01$. SOC, soil organic carbon; TN, total nitrogen; P_{av}, available phosphorus; CEC, cation exchange capacity; Ex. Al^{3+}, exchangeable Al^{3+}; ST, sole *teff* cropping system; FY1, fallowed lands in the first rotation during the first *teff* production year; FY2, fallowed lands in the first rotation during the second *teff* production year

The fallow system was found to increase ($p < 0.05$) biomass yield, grain yield and plant height of *teff* crop in both production years compared to the ST system (Figure 4.3). The increase was by 118 and 76% for biomass yield, 82 and 63 % for grain yield and 19 and 10% for plant height over the ST system in the first and second years of *teff* production, respectively. The harvest index of *teff* was found significantly higher in the ST system than in the fallow system. *Teff* plants grown on acacia fallows in the first production year were taller and had higher biomass and grain yields than in the second production year.

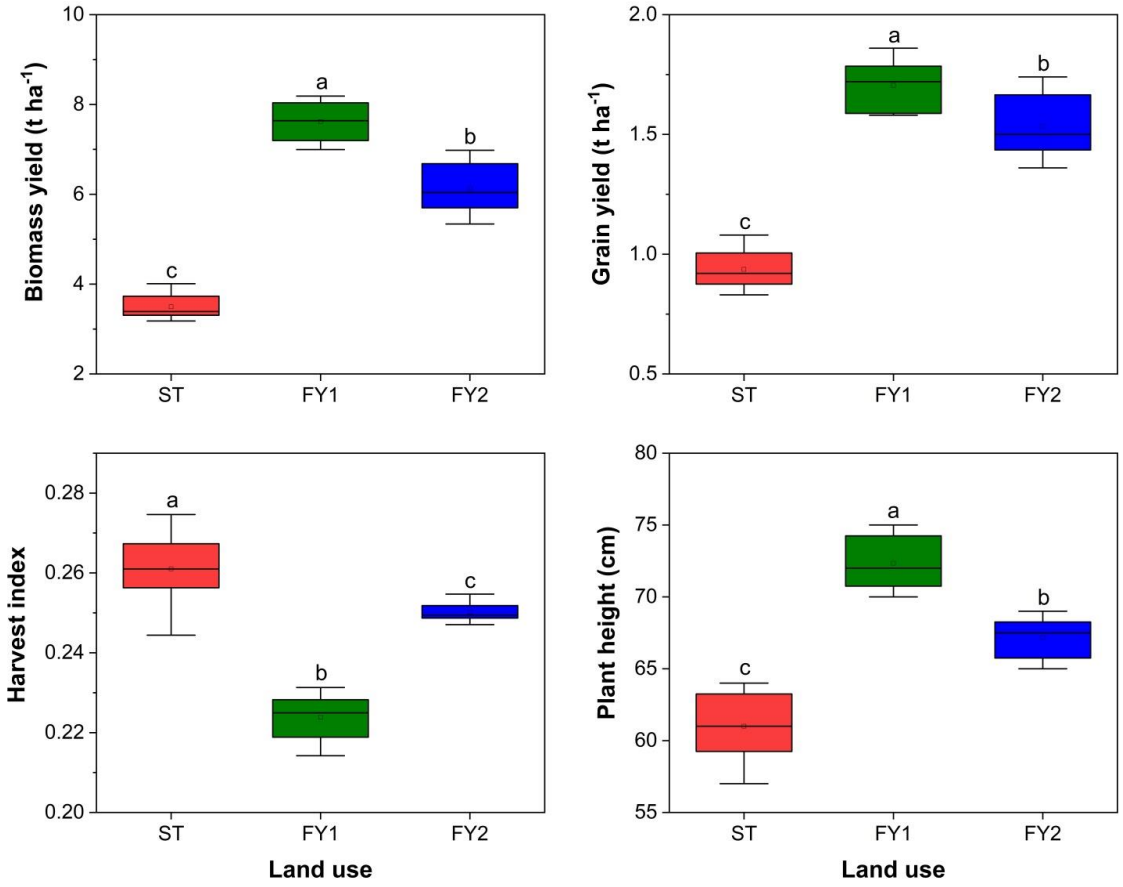

Figure 4.3 Effect of acacia fallow on *teff* performance during two successive production years. Different letters indicate significant differences at $p < 0.05$; ST, sole *teff* cropping system; FY1, fallowed lands in the first rotation during the first *teff* production year; FY2, fallowed lands in the first rotation during the second *teff* production year

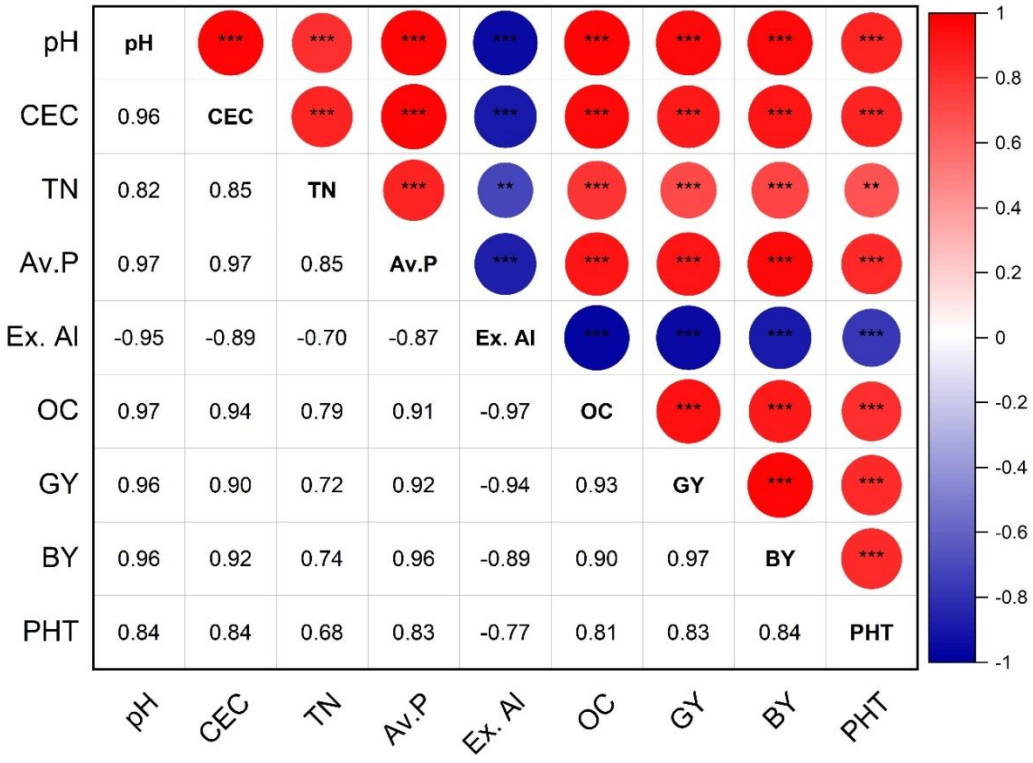

Figure 4.4 Pearson correlation heatmap of *teff* performance with soil properties and among soil properties. Correlation is significant at *$p < 0.05$ and **$p < 0.01$; GY, grain yield; BY, total aboveground biomass yield; PHT, plant height; OC, organic carbon; Av.P, available phosphorus; TN, total nitrogen; Ex. Al, exchangeable Al^{3+}; CEC, cation exchange capacity

4.3.2 Soil properties and *teff* performance as a function of distance from the acacia woodlot

Soil moisture content was higher at plots closer to acacia woodlots and continued to decline with increasing distance (Table 4.4). Significantly higher values were found at plots located within the first 3 m distance (0 –2 and 2 – 4 m strips) for pH, TN and CEC and 6 m distance (0 –2, 2 – 4 and 4 – 8 m strips) for Pav and SOC and these values generally decreased with increasing distance from the acacia woodlot. Compared to the control plot (25 m), moisture content was significantly increased by 38 – 65% within a 0 – 10 m strip in the *teff*–acacia woodlot interface. Similarly, there were 22 – 35% more TN and 20 – 30% more CEC within the 0 – 4 m strip and 20 – 49% more Pav and 40% more SOC within the 0 – 8 m strip.

Table 4.4 Soil properties (mean) with increasing distance from a 4-year-old acacia woodlot (n = 3)

Distance (m)	Soil properties					
	Moisture (%)	pH (H_2O)	SOC (%)	TN (%)	Pav (mg kg^{-1})	CEC ($cmol_+ kg^{-1}$)
1	36.7a	4.76a	2.93a	0.31a	8.60a	29.1a
3	34.0ab	4.71a	2.92a	0.28a	7.55b	26.9ab
6	32.3ab	4.53b	2.92a	0.24b	6.97c	24.0bc
10	30.7b	4.52b	2.07b	0.24b	5.98d	24.4bc
14	25.3c	4.56b	2.14b	0.22b	5.89d	24.5bc
18	23.1c	4.50b	2.13b	0.23b	5.78d	22.4c
25	22.3c	4.48b	2.09b	0.23b	5.79d	22.4c
$LSD_{0.05}$	3.3978	0.115	0.1948	0.0365	0.5389	3.14
CV (%)	4.17	0.89	2.88	6.03	2.91	4.54
P-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Means followed by different letters in a column are significantly different at $p < 0.05$. Data was pooled since there was no difference between the east and west sides in each respective stratum at various distances in the *teff*-acacia woodlot interface. SOC, soil organic carbon; TN, total nitrogen; Pav, available phosphorus; CEC, cation exchange capacity

Teff performance across the *teff*–acacia woodlot interface was significantly reduced over a considerable distance (Table 4.5). *Teff* plants grown near acacia woodlots were shorter and a significant reduction in height growth occurred up to 6 m distance which ranged between 17 and 74%. Significant biomass and grain yield reductions occurred over the first 10 m distance from the woodlot. The yield drop was 17–84% and 36–96% for biomass yield and grain yield, respectively. The highest reductions in *teff* biomass and grain yields were recorded within the first 3 m (0 – 2 and 2 – 4 m strips) at the *teff*-acacia woodlot interface.

Table 4.5 *Teff* performance (mean + SE) with increasing distance from a 4–yr–old acacia woodlot (n = 3)

Distance (m)	Growth and yield of *teff*		
	Height (cm)	Biomass yield (t ha^{-1})	Grain yield (t ha^{-1})
1	17.3 ± 0.5d	0.33 ± 0.03e	0.03 ± 0.004e
3	36.5 ± 0.7c	0.62 ± 0.08d	0.07 ± 0.006e
6	55.3 ± 0.8b	1.73 ± 0.1c	0.22 ± 0.012d
10	59.7 ± 0.5ab	2.57 ± 0.01b	0.45 ± 0.005c
14	63.4 ± 0.9a	3.01 ± 0.04a	0.68 ± 0.02b
18	66.3 ± 0.6a	3.12 ± 0.02a	0.77 ± 0.021a
25	66.9 ± 0.8a	3.09 ± 0.01a	0.70 ± 0.013b
$LSD_{0.05}$	3.0128	0.2495	0.0629
CV (%)	5.34	4.33	5.39
P-value	< 0.0001	< 0.0001	< 0.0001

Means followed by different letters in a column are significantly different at $p < 0.05$. Data was pooled since there was no difference between the east and west sides in each respective stratum at various distances in the *teff*-acacia woodlot interface.

4.3.3 Farmers' perceptions and management practices

Farmers generally had positive responses regarding the effects of the acacia fallow on soil properties and crop production (Table 4.6). All agreed regarding soil fertility improvement by the acacia fallow system. All the farmers mentioned better growth and yield of *teff* under the fallow system than in the ST system and they further noted higher *teff* performance in the second rotation than in the first rotation of the fallow system. About 87% of the respondents reported a reduction in inorganic fertilizer application (DAP and Urea) to cultivate annual crops on fallowed lands compared to the ST system. Most of the farmers (83%) observed harvesting of two crops for two consecutive years on farmlands converted into the acacia fallow system. All the respondent farmers noticed crop yield losses on farmlands adjacent to acacia woodlots and all of them thought that crop yield losses near acacia woodlots were due to shading effects, with 30% of them also mentioning competition for soil nutrients as a factor for yield losses. About 90% of the farmers responded increased effects of shading at the stand ages of 4 and 5 years. Farmers employed various mechanisms to reduce the impact of shading on croplands close to acacia woodlots.

Table 4.6 Farmers' perceptions, observations and management practices on the effects of acacia fallows on soil fertility and *teff* performance compared to the ST system (n = 30)

Characteristics	Farmers' responses	Proportion (%)
Soil fertility	Improved	100
Application of chemical fertilizer	Reduced by half	87
Crop performance	Increased	100
Crop cultivation	Two crops in two years	83
Acacia woodlots effect on *teff* production at adjacent croplands	Reduced crop performance	100
The factor for reduced crop performance near acacia woodlots	Shading effects	100
	Competition for soil nutrients	30
Stand age at which the shading effect begins	After the second year	83
Stand age at which the shading effect becomes more significant	In the fourth and fifth year	90
Practices to reduce the shading effects of acacia woodlots	Stand establishment at a similar time	100
	Leaving untilled strips	10
	Lopping of lateral branches	73

4.4 Discussion

4.4.1 Fallowing with acacia improved soil fertility and *teff* performance

The results of the present study have shown that soil properties under acacia fallows in two successive rotations and for two subsequent production years were improved compared to the ST system. Fallowed lands had significantly higher soil pH, SOC, P_{av}, TN and CEC but lower exchangeable Al^{3+} than the ST system. Consistent with this study, tree fallows in the highlands of Ethiopia have been shown to reduce soil acidity and enhance the contents of soil nutrients (Bazie et al., 2020; Beshir et al., 2022; Mamuye et al., 2020). Previous studies elsewhere have also shown a decrease in soil acidity and an increase in carbon and soil nutrient contents in tree-based fallowing systems compared to continuously cultivated systems (Basga et al., 2018; Vyamana et al., 2021). Improved soil properties under acacia fallows might be due to the addition of nutrients through the N_2-fixation process, litterfall and the decomposing acacia root systems, low level of disturbance primarily by tillage, reduced erosion and nutrient uplift (Ketema & Yimer,

2014; Kim & Isaac, 2022; Ngaba et al., 2024). Moreover, farmers' practice of on-site charcoal production (Figure S4.1) can alter soil properties in the fallow system through the addition of a significant amount of biochar into the soil at the charcoal production sites (Glaser et al., 2002; Kim et al., 2022). Farmers perceived the positive effects of charcoal production on soil fertility, and hence, they spread over charcoal fragments to the surrounding areas from the charcoal production sites during tillage operations (Table 4.6). In line with farmers' practice, Dubiez et al. (2019) reported greater effects of spreading charcoal fines (biochar) from carbonization sites on soil properties.

In this study, acacia fallows increased soil pH by 0.5 – 1.0 units and decreased exchangeable Al^{3+} by 77 – 81% over the ST system indicating the benefits of the fallow system in ameliorating soil acidity (Mamuye et al., 2020). Acacia fallows in the second rotation improved soil pH to the level within the optimum range for nutrient availability and plant performance (Weil & Brady, 2017). *A. decurrens* trees can ameliorate soil acidity by the return of more organic matter to the soil, improving cycling of basic cations by decreasing water drainage and through pumping (Ngaba et al., 2024; Riyadh et al., 2018). The practice of *in situ* charcoal production at several spots in acacia fallows can increase soil pH (Amare et al., 2022) and consequently decrease exchangeable Al^{3+} concentration in the soil. In the ST system, prolonged use and increased application of inorganic fertilizer (Table 4.6) can lower soil pH (Goulding, 2016).

In comparison with the ST system, acacia fallows improved P_{av} by 77 – 200%. Consistent with this study, tree fallows in Northwestern Ethiopia increased available P by 86 – 168% (Beshir et al., 2022; Kim et al., 2022). The increase in P_{av} in the acacia fallows can be attributed to the increased organic matter returned to the soil by litterfall and root turnover and pumping (Fahad et al., 2022; Sileshi et al., 2014). Whereas, the decrease in P_{av} in the ST system may be due to the greater P losses through crop harvest and soil erosion and P fixation through the formation of insoluble Al phosphates (Glaser et al., 2002; Weil & Brady, 2017). The reduction in the amount of exchangeable Al^{3+} in acacia fallows may increase P_{av} as shown in the correlation analysis where there was a strong relationship of P_{av} with exchangeable Al^{3+} ($r = -0.87$, $p < 0.01$). Moreover, biochar formed as a by-product of the *in situ* charcoal production practice can be a source of P on fallowed lands. *A. decurrens*-derived wood biochar contains about 278 mg kg^{-1} P_{av}

(Mulualem et al., 2021) that can be incorporated into the soil at charcoal production spots (Kim et al., 2022) or become distributed over a larger area (Table 4.6) during tillage operations.

Higher TN contents observed in acacia fallows can be attributed to the nitrogen enrichment of the soil from litterfall and dead tree roots (Ortega et al., 2002) and through nitrogen fixation (Chikowo et al., 2004; Muyayabantu et al., 2019). In the ST system, however, crop residues are usually removed with the harvest thereby reducing nitrogen import to the soil. In the same study area, Belete (2015) reported *A. decurrens* trees yielding large quantities of nodules within the age of 18 months. Moreover, the presence of trees can reduce the loss of nitrogen in acacia fallows through erosion (Muchane et al., 2020). Our findings align with Kuyah et al. (2019) who demonstrated higher soil nitrogen contents in agroforestry systems than in mono-cropping agricultural systems in sub-Saharan Africa.

The contents of SOC were higher in the acacia fallows (3.7 – 4.5%) than in the ST system (2.3%) suggesting the benefits of agroforestry systems to enhance SOC accumulation in soils and the overall soil quality. In the acacia fallow, the soil is less disturbed and *A. decurrens* trees can contribute more carbon inputs to the soil through increased organic matter accumulation (Shi et al., 2018). Farmers usually plant *A. decurrens* at very high density (Nigussie et al., 2017). Hence, the overall biomass production per unit area of land would be higher to provide more carbon inputs through increased litterfall and root decay to the soil than those of lower tree density (Gebremeskel et al., 2021; Syano et al., 2024) or complete absence of tree cover in the ST system. Moreover, the increase in SOC in the acacia fallow system could also be attributed to the *in situ* charcoal production practice (Amare et al., 2022; Kerré et al., 2017; Kim et al., 2022). Whereas, in the ST system, SOC content is lower since the soil is subjected to frequent disturbance by conventional tillage, the vegetation cover is less or absent and there is complete removal of crop residue (Haileslassie et al., 2005; Ketema & Yimer, 2014). Earlier studies have demonstrated higher amounts of SOC in tree woodlot systems (Amare et al., 2022; Vyamana et al., 2021). A meta-analysis by Muchane et al. (2020) in the humid and sub-humid tropics revealed an increase of SOC by 21% under agroforestry systems compared to crop monocultures.

The results of this study also showed that CEC was positively influenced by the acacia fallow system. The higher level of CEC in the acacia fallows could be associated with increased accumulation of organic matter (Weil & Brady, 2017). In the ST system, removal of crop residue and frequent cultivation practices could deplete organic matter (Ketema & Yimer, 2014) and hence result in lower CEC.

Our results also showed that the enrichment of soil properties was better in the second rotation than in the first rotation of the acacia fallow system (Table 4.2). Acacia fallows in the second rotation which represent 10 years of fallow duration increased pH, SOC, TN, P_{av} and CEC by 7, 15, 26, 55 and 26%, but decreased exchangeable Al^{3+} by 17% as compared to the acacia fallows in the first rotations representing 5 years of fallow duration. A better soil condition in the second rotation could arise from progressive increases in the amount of organic matter added to the soil through the N_2-fixation process, litterfall and the decomposing acacia root systems (Muchane et al., 2020; Ngaba et al., 2024). According to Beshir et al. (2022) and Kim et al. (2022), increases in the contents of SOC and TN were greater in the second rotation than in the first rotation of *A. decurrens*-based fallow system in Northwestern Ethiopia. Mapenzi et al. (2024) found that soil pH and TN considerably increased in the agroforestry system with the increase in cropping seasons in the Congo Basin. Wang et al. (2023) noted total carbon stock increased with aging in poplar-crop agroforestry chronosequence in Subtropical Central China. Land management under the agroforestry system for 5, 10 and 15 years resulted in the increase of SOC by 16, 53 and 88%, respectively, compared to maize-based conventional tillage in southern Ethiopia (Ketema & Yimer, 2014). A study by Bhojvaid et al. (1996) revealed that the ameliorative effects of *Prosopis juliflora* plantation increased with the duration of tree occupancy. In plantations consisting of N_2-fixing trees, the levels of carbon and major soil nutrients generally increase with plantation ages (Kasongo et al., 2009). Furthermore, under the acacia fallow system, there is harvesting of acacia woodlots at the fifth age followed by on-site charcoal production. As a result, enhanced soil qualities might be due to a greater amount of charcoal fragments added into the soil by the repeated charcoal production on fallowed lands in the second rotation than in the first rotation, where charcoal production took place only once (Figure 4.1).

Soil assessment in the first rotation demonstrated the potential of acacia fallows to improve soil chemical properties within a short period of five years. These results corroborate well with the results reported by Vyamana et al. (2021) for *Albizia harveyi* and *Albizia versicolor* tree fallows in Tanzania that increased OC, TN and extractable P in four years in comparison with continuous cropping. After a 4–year fallow period, Amare et al. (2022) observed a significant increase in soil pH, SOC, and CEC in *A. decurrens* woodlots compared to continuously cultivated croplands. The report from Mamuye et al. (2020) also indicated considerable improvements in soil pH, SOC and TN of degraded soil due to short-rotation legume fallows in southwestern Ethiopia.

In the acacia fallow system, farmers have practiced growing annual crops for one or two years between repeated rotations (Table 4.6). Our results have shown that *teff* performance on fallowed lands in two successive rotations and for two subsequent production years was improved compared to the ST system. *Teff* performance was the least in the ST system with the highest increases in height growth and biomass and grain yield of *teff* observed on fallowed lands (Figures 4.2 and 4.3). The harvest index was, however, higher in the ST system than in the fallow system reflecting a greater allocation of resources to grain production under resource-poor conditions (Mugunga et al., 2017). Greater improvements in *teff* performance in the second rotation than in the first rotation of the fallow system suggest the progressive development of the restoration processes upon repeated rotations. Enhanced *teff* production in both production years shows the contribution of the fallow system in benefiting farmers through the cultivation of two annual crops in two years. Croplands, unless converted into the acacia fallow system, can only be cultivated with one annual crop in two years due to severe land degradation. In line with the results at the field level, farmers' responses also showed the benefit of the fallow system through sustaining the cultivation of two crops in two years on croplands (Table 4.6). The results also showed that farmers could go for the third cropping rather than converting back into the acacia plantations (Table 4.3). The results revealed the potential benefits of the fallow system to restore and sustain soil properties and crop performance on degraded agricultural lands.

Compared to the ST system, the acacia fallow system increased *teff* grain yields by 63 – 103% and the yields obtained (ranging from 1.53 to 1.93 t ha^{-1}) were higher than

the average national yield (1.2 t ha^{-1}) from 2001-2017 (Cochrane & Bekele, 2018), but comparable to the recent average national yield reported by CSA (2021). Consistent with our results, tree-based fallowing in Tanzania resulted in increases in maize grain yields by 100 – 335% (Kimaro et al., 2008; Vyamana et al., 2021). *Sesbania sesban*-based fallowing in southern Africa resulted in doubling or tripling of maize yields compared to control plots (Akinnifesi et al., 2010). Mamuye et al. (2020) presented an increase in maize grain yield by 40 – 80% under improved fallows with two shrub legumes in Ethiopia. Tadele and Teketay (2014) indicated that the conversion of croplands into *Eucalyptus* plantations can increase the post-felling yields of cereal crops in Ethiopia. The increase in *teff* performance can be attributed to the benefits of the fallow system by reducing soil acidity and improving supply of soil nutrients (Tables 4.2 and 4.3) to crops in the subsequent production on fallowed lands.

Overall, the results of the current study have shown that acacia fallows substantially contributed to the improvements in soil acidity and contents of soil nutrients including TN, OC, P_{av} and CEC. These benefits have led to an increase in *teff* crop performance as shown in the correlation analysis (Figure 4.4) and can also potentially reduce the need for inorganic fertilizers. In line with the field results, farmers have noticed soil fertility restoration and enhanced *teff* performance on fallowed lands. Consequently, the farmers have reduced inorganic fertilizer application on fallowed lands by 50% (Table 4.6) which implies an increased economic return to the smallholder farmers from the system. Nigussie et al. (2020) demonstrated higher economic benefits from *teff* (*Eragrostis te*f) – *A. decurrens* woodlot system than monocultures of either *A. decurrens* woodlot or *teff* crop. Farmers perceived reduced soil erosion, increased organic matter accumulation, and on-site charcoal production on croplands as factors for soil fertility improvement in *A. decurrens*-based fallowing.

4.4.2 Soil fertility and *teff* performance varied with distance from the acacia woodlot

The soil properties exhibited a decreasing trend with increasing distance from the acacia woodlot. Soil moisture was higher near the woodlot and continued to decrease with increasing distance up to 10 m. The observed values of pH, TN and CEC were

significantly higher within a 3 m distance, and for SOC and P_{av}, the values were significantly higher within a 6 m distance of the acacia woodlot system than the values in the control plots. Studies conducted so far showed improved moisture contents and soil fertility under or near the canopy of trees in agroforestry systems (Haile et al., 2021; Sirohi et al., 2022). Birhane et al. (2019) reported higher levels of TN, SOC and CEC beneath the canopy of *Acacia polyacantha* where litterfall accumulated than in the open field in northern Ethiopia. A review by Kim and Isaac (2022) showed global average nitrogen inputs of 240 kg ha^{-1} y^{-1} among agroforestry systems through nitrogen fixation. In agroforestry systems, trees can influence soil properties in their vicinity through various mechanisms including litter accumulation, root decay, nutrient uplift and nitrogen fixation (Lorenz & Lal, 2014; Ngaba et al., 2024). The results also showed the visibility of the negative effect of acacia woodlot on *teff* performance up to 10 m distance. The average reduction over the first 10 m distance was 58% for biomass yield and 73% for grain yield. *Teff* plants were shorter near the acacia woodlot and the effect extended up to 6 m distance. The results are consistent with the previous studies (Khan et al., 2023; Mitiku et al., 2022) highlighting reduced performances of crops grown beneath or close to tree canopies.

Tree-crop interactions can vary with distance through competition for resources (soil moisture, nutrients and light environment) and allelopathy. In this study, we found higher contents of soil moisture and nutrients close to acacia woodlots (Table 4.4) and the reduction of *teff* growth and yield through competition for these resources would be low. Further, the inhibitory effect of acacia trees on *teff* growth and yield is not expected as indicated in Figures 4.2 and 4.3, where *teff* performance was enhanced on croplands formerly planted with acacia trees for a period of 5 and 10 years. Considering the prevailing improved soil conditions near acacia woodlots coupled with less likelihood of inhibitory effect through allelopathy revealed that competition for the light environment would be a factor limiting *teff* production at adjacent crop fields (Chanie et al., 2013; Surki et al., 2020). Because of high planting density, the shaded areas were less exposed to sunflecks and as a result, grain yields of *teff* over the first 4 m distance from the acacia woodlot were negligible and the yield reduction exceeded 90% compared to the values at

the control plots (Table 4.5). *Teff* is highly susceptible to shading compared to commonly cultivated crops such as barley, wheat and maize (Haile et al., 2021; Kidanu et al., 2005).

Farmers' observation and perception also revealed the shading effects of acacia woodlots which thereby reduced *teff* performance at adjacent croplands. All respondents stated that shading begins after the second year and the effect on crop production increases with the woodlot's age. They stated that the shading effect can extend up to 5 to 7 m into the crop field, in line with the observed *teff* performance reduction up to 10 m distance (Table 4.5). Surki et al. (2020) demonstrated the increase of solar radiation intercepted by barley and wheat with distances from trees in the agroforestry system and the associated reduction in crop yields at the adjacent crop fields. According to Mugunga et al. (2017), solar radiation continued increasing from the *Eucalyptus* woodlot-maize interface up to 18 m which partly contributed to the reduction of maize grain yield by 80% in the 10.5 m strip next to the woodlot. Farmers tried to manage shading effects on crop production by establishing woodlots at the same time so that woodlots would be harvested at similar times and crop production between repeated rotations would not be affected. They also practiced lopping of lateral branches to minimize the extent of shading effects (Table 4.6).

4.5 Conclusion

We have focused on the effects of *A. decurrens*-based fallowing on soil properties and crop performance of degraded agricultural land. The acacia fallow system in the first and second rotations improved soil chemical properties and *teff* performance compared to the sole cropping system. And the fallow system had greater effects in the second rotation than in the first rotation. The system can sustain two or even three *teff* crop harvests between repeated rotations and reduce the need for chemical fertilizer application. The positive effects of the acacia fallow on soil properties and crop performance suggest *A. decurrens* can be integrated into the cropping system to restore degraded agricultural land and thereby increase crop performance. Acacia woodlots can reduce *teff* crop yields at adjacent croplands up to 10 m distance in the crop-woodlot interface through shading effects. Further investigation based on multiple rotations and production years is required

to ascertain the sustainability of the acacia fallow system on a long-term basis. Furthermore, proper agroforestry design and layout may also be necessary to reduce the shading effects of acacia woodlots on adjacent croplands.

CHAPTER 5: *ACACIA DECURRENS* WOOD BIOCHAR IMPROVED SOIL PROPERTIES AND SUSTAINED HIGHER CROP YIELDS IN NORTHWESTERN ETHIOPIA[3]

Abstract

Biochar has been used as an amendment to improve soil properties and crop performance. We assessed locally produced *A. decurrens* wood biochar-induced changes in soil properties and crop performance during a two–year field study in the Guder watershed, Northwestern Ethiopia. Biochar was added once to a degraded acidic agricultural soil at four rates (0, 5, 10 and 20 t ha^{-1}) and planted with *teff* in the first year. In the second year, barley was grown to investigate the residual effects of biochar in permanent plots. Compared to the control, a single addition of biochar at higher rates (10 and 20 t ha^{-1}) significantly increased soil moisture content, pH, SOC, P_{av} and TN, but decreased bulk density and exchangeable Al^{3+} over two years. Similarly, biochar addition at higher rates significantly improved crop performance for two consecutive years. Biochar increased plant height, biomass and grain yields of *teff* by 22 – 37%, 65 – 103% and 56 – 85% and barley by 18 – 32%, 81 – 126% and 69 – 117%, respectively. Barley leaf chlorophyll content was increased by 23 – 120% following the increase of biochar addition from 5 to 20 t ha^{-1}. Overall, amending acidic soil with *A. decurrens* wood biochar had greater effects with increasing rates and persistently improved soil fertility and crop performance over two years. The results highlight the potential for the agricultural benefits of amending degraded acidic agricultural soil with locally produced biochar from *A. decurrens* wood in a smallholder farming system.

***Keywords*:** Barley, crop performance, soil fertility, *teff*

[3] Tadele, D., Adgo, E., & Meshesha, D. T. (2025). Amending degraded agricultural soil with *Acacia decurrens* wood biochar improved soil properties and crop productivity over two years **(s**ubmitted to **Journal of Environmental Quality**)

5.1 Introduction

Land degradation and the associated soil acidity development are the major constraints for crop production in Ethiopia (Schmidt & Tadesse, 2019). The problem is more severe and has resulted in low agricultural productivity and food insecurity in the highlands of the country (Bewket, 2007; Ebabu et al., 2019). In these areas, smallholder farmers are even forced to shift their farming system from sole cultivation of annual crops into planting of trees such as acacia and eucalypts in the agricultural landscape (Abiyu et al., 2016; Dessie et al., 2022; Wondie & Mekuria, 2018). In the Fagita Lekoma district of Northwestern Ethiopia, following soil acidity and low soil fertility-related problems, farmers introduced innovative agriculture by integrating *A. decurrens* trees in the cropping system. This innovative agriculture involves the establishment of *A. decurrens* woodlots on farmlands, *in situ* charcoal production from *A. decurrens* wood after harvesting of the acacia woodlots at the age of five years and cultivation of annual crops between successive harvests. Farmers produce charcoal *in situ* using traditional charcoal kilns and a large amount of biochar can be obtained as a waste product from charcoal production (Kim et al., 2022; Tazebew et al., 2023). In this new cropping system, reports showed soil acidity amelioration and nutrient restoration (Amare et al. 2022; Beshir et al. 2022). Farmers noticed the positive effects of charcoal production on soil fertility and crop production (Nigussie et al., 2020).

Biochar is formed through the pyrolysis of biomass under high temperatures in the partial or total absence of oxygen. Biochars, which are influenced by feedstock and pyrolysis conditions, are highly variable in their properties (Gezahegn et al., 2024; Pariyar et al., 2020). Upon application to the soil, the high proportion of recalcitrant carbon present in biochar resists decomposition and increases soil carbon that contributes to carbon sequestration (Lorenz & Lal, 2014). Biochar-induced improvements in soil conditions are reported, which are attributed to the addition of nutrients from the biochar itself, soil acidity reduction, increased nutrient availability and retention, reduction of bulk density and improvements in moisture contents (Elias et al., 2020; Glaser et al., 2002; Gul et al., 2015; Zhou et al., 2020). Associated with the improvements in soil properties, amending soils with biochar can increase crop performance and reduce the

need for inorganic fertilizer (Domingues et al., 2017; Yamato et al., 2006). A meta-analysis for biochar that can increase crop yield between 17 and 25% are reported (Jeffery et al., 2017; Singh et al., 2022). The review by Yu et al. (2019) showed that biochar can stimulate crop performance in acid soils ranging from 28 to 363%. And yet, neutral or even negative effects of biochar on crop performance are also reported (Jeffery et al., 2017; Liao et al., 2020). Biochar effects on soil properties and crop performance could be for a short-term that fade away after one or two growing seasons or for a long-term that persist over multiple seasons (Cornelissen et al. 2018; Jin et al. 2019; Kätterer et al. 2019; Zhang et al. 2019). Despite the existing positive benefits, there are uncertainties regarding the impacts of biochar on soil properties and crop performance that can originate from many factors including biochar characteristics, soil properties, climatic conditions, application rates and crop types (Elias et al., 2020; Gezahegn et al., 2024; Glaser & Lehr, 2019; Manickam et al., 2015).

A large quantity of wood biochar (WB) can be produced as a result of the rapid expansion of *A. decurrens* plantation in the study area and the neighboring districts (Alemayehu et al., 2024; Worku et al., 2021) and the growing demand coupled with low efficiency of charcoal production (Tazebew et al., 2023). A report by Kim et al. (2022) showed the production of about 11 tons of biochar on a hectare of farmland by the *in situ* charcoal production practice from *A. decurrens* wood. The use of *A. decurrens* WB as a soil amendment has paramount significance in reclaiming soil acidity, which affects about 43% of farmland area (ATA, 2014), and land degradation is severely limiting agricultural productivity in Ethiopia (Agegnehu et al., 2021; Schmidt & Tadesse, 2019). However, specific information on the effects of *A. decurrens* WB addition on soil properties and crop performance is limited (Tazebew et al., 2024). Furthermore, the residual effects of biochar produced from *A. decurrens* wood for a sustainable agricultural practice under this innovative cropping system remain unexplored. This study extends our knowledge regarding using non-commercial by-products of traditional charcoal production as a soil amendment. In this study, therefore, we conducted a field experiment to examine the effects of *A. decurrens* WB application to acidic agricultural soil, grouped by application rate, on soil properties and crop performance for two successive growing seasons under *teff*-barley rotation. We hypothesized that: (i) addition

of biochar to acidic soil would increase crop performance due to alleviation of soil acidity and improvement in plant nutrient availability, (ii) the effect of biochar on soil properties and crop performance would be sustained over two successive growing seasons following a single application of biochar in the first year.

5.2 Materials and Methods

5.2.1 Study site description

In the main production seasons of 2020 and 2021, a two-year field trial was conducted in the Guder watershed situated in Fagita Lekoma district of Amhara Region, Northwestern Ethiopia (Figure 2.1). The detailed site description is available in Chapter 2, section 2.1.

5.2.2 Biochar production and initial soil characteristics

Wood biochar was produced from the trunks and major branches of *A. decurrens* using traditional charcoal kilns, as practiced by the local farmers. *A. decurrens* trees that were around five years old were harvested near the ground, and the main branches and stems were cut into cutting logs that were 30 to 50 cm long (Tazebew et al. 2023). For the carbonization process, the logs were piled into a mound surrounding the kiln site and covered with soil and crop residues. This allowed the wood to be heated to a temperature of 400 to 450 ^{o}C (Emrich 1985) in an oxygen-limited atmosphere. The carbonization process took on average about 5 days. Once the carbonization process was completed, the carbonized material (charcoal) was taken out and manually ground and sieved using a 4 mm sieve to ensure uniform particle sizes prior to application. Table 1 shows selected biochar and soil characteristics at the experimental plots prior to biochar addition to the soil.

Table 5.1 Selected initial characteristics of surface soil (0 – 15 cm) at the experimental plots and *A. decurrens*-derived wood biochar

Parameters	Unit	Soil	Biochar
Bulk density	g cm^{-3}	1.22	
Textural class		Loam	
pH (H_2O)		4.61	9.63
Soil organic carbon	%	2.20	65[a]
Total N	%	0.21	0.66[a]
Available P	mg kg^{-1}	8.40	278[b]
Cation exchange capacity	$cmol_+ kg^{-1}$	23.7	47
Exchangeable Al^{3+}	$cmol_+ kg^{-1}$	3.15	Below detection level
Particle size	mm	< 2	< 4

[a]Tazebew et al. (2024); [b]Mulualem et al. (2021)

5.2.3 Study design

The field trial was established in 2020 at the Guder watershed using an existing farmland. The trial plots (2.5 m x 3 m) were laid out in a randomized complete block design with four biochar treatments in three replications resulting in a total of 12 experimental plots. The farm field was tilled with oxen-plough to a depth of 15 cm. Biochar was then manually surface spread on the plots 14 days before planting in the first year at rates of 0, 5, 10 and 20 t ha^{-1}, and manually mixed two times to have a uniform mix of biochar and the soil. In order to evaluate the potential residual effect of biochar application, the same plots were cultivated without biochar application in the second year. Plots were separated by a 0.5 m space while a 1.0 m space was kept between blocks to prevent possible confounding effects of biochar movement by wind, water or tillage. The plots were planted with *teff* crop in the first growing season and with barley crop in the second growing season. At planting time in both growing seasons, each plot received the same amount of inorganic fertilizer as Urea and diammonium phosphate (DAP), each 60 kg ha^{-1} based on the existing local experience.

5.2.4 Soil sampling and analysis

A composite of three soil samples (0–15 cm) was taken from each treatment at the end of each growing season. The samples were analyzed for soil moisture, bulk density, pH, SOC, TN, P_{av} and exchangeable Al^{3+} following the methods described in section 2.2 of Chapter 2.

5.2.5 Crop performance

Teff and barley were planted in rotation on the experimental plots. The crops were chosen for this study since they are commonly cultivated in the study area. *Teff* was sown in the first week of August 2020 in the first season and in the second season barley was sown in the third week of August 2021. The test crops were managed and harvested as per local farmers' practice. Crop performance was assessed by measuring plant height, aboveground biomass yield and grain yield at crop maturity from a 0.5 m x 0.5 m subplot at three locations from each plot. For both crops, plant height was measured using four randomly selected plants in each subplot. The three subplots in each plot were harvested close to the soil surface to determine the aboveground biomass and grain yields. Detailed information regarding plant height, biomass and grain yield measurements is given in Section 2.2 of Chapter 2. Chlorophyll content was measured during the second growing season in 2021 using a chlorophyll meter (MC-100, USA) at the vegetative stage with triplicate readings on three young and fully expanded leaves per plant. Two plants per subplot were chosen randomly to repeat the procedure.

5.2.6 Statistical analysis

Soil and plant-related data were analyzed with one-way ANOVA, with biochar treatment rates as a factor affecting soil properties and crop performance. Pearson correlation analysis was performed to test the correlation between soil characteristics and crop performance. The significant differences between treatment means were separated using Tukey's HSD test at 1 and 5 % levels of significance.

5.3 Results

5.3.1 The effects of biochar on soil physical properties

The values of soil bulk density and moisture content under various *A. decurrens* WB additions in two successive growing seasons are shown in Table 5.2. The values of bulk density become lower with increasing rates of biochar addition in both seasons. Biochar addition at the rate of 20 t ha^{-1} consistently caused the highest reduction of bulk density by 19 and 21% over the control treatments in the first and second seasons, respectively. In contrast, an increase in soil moisture content was observed under the different biochar additions over the corresponding controls in both seasons. The increase in moisture content was greater at higher rates and ranged from 7 to 19% in the first season and 6 to 20% in the second season.

Table 5.2 Effects of *A. decurrens* WB rates on soil physical properties (means + SE) over two seasons

Soil properties	B0	B5	B10	B20	*P*-value	$LSD_{0.05}$	CV (%)
First year							
Bulk density (g cm^{-3})	1.19 ± 0.02a	1.15 ± 0.02a	0.98 ± 0.01b	0.96 ± 0.01b	< 0.0001	0.0743	2.65
Moisture content (%)	22 ± 0.88b	24 ± 1.0ab	25 ± 1.15ab	27 ± 0.88a	0.019	4.47	6.97
Second year							
Bulk density (g cm^{-3})	1.19 ± 0.02a	1.14 ± 0.02a	0.97 ± 0.01b*	0.94 ± 0.01b*	< 0.0001	0.0696	2.51
Moisture content (%)	23 ± 1.15b	24 ± 0.67ab	26 ± 0.33ab	28 ± 0.67a	0.019	3.46	5.22

Values followed by different letters in a row are significantly different at $p < 0.05$; * significant at $p < 0.01$. B0, control; B5 biochar at 5 t ha^{-1}; B10, biochar at 10 t ha^{-1}; B20, biochar at 20 t ha^{-1}

5.3.2 Biochar effects on soil chemical properties

Changes following the acacia WB addition on soil chemical properties are presented in Figures 5.1 and 5.2. Compared to the control, the values of soil pH, SOC, Pav and TN tended to increase with increasing rates of biochar addition in both growing seasons,

whereas, the contents of exchangeable Al^{3+} exhibited a reduction with increasing amounts of biochar addition. Biochar increased pH by 7 – 26% and 5 – 22% and Pav by 18 – 275% and 16 – 262% over the control in the first season and second season, respectively. The reduction of exchangeable Al^{3+} ranged between 78 and 94% in the first season and 77 and 92% in the second season as compared to the control. The results showed that biochar had greater effects on Pav than the effects on improving soil pH.

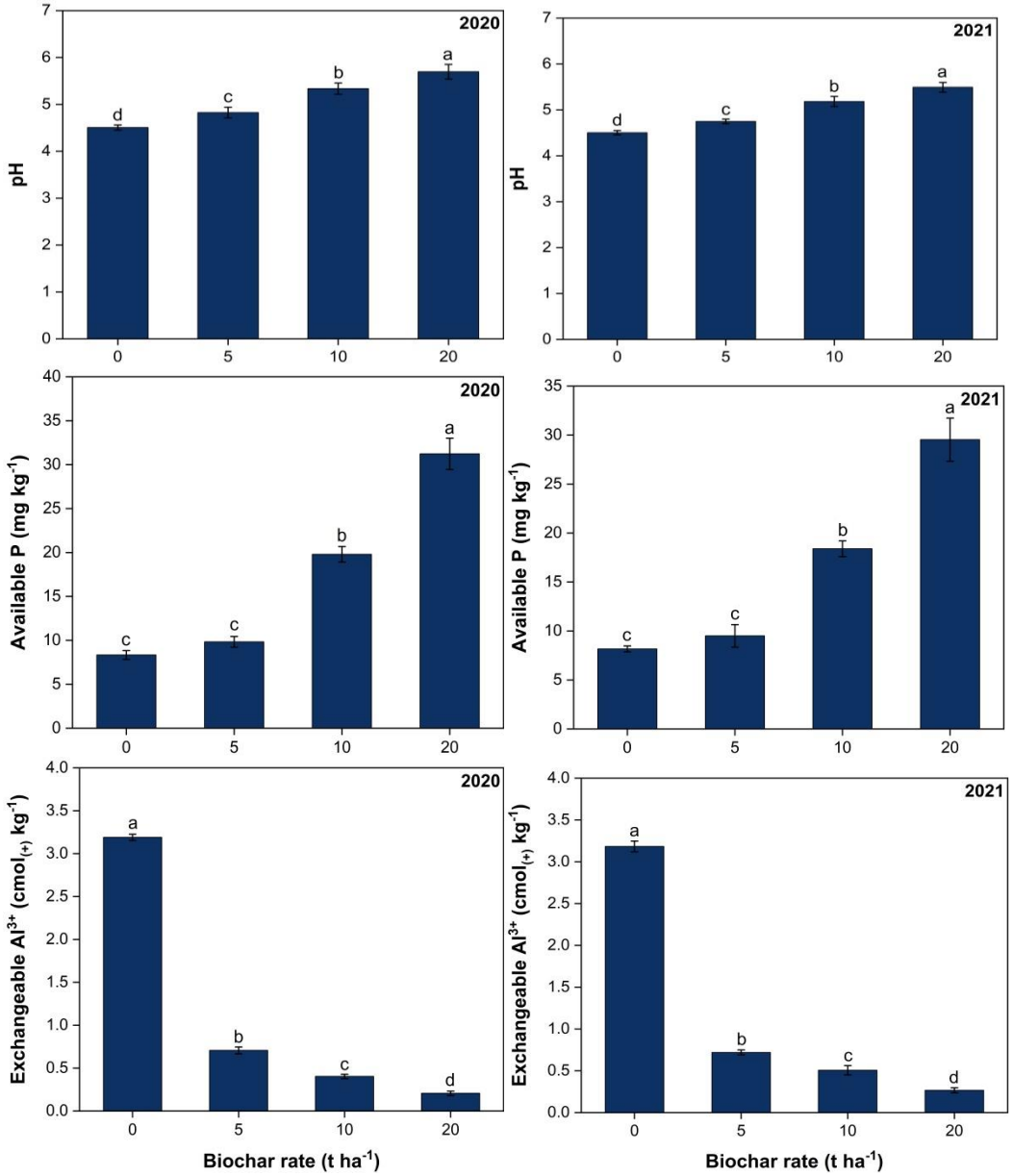

Figure 5.1 Effects of *A. decurrens* WB rates on soil pH, available P and exchangeable Al^{3+} (means + SE) over two cropping seasons (2020 and 2021). Different small letters indicate significant differences at $p < 0.05$. Bars indicate + standard error

With increasing rates of acacia WB addition, the contents of SOC were increased by 8 – 89% and 7 – 93% in the first and second seasons, respectively. Similarly, the contents of TN were increased by 4 – 20% in the first season and 2 – 17% in the second season. Biochar addition at 5 t ha^{-1} had no significant effects on Pav and TN in both production seasons.

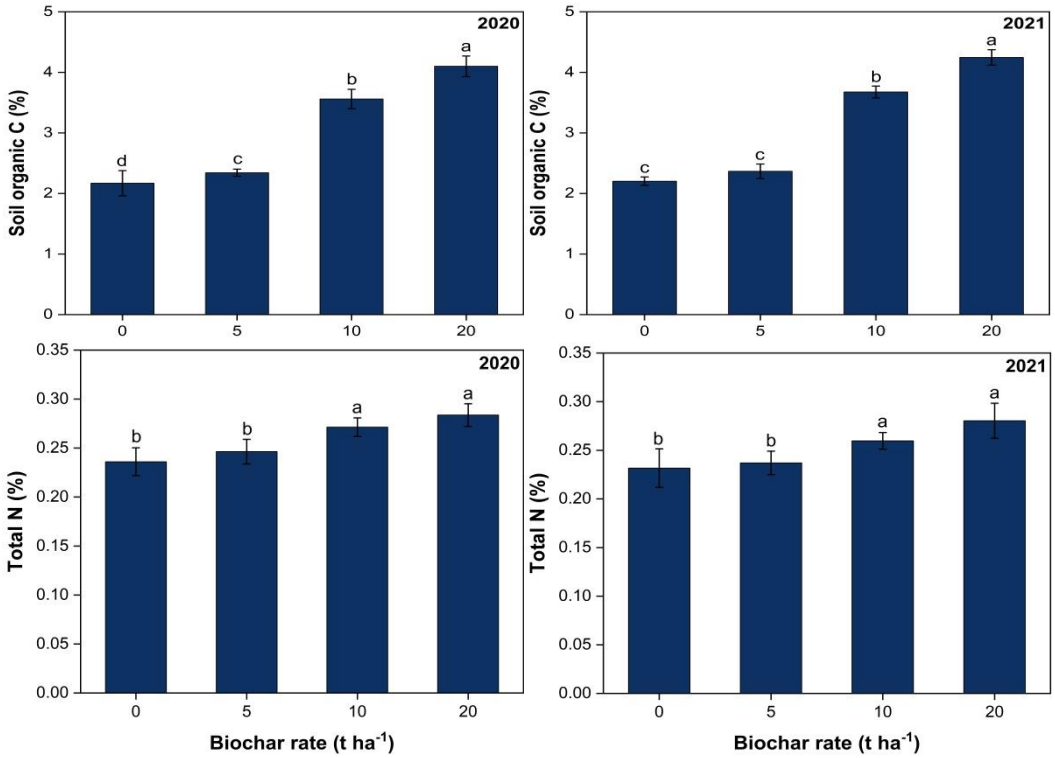

Figure 5.2 Effects *A. decurrens* WB rates on soil organic carbon and total N (means + SE) over two seasons (2020 and 2021). Different small letters indicate significant differences at $p < 0.05$. Bars indicate + standard error

5.3.3 Biochar effects on crop performance

Growth and grain yields of barley and *teff* after a single application of biochar based on the two–year monitoring are shown in Table 5.3. The results generally showed that during the two growing years aboveground biomass yield and grain yield of *teff* and barley had an increasing tendency with increased rates of biochar addition. Increases in biomass yields were significant at all biochar rates, whereas the increases in grain yields were significant at higher rates of 10 and 20 t ha^{-1}. Compared to the control, biochar addition increased biomass yield and grain yield of *teff* by 14 – 103% and 9 – 85% in the

first year and barley by 18 – 126% and 10 – 117% in the second year, respectively. Likewise, biochar addition increased the height of *teff* by 3 – 37% and barley by 4 – 32% and the effect of the biochar was significant at higher application rates. Leaf chlorophyll content of barley was also increased by 23 – 120% following an increase of biochar addition from 5 to 20 t ha^{-1} and the differences were significant across all rates of biochar addition.

Table 5.3 Effects of *A. decurrens* WB addition on the performance (mean + SE) of *teff* (first year) and barley (second year)

Biochar rate (t ha^{-1})	Biomass yield (t ha^{-1})	Grain yield (t ha^{-1})	Plant height (cm)	Chlorophyll content (SPAD-Unit)
First year				
B0	4.36 ± 0.04d	1.01 ± 0.03c	61.5 ± 1.32c	
B5	4.95 ± 0.05c	1.10 ± 0.02c	63.5 ± 0.76bc	
B10	7.18 ± 0.05b	1.58 ± 0.04b	75.0 ± 0.58b	
B20	8.85 ± 0.07a	1.87 ± 0.03a	84.0 ± 1.15a	
P-value	< 0.0001	< 0.0001	< 0.0001	
$LSD_{0.05}$	0.2442	0.1422	5.19	
CV (%)	1.47	3.92	2.79	
Second year				
B0	5.60 ± 0.17d	2.15 ± 0.02c	86.7 ± 1.45c	18.8 ± 0.54d
B5	6.59 ± 0.15c	2.36 ± 0.03c	90.4 ± 1.39c	23.2 ± 1.25c
B10	10.13 ± 0.1b	3.75 ± 0.08b	102.1 ± 1.76b	36.8 ± 0.2b*
B20	12.68 ± 0.1a*	4.91 ± 0.04a*	114.1 ± 1.82a	41.4 ± 0.34a*
P-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$LSD_{0.05}$	0.4899	0.2237	7.318	3.2121
CV (%)	2.07	2.60	2.85	4.09

Values followed by different letters in a column across years are significantly different at $p < 0.05$; * significant at $p < 0.01$. B0, control; B5 biochar at 5 t ha^{-1}; B10, biochar at 10 t ha^{-1}; B20, biochar at 20 t ha^{-1}

5.4 Discussion

5.4.1 Effects of *A. decurrens* wood biochar on soil physical properties

Soil bulk density consistently declined with increased acacia WB addition over two successive seasons that ranged between 1.19 and 0.96 g cm^{-3} in the first season and 1.19 and 0.94 g cm^{-3} in the second season. Whereas, soil moisture content followed the reverse pattern, becoming higher with increasing rates of WB addition. Consistent with our results, Fentie et al. (2024) and Tazebew et al. (2024) have shown similar changes in soil bulk density and moisture contents under increased rates of biochar addition. Biochar has a low bulk density, generally less than 0.6 g cm^{-3} (Blanco-canqui, 2017), porous surface and high surface area, hence, soils amended with biochar have shown a decrease in bulk density and subsequent increase in moisture content (Blanco-canqui, 2017; Singh et al., 2022). The benefits of biochar to improved crop performance are often attributed to the changes in soil properties including reduction of bulk density and improvements in moisture contents (Agegnehu et al., 2016; Gul et al., 2015). The decrease in bulk density can improve water and gas circulation in soils (Lehmann et al., 2003) and reduce physical resistance that restricts root growth (Bruand & Gilkes, 2002). Increased water content in biochar-amended soils shows improvement in water holding capacity of treated soils and thus biochar can improve soil water content to supply the required moisture for crops reflecting the potential of acacia WB as a viable option in low rainfall areas and during periods of moisture shortage (Abdou et al., 2024; Fentie et al., 2024).

5.4.2 Effects of *A. decurrens* wood biochar on soil chemical properties

The results showed that the addition of acacia WB had ameliorative effects on the chemical properties of the soil (Figures 5.1 and 5.2). The effects were more pronounced at higher application rates and consistent over two successive cropping seasons. Biochar applied at 20 t ha^{-1} resulted in the greatest reduction in soil acidity and increase in nutrient contents suggesting the highest degree of soil fertility and higher application rates of acacia WB may be possible. Increased soil nutrients with the rise in biochar application rate (Phares et al., 2020; Tazebew et al., 2024) can presumably be due to the nutrient

addition from the biochar itself or improved nutrient availability through the increased soil pH (Gul et al., 2015; Zhou et al., 2020). The acacia WB had relatively larger amounts of P_{av} and TN (Table 5.1). Biochar effects on soil properties could last for one to two seasons or multiple seasons (Griffin et al., 2017; Jin et al., 2019; Kätterer et al., 2019). In this study, soil properties sustained over two cropping seasons highlight the benefits of amending degraded acidic agricultural soil with a single application of acacia WB in restoring soil fertility at least for the first two cropping seasons.

The addition of acacia WB increased the pH of the acidic soil. Compared to the control treatment, the soil pH was raised by 0.32 – 1.18 units along with the increased addition of biochar from 5 to 20 t ha^{-1}. Biochar additions at higher rates resulted in greater increases in pH (Zong et al., 2017). The soil pH range observed in the acacia WB amended soils at 20 t ha^{-1} lies within the optimum range for nutrient availability and crop performance (Weil & Brady, 2017). Soil pH increased by acacia WB addition shows the high inherent pH of biochar and its liming potential presumably due to the accumulation of basic cations in ashes (Domingues et al., 2017; Mulualem et al., 2021; Zhu et al., 2014). As a legume tree, the biochar derived from *A. decurrens* wood can have a liming potential (Wang et al., 2009; Weil & Brady, 2017). The acacia WB exhibited a pH of 9.63 indicating that the biochar has an alkaline nature and hence a liming effect on acidic soils.

Acacia WB greatly reduced the amount of exchangeable Al^{3+} in the soil. Similar results were reported indicating the role of biochar application to reduce exchangeable Al^{3+} in acidic soils (Dume et al., 2017; Yamato et al., 2006). The reduction in the contents of exchangeable Al^{3+} in the soil followed the same order with the increase in soil pH, which implies the advantage of biochar addition to reduce the level of exchangeable Al^{3+} in acidic soils by increasing soil pH (Purakayastha et al., 2019). There was a significant negative correlation of pH with exchangeable Al^{3+} (Figure 5.3). In acidic soils below pH 5.5, Al^{3+} toxicity can be expected (Singh et al., 2017) and becomes one of the major limiting factors for crop production (Sade et al., 2016). In this study, acacia WB addition at higher rates (10 and 20 t ha^{-1}) raised the pH of the soil above the threshold level to ameliorate Al^{3+} toxicity (Lin et al., 2018). Biochar amendment can decrease the contents of exchangeable Al^{3+} in acidic soils through complexation (Butnan et al., 2015;

Haynes & Mokolobate, 2001). Overall, the increased soil pH coupled with the decline in exchangeable Al^{3+} suggests the potential of acacia WB addition to soil fertility restoration in highly weathered, acidic soils widespread in Ethiopia and elsewhere (Abate et al., 2017; Agegnehu et al., 2021; Thomaz, 2017; Zhu et al., 2014).

In acidic soil, the availability of P in the soil solution is reduced through the formation of insoluble Al phosphates (Glaser et al., 2002; Weil & Brady, 2017). Consistent with previous reports (Dume et al., 2017; Glaser & Lehr, 2019; Yamato et al., 2006), acacia WB addition substantially increased the contents of P_{av} in the soil. The increase in P_{av} contents in the soil could be associated with the reduction in soil acidity and the addition from the biochar itself. The changes in P_{av} contents had strong relationships with soil pH and exchangeable Al^{3+} (Figure 5.3). After an incubation period of two months, Dume et al. (2017) observed an increase in P_{av} in acidic soil through the application of biochar that was closely related to an increase in pH and a reduction in exchangeable Al^{3+}. Chintala et al. (2014) reported a reduction of P sorption onto Fe and Al oxides following the increase in soil pH by the biochar application to acidic soils. Meanwhile, the biochar itself can supply P in soil (Zhou et al., 2020). Acacia WB had a relatively high amount of P_{av} (Table 5.1) that can be returned to the soil by biochar addition. The greater effects of acacia WB addition on P_{av} than the effects on improving soil pH (Fig.5.1) suggest the direct supply of P to the soil from the biochar.

Compared to the control treatment, a single addition of acacia WB at 10 and 20 t ha^{-1} resulted in a marked increase of SOC contents that ranged between 64 and 93% for the first two cropping seasons. The results are consistent with the earlier studies that showed an increase in SOC contents in biochar-amended soils (Amare et al., 2022; Liu et al., 2019). Tazebew et al. (2024) noted an increase of SOC by 61 – 127% through a single amendment of biochar derived from *A. decurrens*. Acacia WB produced as a by-product during charcoal production was found to raise the levels of SOC at kiln sites by 48% (Kim et al., 2022). Zhang et al. (2019) reported an increase in SOC by 60 – 250% following wheat straw biochar addition. The observed increase of SOC content could be attributed to the high carbon content of biochar, which is recalcitrant to biodegradation (Lorenz & Lal, 2014; Wang et al., 2016). The increased SOC content can also be resulted from the retarded native soil organic matter decomposition (Wang et al., 2016) and

enhanced crop performance in biochar-amended soils that might have increased organic matter return to soil (Cai et al., 2019). The results demonstrate that the recalcitrant carbon following acacia WB amendment could be sequestered in the soil, and hence the carbon content remains high compared to unamended soil, thereby contributing to improved soil fertility and more stable carbon storage in agricultural systems.

Biochar application at 10 and 20 t ha^{-1} significantly increased TN contents that were sustained over two cropping seasons. The observed increase in TN could be associated with the addition from the biochar itself (Phares et al., 2020; Purakayastha et al., 2019). Acacia WB had the TN content of 0.66% which is much higher than in the soil (Table 5.1). In addition, biochar addition might improve nitrogen utilization by plants (Xia et al., 2020). We observed a significant increase in leaf chlorophyll content in barley crop grown in acacia WB-amended soil (Table 5.3), suggesting increased uptake of nitrogen from the soil (Bista et al., 2019). Agegnehu et al. (2015) observed an increase in leaf chlorophyll content under biochar addition that was significantly correlated with soil and plant contents of nitrogen.

5.4.3 Effects of *A. decurrens* wood biochar on crop performance

In acidic tropical soils, crop production is limited by low soil fertility, and biochar is added into the soil with the objective primarily to increase the fertility of soils and thereby to enhance crop performance. This study showed that crop performance was affected by biochar addition in a *teff*-barley rotation system throughout a two-year field study. Acacia WB addition on a degraded acidic agricultural soil considerably reduced soil acidity and increased soil nutrient contents (Figures 5.1 and 5.2). Consequently, plant height, chlorophyll content, aboveground biomass and grain yields have increased significantly (Table 5.3). Biochar addition to the soil at higher application rates (10 and 20 t ha^{-1}) promoted performance of *teff* and barley ranging from 56 to 128% based on either aboveground biomass yield or grain yield. The result of yield increment for *teff* and barley by acacia WB amendment is greater compared to meta-analysis for biochar that can enhance crop yield by 17% (Singh et al., 2022) and 25% (Jeffery et al., 2017), but

lies within the review for biochar that can increase crop performance in acid soils that ranged between 28% and 363% (Yu et al., 2019).

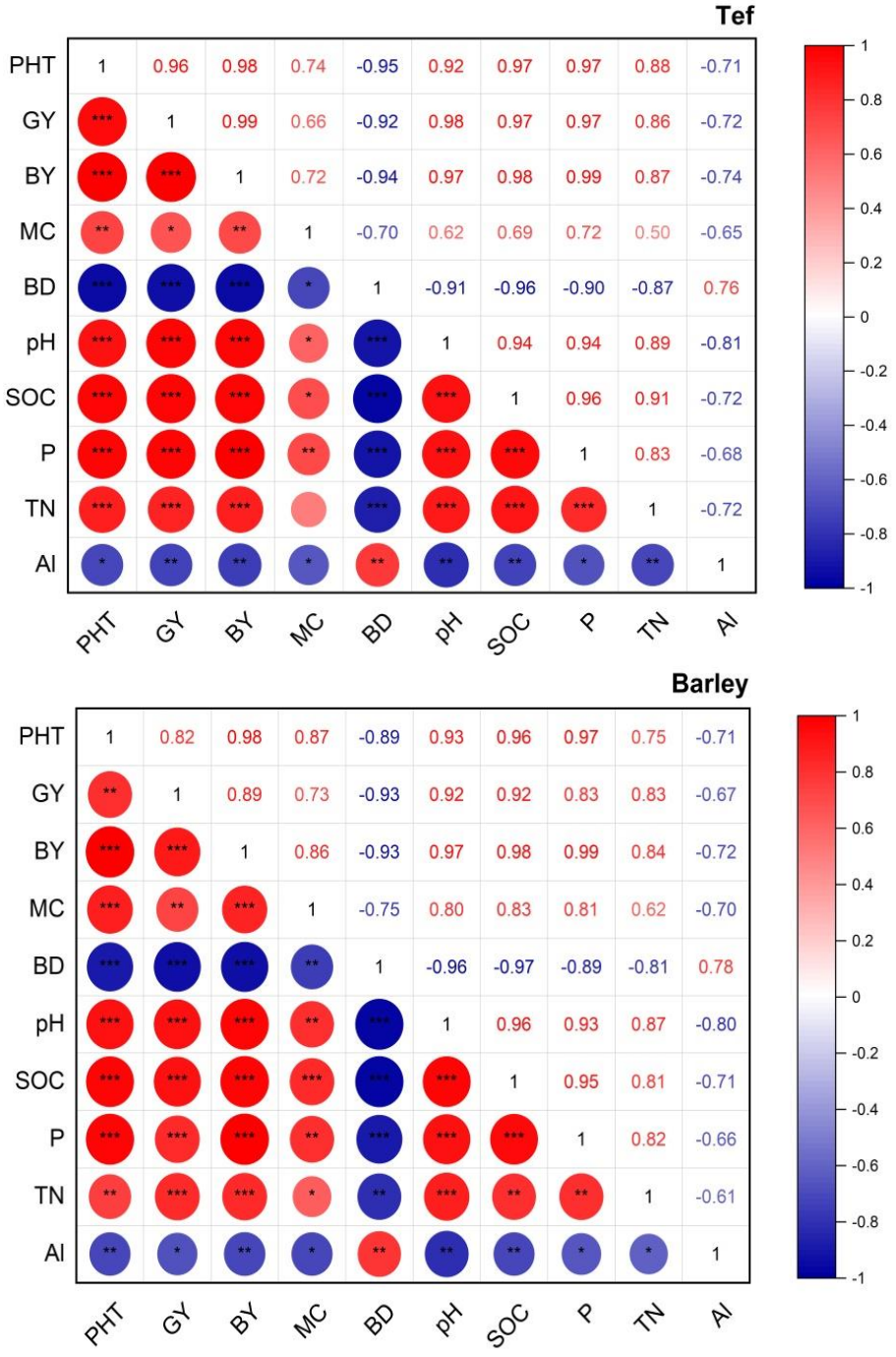

Figure 5.3 Pearson correlation heatmap of *teff* and barley performance with soil properties and among soil properties. Correlation is significant at $*p < 0.05$, $**p < 0.01$ and $***p < 0.001$. BD, bulk density; MC, moisture content; GY, grain yield; TB, total aboveground biomass; PHT, plant height; SOC, soil organic carbon; AP, available phosphorus; TN, total nitrogen, Al, exchangeable Al^{3+}

There were differences in the response of crop performance to the various biochar application rates. For both crops over two successive seasons, a larger biochar rate resulted in a greater increase in plant height, biomass yield, grain yield and leaf chlorophyll content. Previous studies have shown greater effects of biochar on crop responses with increased application rates (Cornelissen et al., 2013; Manickam et al., 2015; Zhang et al., 2019). Interestingly, acacia WB addition at 20 t ha^{-1} resulted in a grain yield increase over the average national yield by 56 % for *teff* from 2001-2017 (Cochrane & Bekele, 2018) but similar to that in 2020 (CSA, 2021) and 115 and 125% for barley in 2018 (CSA, 2019) and 2020 (CSA, 2021), respctively. Increased crop performance of the soil from biochar addition is strongly related to the reduction in soil acidity and improved nutrient contents (Figure 5.3). The positive effects of biochar on crop performance in both cropping seasons imply that the agricultural benefits of adding acacia WB on a degraded acidic agricultural soil are sustained with time. The results are in line with earlier reports indicating a beneficial effect of biochar amendment on crop performance that can persist for two cropping seasons (Cornelissen et al., 2018; Manickam et al., 2015) or multiple seasons (Cornelissen et al., 2018; Kätterer et al., 2019). The results showed the crop yield benefits of a single addition of acacia WB that might extend even beyond two or more cropping seasons. Crop yield benefits at least for two successive years in biochar-amended treatments are indicative of the advantage of acacia WB amendment over the existing farming practice, where only one crop harvest in two years is possible due to severe land degradation.

5.5 Conclusion

We evaluated the changes in soil properties and crop performance at different rates of *A. decurrens* wood biochar addition over two cropping seasons under *teff*-barley rotation in the field conditions. The results showed that biochar amendment consistently increased soil pH, moisture content, SOC, P_{av} and TN, but decreased soil bulk density and exchangeable Al^{3+} and, thus, positively influenced the performance of *teff* and barley. Biochar effects on soil properties and crop performance were greater at higher application rates that persisted for two cropping seasons. The positive effects observed after two

growing seasons at application rates of either 10 or 20 t ha^{-1} suggest that crop production over multiple seasons or higher application rates of acacia wood biochar may be possible. Overall, the acacia wood biochar addition significantly improved soil properties and crop growth and yield. Further study on acacia wood biochar addition at higher rates and the residual effects over multiple seasons and locations is required. Moreover, biochar application in combination with different fertilization rates is also required to assess the potential for *A. decurrens* wood biochar to improve nutrient management.

CHAPTER 6: BIOMASS AND SOIL CARBON STOCKS OF *ACACIA DECURRENS* AND *EUCALYPTUS CAMALDULENSIS* WOODLOT SYSTEMS IN THE HIGHLANDS OF NORTHWESTERN ETHIOPIA[4]

Abstract

Short-rotation woodlots in agroforestry systems can influence carbon storage in degraded agricultural lands. In recent decades, the conversion of degraded agricultural lands into short-rotation woodlots has been widely undertaken to restore soil qualities and for a greater economic benefit in the highlands of Northwestern Ethiopia. However, information on the carbon storage of degraded agricultural lands following the establishment of woodlots of fast-growing tree species remains largely unexplored. In this study, therefore, we examined the carbon storage of five-year-old *Acacia decurrens* and *Eucalyptus camaldulensis* woodlots established on degraded acidic agricultural soil in an agroforestry system. Biomass carbon stock was calculated using allometric equations, and SOC stock was determined at two depths (0–20 and 20–40 cm). Woodlots increased the SOC stock of degraded agricultural land by 59% at 0 – 40 cm depth. The accumulation of SOC was higher in *A. decurrens* woodlot (138 t ha^{-1}) than in *E. camaldulensis* woodlot (120 t ha^{-1}) and generally becomes lower in the subsurface soils by 21 – 27%. Biomass carbon was also greater in the *A. decurrens* (123 t ha^{-1}) than in *E. camaldulensis* woodlots (57 t ha^{-1}). The results showed higher carbon storage in woodlots of *A. decurrens* than *E. camaldulensis*. The marked increases in carbon stock by *A. decurrens* and *E. camaldulensis* woodlots demonstrate the potential of establishing woodlot systems with fast-growing tree species on degraded agricultural lands in mitigating climate change through enhanced carbon storage.

***Keywords*:** Agroforestry system, biomass production, carbon storage, short-rotation woodlots

[4] Tadele, D., Adgo, E., & Meshesha, D. T. (2025). Biomass and soil carbon stocks of *Acacia decurrens* and *Eucalypts camaldulensis* woodlot systems in the highlands of Northwestern Ethiopia**.** Manuscript prepared for submission to a journal.

6.1 Introduction

In Ethiopia, the dwindling forest cover, coupled with increasing demand from the rapidly growing human population has created a large gap between demand and supply of forest resources, leading to the expansion of forest plantations of fast-growing tree species (Bayle, 2019; FAO, 2020). And forest plantations, which consist of tree species mainly from the genera *Eucalyptus*, *Cupressus*, *Pinus* and *Acacia*, can provide alternative forest resources, and thus help reduce the pressure on the remaining patches of natural forests (Gizachew, 2017; Pohjonen & Pukkala, 1990; Zerga et al., 2021). Previously, degraded farmlands were converted into large forest plantations (Pohjonen & Pukkala, 1990). Nowadays, the establishment of short-rotation woodlots on farmlands has become a common practice in the highlands of Ethiopia (Abiyu et al., 2016; Debie, 2024; Worku et al., 2021; Yirga et al., 2024). Increased economic benefits primarily from wood production and low yield of annual crops are the major driving factors for the conversion of farmlands into woodlot systems in the Ethiopian highlands (Alemayehu & Melka, 2022; Debie, 2024; Nigussie et al., 2020, 2021).

Short-rotation tree plantations consisting of fast-growing species can fix large amounts of carbon over a short period, and thus can play a significant role as a potential source of carbon sink (Dessie et al., 2022; Semere et al., 2024; Singh et al., 2019). In the Fagita Lekoma district of Northwestern Ethiopia, the study area, *Acacia decurrens* and *Eucalyptus camaldulensis* are the most commonly planted fast-growing tree species in smallholder farmlands as a woodlot system (Alemayehu et al., 2024; Wondie & Mekuria, 2018; Worku et al., 2021). *A. decurrens* woodlots are established on farmlands for wood production and soil fertility restoration and typically maintained for five years, whereas *E. camaldulensis* woodlots are cultivated for wood production and maintained for 5 – 7 years. *A. decurrens* is replanted after harvest, while *E. camaldulensis* stand is used for several rotations through coppicing.

The conversion of farmlands into short-rotation woodlots is on the increase in the highlands of Ethiopia (Alemayehu et al., 2024; Worku et al., 2021). As a fast-growing tree species, integrating *A. decurrens* and *E. camaldulensis* in the farming system can contribute to increased carbon storage (Singh et al., 2019). There exists, however, limited

information in relation to the effects of short-rotation woodlots of *A. decurrens* and *E. camaldulensis* on carbon storage in agroforestry systems. In this study, therefore, we assessed the impact of land use change from agricultural land into a short-rotation woodlot system on organic carbon storage in the biomass and soil up to 0.4 m depth under the local farmers' management practices. We hypothesized that: (i) SOC storage on degraded agricultural land can be boosted through the establishment of short-rotation woodlots using fast-growing tree species, and (ii) there would be a greater storage of organic carbon in woodlots of tree species under *A. decurrens* than under *E. camaldulensis*. The information generated from this study could be important in the management of tree plantations cultivated on degraded agricultural lands in short rotation for addressing issues of agricultural sustainability and climate change mitigation through increased carbon storage.

6.2 Materials and Methods

6.2.1 Study area description

The study was conducted in Amesha Shinkuri kebele (the smallest administrative unit in Ethiopia) of Fagita Lekoma district, Amhara region, Northwestern Ethiopia (Figure 6.1). The altitude in the kebele ranges between 2342 and 2676 m above sea level. Based on the climatic records from 2000 to 2022 at the nearest station in Addis Kidam town, the kebele had a mean annual rainfall of 1420 mm and a mean monthly temperature of 24.5 ^{o}C (Figure 6.2). The soil type in the sampling plots is Luvisols. Agroforestry systems consisting of woodlots of *A. decurrens* and *E. camaldulensis* and cropland are the dominant land use systems in the agricultural landscape in the study area. The land use systems had a similar textural class (loam). A description of site-specific soil properties and previous land use history of the land use systems is summarized in Table 6.1. The mixed crop-livestock farming system is the main livelihood of the people in the kebele. The major crops cultivated include *teff* (*Eragrostis tef*), finger millet (*Eleusine coracana*) and maize (*Zea mays*).

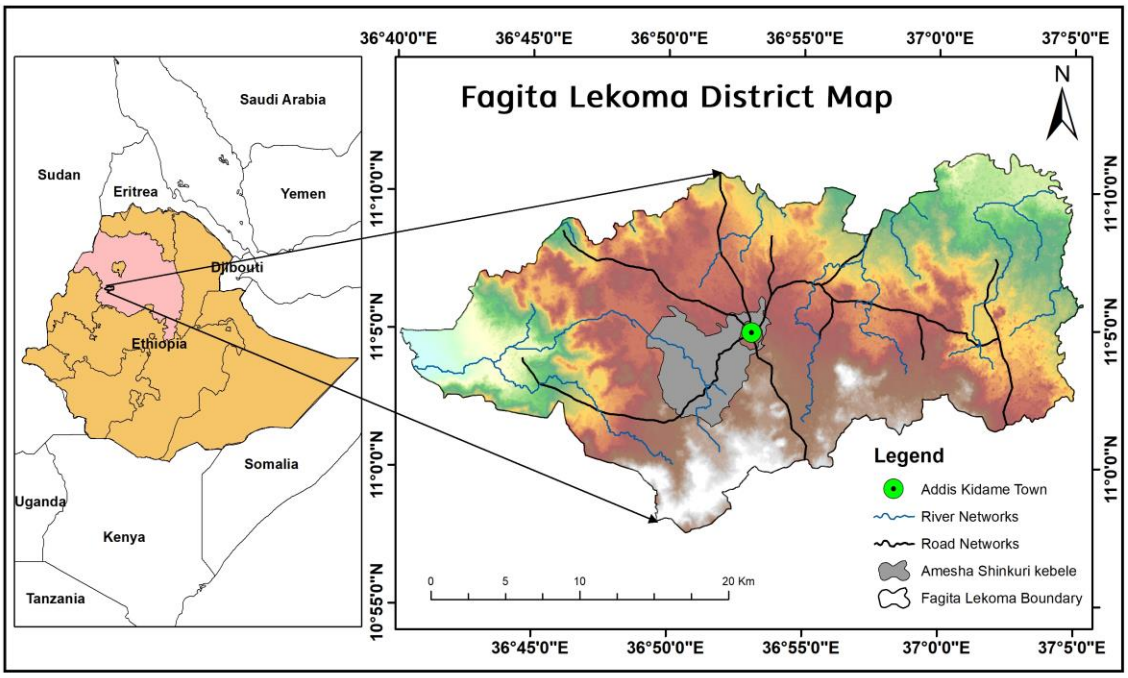

Figure 6.1 Map of the study area

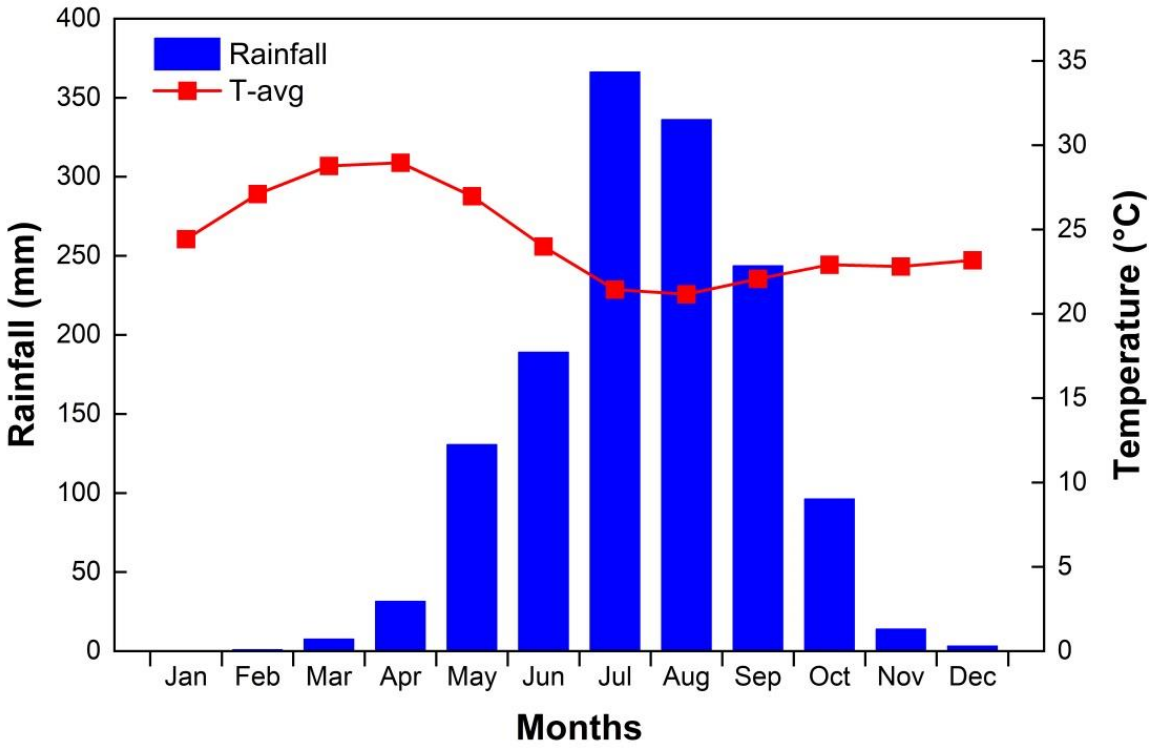

Figure 6.2 Mean monthly rainfall and temperature records of the study area from 2000 to 2022

6.2.2 Description of *A. decurrens* and *E. camaldulensis* woodlot systems

The practice of growing fast-growing tree species in short-rotation woodlot systems on farmlands by smallholder farmers is an emerging land use change in the Fagita Lekoma district, Northwestern Ethiopia. *A. decurrens* and *E. camaldulensis* dominate the woodlot system and the establishment of woodlots is on the increase on agricultural land as a coping mechanism for the exhausted agricultural land and following increased economic benefits. Farmers integrate *A. decurrens* in the cropping system by intercropping acacia seedlings with annual crops during the first year of woodlot establishment. Since most farmers have practiced planting *A. decurrens* adjacent to each other, the *A. decurrens* woodlot system in the Fagita Lekoma district gradually becomes a large-scale plantation. Once planted *A. decurrens* stands are protected from disturbances by grazing through wood fencing. Farmers collect fodder grass till the stand canopy cover gets closed. At the age of five years, the farmers harvest *A. decurrens* stands by clear-cutting. Immediately after tree harvesting, the next rotation will continue by intercropping annual crops with acacia seedlings in the rainy season. Unlike the way *A. decurrens* woodlot was established, *E. camaldulensis* seedlings were planted in monoculture with no intercropping. The *Eucalyptus* plants were protected from grazing during the first two years, but then they were exposed to grazing impacts. Farmers harvest *Eucalyptus* stands at an average age of 5 – 7 years and multiple harvests are possible through coppicing. In other words, *E. camaldulensis* is established on former croplands in a permanent woodlot while *A. decurrens* is replanted in rotation with annual crops.

Table 6.1 Description of the major land use systems in the agricultural landscape in the study area

Characteristics	*A. decurrens* woodlot	*E. camaldulensis* woodlot	Cropland
Previous history	Established on former cropland	Established on former cropland	Mono-cropped for a long time
Stand age (years)	Five	Five	
Rotation cycle (number)	First	First	
Soil bulk density (g cm^{-3})	1.01	1.05	1.09
Soil texture			
Sand (%)	36	44	34
Silt (%)	40	34	42
Clay (%)	24	22	24
Textural class	Loam	Loam	Loam
Soil pH (H_2O)	5.32	5.52	5.43
Soil organic carbon (%)	3.64	3.21	2.16

Soil sampling depth at 0 – 20 cm

6.2.3 Woodlot sampling and tree biomass measurements

Acacia and *Eucalyptus* woodlot systems (Figure S6.1) are widespread in the agricultural landscape in Amesha Shinkuri kebele of Fagita Lekoma district. *A. decurrens* is the predominant species followed by *E. camaldulensis*. We sampled a total of eight woodlots of *A. decurrens* and *E. camaldulensis*, each with four replications. All the sampled woodlots were at the age of five years and in the first rotation cycle. *A. decurrens* seedlings were planted at a spacing of 0.50 m by 0.75 m, whereas *E. camaldulensis* seedlings were cultivated at a relatively wider spacing of 1.0 m by 1.0 m. The sampled woodlots generally had a size of less than 0.5 ha. Moreover, the sampling sites had similar site conditions. The woodlots were located close to each other and in similar topographic positions, soil conditions and land management history (established on farmlands formerly used for annual crop production). We sampled woodlots if they occurred near croplands which were used as references for the analysis of soil physicochemical properties and SOC stocks.

A plot of size 5 m x 10 m was established at the center of each sampled woodlot to estimate the growth of tree species. In each plot, the height and diameter at breast height (DBH) of all trees were measured. The height and DBH measurements were then

incorporated into the allometric equations to estimate the total dry tree biomass and the associated organic carbon accumulation of the planted species under the woodlot system. Aboveground biomass (AGB) of *A. decurrens* (Equation 1) was estimated using the allometric model developed for *Acacia mearnsii* (Tandon et al., 1989). For *E. camaldulensis*, a specific allometric model developed by Kuyah et al. (2013) was used for aboveground biomass estimation (Equation 2).

$$AGB = 3.1582 + 0.0337D^2 \times H \quad \ldots\ldots\ldots\

soil bulk density determination. Bulk density was determined after the soil core samples were oven-dried at 105 ^{0}C for 24 h. The collected soil samples were air-dried, ground and then sieved using a 2 mm sieve. Soil pH was measured using a digital pH meter in 1: 2.5 soil-to-water suspension and texture using the hydrometric method. SOC was analyzed following the Walkley and Black oxidation method (Walkley & Black, 1934). SOC stocks (Equation 5) in the woodlot systems and cropland were determined following Pearson et al. (2007).

$$\text{SOC stock} = \%\text{SOC} * \text{BD} * \text{D} * 100 \quad (5)$$

Where SOC stock is soil organic carbon stock in t ha^{-1}, %SOC is soil organic carbon content, BD is the bulk density in t m^{-3} and D is the sampling depth in m.

6.2.5 Statistical analysis

Two-way ANOVA was employed to analyze soil bulk density, SOC concentration and SOC stock among three land use systems at two soil depths. Multiple comparisons of means were performed using Tukey's HSD test at 1% and 5 % levels of significance. Variations in planting density, growth and carbon storage between *A. decurrens* and *E. camaldulensis* woodlot systems were compared using a t-test. Correlation analysis and linear regression were also used to show relationships between biomass production and carbon storage with tree growth parameters in a woodlot system.

6.3 Results

6.3.1 Soil bulk density and SOC concentrations among the woodlot systems and cropland

The results showed that soil bulk density was not affected by soil depth; however, the bulk density values were slightly higher at the lower soil depth (Table 6.2). Bulk density was generally higher in the cropland than in the woodlot system with a significant difference observed only between the cropland and *A. decurrens* woodlot. The observed

relatively higher bulk density in croplands may be due to variations in soil management practices and less organic matter inputs in the croplands than the woodlot systems with more vegetation, resulting in an increase in soil bulk density. In the top 40 cm soil depth, *A. decurrens* woodlots had the highest carbon concentrations (3.4%) followed by *E. camaldulensis* woodlots (2.85%) and croplands (1.85%). Across all the land uses, carbon concentrations tended to be higher in the surface soils than in the subsurface soils. Soil OC contents averaged 3.88 and 2.91% in *A. decurrens* woodlot, 3.33 and 2.38% in *E. camaldulensis* woodlot and 2.13 and 1.57% in the cropland at 0 – 20 and 20 – 40 cm soil depths, respectively.

Table 6.2 Effects of cropland conversion into woodlot systems on soil bulk density and SOC contents

Treatment	Bulk density (g cm^3)	SOC (%)
Soil depth (cm)		
0 - 20	1.04 ± 0.02	3.11 ± 0.24a
20 - 40	1.08 ± 0.02	2.29 ± 0.17b
Land use systems		
Cropland	1.10 ± 0.02a	1.85 ± 0.11c
A. decurrens	1.02 ± 0.02b	3.40 ± 0.22a
E. camaldulensis	1.07 ± 0.02ab	2.85 ± 0.20b
ANOVA (*p*-value)		
Depth	0.068^{ns}	< 0.001
Land use	0.023	< 0.001
Interactions	0.759^{ns}	0.293^{ns}
CV (%)	4.55	10.6

ns, non-significant; mean values followed by different small letter (s) in a column are significantly different ($p < 0.05$) for each parameter.

6.3.2 Characteristics of *A. decurrens* and *E. camaldulensis* woodlot systems

Stand characteristics of the woodlot systems in Amesha Shinkuri kebele of Fagita Lekoma district are shown in Table 6.3. The results showed that after five years of establishment, the mean population density and the basal area were significantly ($p < 0.05$) different between the two woodlot systems. *A. decurrens* woodlot had a population density of 8400 trees ha^{-1} and a basal area of 39.3 m^2 ha^{-1}, higher than the population

density (6900 trees ha^{-1}) and the basal area (29.6 m^2 ha^{-1}) of *E. camaldulensis* woodlot. AGB was significantly higher ($p < 0.05$) in *A. decurrens* woodlot (225 t ha^{-1}) than in *E. camaldulensis* woodlot (91 t ha^{-1}). However, plant height, DBH and BGB did not differ ($p > 0.05$) between the two woodlot systems. Despite the higher AGB, the BGB of *A. decurrens* was less due to its shallow lateral root system (Shumie et al., 2022). Dry biomass production of both species, under the woodlot system and the existing farmers' management practices, had a positive correlation with plant height, DBH and basal area (Figure 6.3).

Table 6.3 Characteristics of sampled *A. decurrens* and *E. camaldulensis* woodlots in Amesha Shinkuri kebele of Fagita Lekoma district, Northwestern Ethiopia

Tree species	Density (tree ha^{-1})	Height (m)	DBH (cm)	BA (m^2 ha^{-1})	AGB (t ha^{-1})	BGB (t ha^{-1})	TB (t ha^{-1})
A. decurrens	8400a	10.93	7.59	39.3a	225a	21	246a
E. camaldulensis	6900b	10.53	7.56	29.6b	91b	29	120b
t statistics	5	1.05	2.21	2.73	4.63	0.17	4.35
P-value	0.015	ns	ns	0.027	0.019	ns	0.022

DBH, diameter at breast height (1.3 m); BA, basal area = л (DBH/2)^2; AGB, aboveground biomass yield; BGB, belowground biomass; TB, total biomass. Values followed by different letters in a column are significantly different at $p < 0.05$.

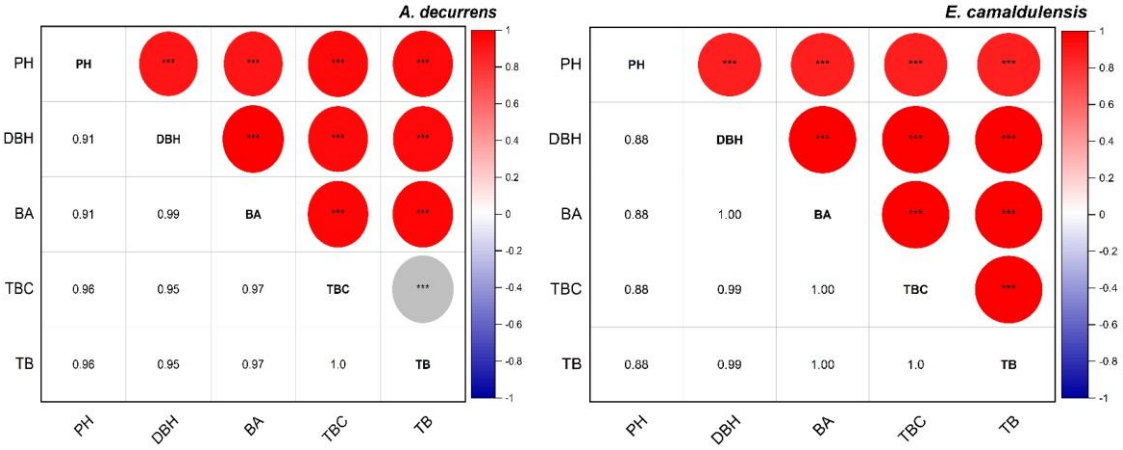

Figure 6.3 Pearson correlation heatmap of growth and biomass carbon accumulation of *A. decurrens* and *E. camaldulensis* trees in a woodlot system. Correlation is significant at *$p < 0.001$; PH, plant height; DBH, diameter at breast height; BA, basal area; TBC, total biomass carbon; TB, total biomass.

6.3.3 Soil carbon stocks in the woodlot systems and cropland

Soil organic carbon stocks to a depth of 0 – 40 cm exhibited significant differences ($p < 0.05$) across the land uses that ranged 81 – 138 t ha^{-1}. The lowest SOC stock was found in the cropland (Figure 6.4). Compared to the cropland, SOC stock was increased by 70% in the *A. decurrens* woodlot system and 48% in the *E. camaldulensis* woodlot system. In the woodlot systems, SOC stocks in the surface soils were higher than those in the subsurface soils. Of the total SOC stock (0–40 cm), the surface soil (0–20 cm) across the land uses contributed, on average, 56 – 58%. Soil OC stock had strong positive relationships with basal area, planting density and biomass production of tree species in the woodlot system (Figure 6. 5).

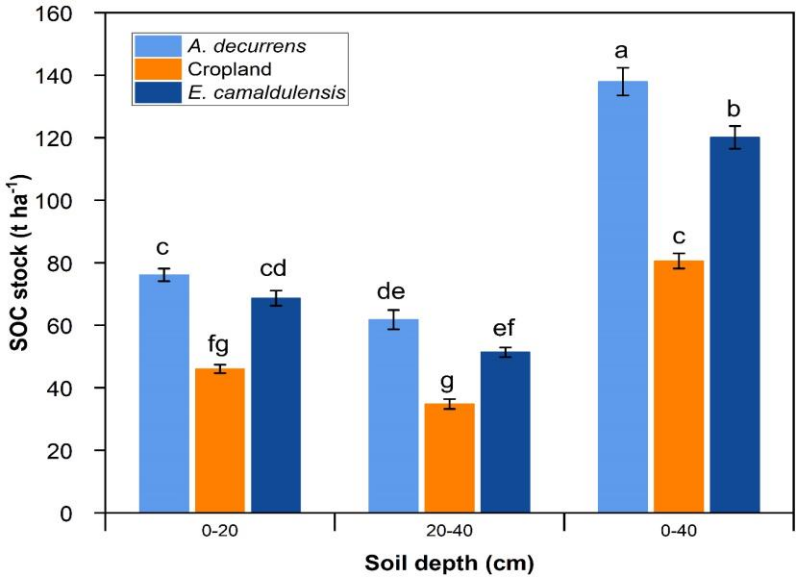

Figure 6.4 Soil carbon stocks among the three land uses at two soil depths. Values followed by a different letter(s) are significantly different at $p < 0.05$.

6.3.4 Biomass carbon and total carbon stocks in the woodlot systems

The biomass carbon stock significantly ($p < 0.01$) varied between *A. decurrens* and *E. camaldulensis* woodlots (Table 6.4). The mean total biomass carbon stock was 123 t ha^{-1} in *A. decurrens* woodlot and 57 t ha^{-1} in *E. camaldulensis* woodlot. The greater biomass carbon stock in *A. decurrens* woodlot is due to its higher productivity (Table 6.3).

Biomass carbon had a significant positive correlation with total biomass production as shown in Figure 6.3. Similarly, the total carbon stock (biomass carbon stock + SOC stock) was also significantly higher in *A. decurrens* woodlot (261 t ha^{-1}) than in *E. camaldulensis* woodlot (177 t ha^{-1}).

Table 6.4 Biomass carbon and total carbon stocks (t ha^{-1}) in *A. decurrens* and *E. camaldulensis* woodlot systems

Tree species	AGBC	BGBC	TBC	SOC	TC
A. decurrens	113 ± 13a*	10 ± 6.8	123 ± 14a*	138 ± 21a	261 ± 24a*
E. camaldulensis	43 ± 8b	14 ± 3	57 ± 13b	120 ± 11b	177 ± 15b
t statistics	4.76	0.677	4.50	9.88	5.33
P-value	0.018	ns	0.0205	0.0022	0.013

AGBC, aboveground biomass carbon stock; BGBC, belowground biomass carbon stock; TBC, total biomass carbon stock (AGBC + BGBC); SOC, soil organic carbon stock (0 – 40 cm); TC, total carbon stock (TBC + SOC). Values followed by different letters in a column are significantly different at $p < 0.05$; *significant at $p < 0.01$.

6.4 Discussion

6.4.1 Soil organic carbon contents in woodlot systems and the cropland

The results indicated that SOC contents were higher in woodlots than in the cropland, consistent with prior reports of higher SOC contents in agroforestry systems than in mono-cropping systems (Maharjan et al., 2024; Shi et al., 2018). Enhanced accumulation of SOC has been reported on degraded lands planted with *Acacia* and *Eucalyptus* species (Amare et al., 2022; Haile et al., 2022; Kimaro et al., 2011). A meta-analysis on the effect of agroforestry on SOC revealed an elevation of SOC content up to 21% in comparison to mono-cropping systems (Muchane et al., 2020). The observed large increase of SOC in the woodlots could be a result of high organic matter inputs, reduced disturbance and soil erosion (Kim et al., 2022; Muchane et al., 2020; Shi et al., 2018). The contents of SOC also varied between the woodlot systems. We found that degraded agricultural land planted with *A. decurrens* had higher SOC content than with *E. camaldulensis*. A study by Dessie et al. (2022) showed higher SOC contents in plantations of *A. decurrens* (4.1%) than in *E. globulus* (3.5%). As a nitrogen-fixing species, there would be a greater accumulation of carbon in *A. decurrens woodlots* compared to *E. camaldulensis* woodlots

(Forrester et al., 2013; Marone et al., 2016). In addition, the contents of SOC were higher in the topsoil than in the subsurface possibly due to reduced organic inputs at the lower soil depth (Osei et al., 2018; Yimam et al., 2024).

6.4.2 Carbon stocks in soils of woodlot systems and cropland

The results revealed that the conversion of degraded agricultural land into a short-rotation woodlot system enhanced SOC stock. After five years of stand establishment, SOC stock to a depth of 40 cm was increased by 48% in *E. camaldulensis* woodlot and 70% in *A. decurrens* woodlot compared to the cropland under continuous cultivation for cereal production. The increase in SOC stock was higher than the reported global meta-analyses of a 10 – 40% increase in SOC stock after the conversion of croplands into agroforestry systems (Feliciano et al., 2018; Muchane et al., 2020). SOC stock was increased at a rate of 11.4 t ha^{-1} yr^{-1} in *A. decurrens* woodlot and 7.8 t ha^{-1} yr^{-1} in *E. camaldulensis* woodlot. Corbeels et al. (2019) reported SOC sequestration up to 14 t ha^{-1} yr^{-1} at 0 – 100 cm soil depth under agroforestry systems in Sub-Saharan Africa.

Lower contents of SOC storage have been reported in soils of continuously cultivated croplands than in short-rotation woodlot systems in Ethiopia (Amare et al., 2022; Haile et al., 2022) and Tanzania (Kimaro et al., 2011). Soil organic carbon stocks in *A. decurrens* (138 t ha^{-1}) and *E. camaldulensis* (120 t ha^{-1}) woodlots are similar to those reported for the woodlots (123 t ha^{-1}) in South Ethiopia (Tadesse & Negash, 2023). The levels of SOC stock in this study fall within the ranges of SOC stock across the globe (30 – 300 t ha^{-1}) and in Ethiopia (49 – 256 t ha^{-1}) under agroforestry systems (Gebeyehu et al., 2017; Nair et al., 2010). The woodlot systems in this study also enriched the SOC close to the reported mean value (149 t ha^{-1}) for five dry Afromontane forests of Awi Administrative Zone, Northwestern Ethiopia (Gebeyehu et al., 2019), reflecting the potential of the planted woodlots on degraded agricultural lands to reclaim SOC to the levels under the natural forests. Increased SOC stocks in the soils of planted woodlot systems can be attributed to reduced tillage operations, organic matter addition through litterfall and root turnover, reduced erosion and atmospheric nitrogen fixation (Kuyah et al., 2019; Marone et al., 2016; Muchane et al., 2020; Shi et al., 2018). Trees fix carbon

from the atmosphere through the process of photosynthesis and increase SOC by transferring this carbon to the soil via litterfall and root decay. Whereas, in soils of cereal-based cropping systems, removal of crop residue, reduced or absence of tree cover, erosion and soil disturbance by the frequent tillage resulted in a reduction of carbon storage (Haileslassie et al., 2005; Ketema & Yimer, 2014; Muchane et al., 2020).

We observed that SOC stocks were higher in the surface soils than in the subsurface soils (Figure 6.4). Reduced carbon contents with increases in soil depth in plantations of fast-growing tree species are reported (Perera & Ratnayake, 2023; Yimam et al., 2024; Zhang et al., 2018). The meta-analysis results by Shi et al. (2013) revealed a decrease in SOC accumulation with increasing soil depth after afforestation of agricultural soils. The buildup of organic matter through increased inputs from litterfall could contribute to a greater SOC accumulation in the surface soils (Guo & Gifford, 2002; Osei et al., 2018).

6.4.3 Carbon stocks in *A. decurrens* and *E. camaldulensis* woodlot systems

After five years of establishment on degraded agricultural land, SOC stock in the top 40 cm soil depth was higher in woodlots consisting *A. decurrens* trees (138 t ha^{-1}) than *E. camaldulensis* trees (120 t ha^{-1}). Consistent with our results, Dessie et al. (2022) observed greater carbon storage in the topsoil under the stands of *A. decurrens* than under *E. globulus* in the highlands of Ethiopia. Since the two woodlot systems had similar soil texture and bulk density (Tables 6.1 and 6. 2), the higher SOC stock in *A. decurrens* woodlot can be explained by the significantly higher SOC content (Gebremeskel et al., 2021). The accumulation of carbon in the biomass was also higher in the woodlot of *A. decurrens* (123 t ha^{-1}) than in *E. camaldulensis* (47 t ha^{-1}). The results further showed that the effect of the woodlot system to enhance carbon stock was greater in the biomass (57 – 123 t ha^{-1}) than in the soil (39 – 57 t ha^{-1}), presumably due to more time needed for the carbon accumulation in soil than in the plant biomass (Manaye et al., 2019). The mean total carbon (soil + biomass) storage in the woodlot system in this study (219 t ha^{-1}) is higher than that reported for the woodlots (134 t ha^{-1}) in the Amhara Region of northern Ethiopia (Getnet et al., 2023), but less than that reported for the woodlots (297 t ha^{-1}) in

South Ethiopia (Tadesse & Negash, 2023). The woodlot systems accumulated greater carbon both in the biomass (90 t ha^{-1}) and in the soil (129 t ha^{-1}) than agroforestry systems in East Africa, 24.2 t ha^{-1} in biomass and 98.8 t ha^{-1} in the soil (Muthuri et al., 2023). The SOC storage in the woodlot systems (129 t ha^{-1}) is comparable to that reported for woodlots consisting of *Leucaena* spp. in Zambia which stored SOC up to 140 t ha^{-1} (Kaonga & Bayliss-Smith, 2009). SOC accumulation in agroforestry systems can be influenced by various factors such as stand density, planted species, age, soil, and climatic conditions (Gebremeskel et al., 2021; Mayer et al., 2020; Yimam et al., 2024).

The variations in carbon storage by the *A. decurrens* and *E. camaldulensis* woodlots could be due to their differences in biomass production. Higher biomass production in *A. decurrens* woodlot may lead to an increase in soil carbon input (Forrester et al., 2013; Zhang et al., 2018). In a five-year-old woodlot system, aboveground biomass production significantly differed between the two woodlot species, which averaged 225 t ha^{-1} for *A. decurrens* and 91 t ha^{-1} for *E. camaldulensis* (Table 6.3). At the age of 64 months, Kindu et al. (2006) reported a greater aboveground biomass yield of *A. decurrens* (217.9 t ha^{-1}) than *E. camaldulensis* (126.2 t ha^{-1}). The variation in biomass production between *A. decurrens* and *E. camaldulensis* could arise due to stand density (Table 6.3) and the branchy and leafy nature of *A. decurrens* (Gebremeskel et al., 2021; Kindu et al., 2006; Syano et al., 2023). Carbon storage would likely increase in the *A. decurrens* woodlot with higher stand density. Ferede et al. (2022) have shown increase of biomass production of a five – year – old *A. decurrens* plantation with stand density. Nair et al. (2010) and Gebremeskel et al. (2021) showed that higher stand density of trees in an agroforestry system enhanced carbon storage. We observed a strong positive relationship between SOC and stand density in the woodlot systems (Figure 6.5). In addition, increased nitrogen availability through fixation of atmospheric nitrogen likely favored the growth of *A. decurrens* compared to *E. camaldulensis* (Marone et al., 2016; Zhang et al., 2018) which in turn enhances carbon accretion (Forrester et al., 2013; Mayer et al., 2020). The results highlight the higher potential of *A. decurrens* woodlot for biomass production and carbon storage than *E. camaldulensis* woodlot under the existing smallholder farmers' management practices.

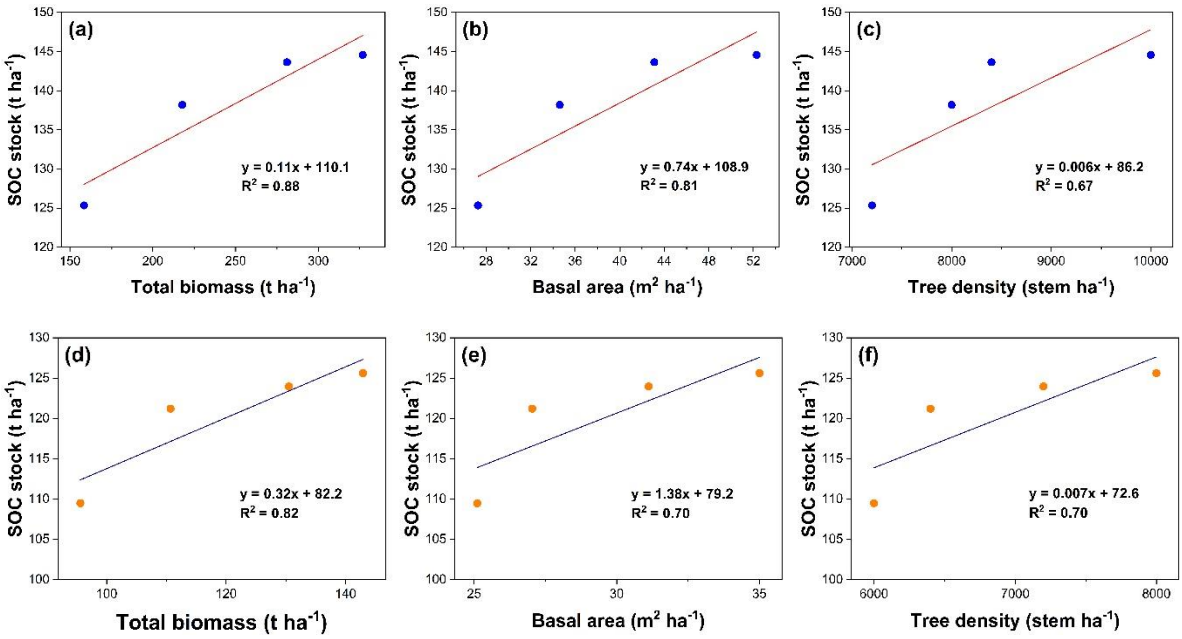

Figure 6.5 Relationships between SOC stock and total biomass, basal area and tree density in *A. decurrens* (a, b & c) and *E. camaldulensis* (d, e & f) woodlot systems

6.5 Conclusion

The carbon storage potential of woodlot systems consisting of *A. decurrens* and *E. camaldulensis* was evaluated in the Fagita Lekoma district of Northwestern Ethiopia. The woodlot systems significantly increased SOC storage in the 0 – 40 cm soil depth of degraded agricultural land. Regardless of the land use systems, SOC storage was higher in the surface soil than in the subsurface soil. Carbon storage in both the soil and biomass was higher under *A. decurrens* woodlot than under *E. camaldulensis* woodlot suggesting greater effectiveness of *A decurrens* in increasing the carbon storage capacity of degraded land under the existing management practices in the study area. Altogether, the establishment of short-rotation woodlots on degraded agricultural land in the highlands of Northwestern Ethiopia appears to have the potential for soil quality improvements and carbon sequestration in a short period. Further study needs to be conducted considering the age of woodlots, repeated rotations and carbon stocks of litterfall and understory vegetation.

CHAPTER 7: SYNTHESIS OF THE RESULTS, GENERAL CONCLUSIONS AND RECOMMENDATIONS

7.1 Synthesis of the Results

Farmers' innovative agricultural practices to address the soil acidity problem and low crop performance

In response to land degradation and the reduction in crop yields, smallholder farmers in the study area have introduced an innovative agricultural practice through the inclusion of *A. decurrens* and charcoal production in the cropping system. Farmers noticed the positive effects of *A. decurrens* trees and charcoal production on soil fertility restoration and the associated yield increase on subsequent crops. As a result, the conversion of croplands into *A. decurrens*-based agroforestry system is expanding and has become an integral part of rural life (Alemayehu et al., 2024; Nigussie et al., 2021). Our results revealed the benefits of farmers' innovative agricultural practices in terms of improving soil fertility and crop performance. The farmers' innovation is of paramount significance compared to correcting soil acidity and nutrient deficiencies through liming and inorganic fertilizer application which are in limited supply and expensive making them beyond the reach of poor farmers. Despite the aforementioned benefits of the new cropping system, the following issues remained still unknown and need to be investigated: (i) *A. decurrens* expansion can affect biodiversity in particular locally adapted grasses and shrubs; (ii) dense *A. decurrens* stands might impact water resources as the transpiration from the tree could deplete ground water and influence irrigation which is the common practice in the area in the dry season; and (iii) since many farmers have been involved in *A. decurrens* planting, monocultured large-scaled plantations of *A. decurrens* are formed, leading to diseases and pest outbreaks.

Soil fertility and crop yield benefits of charcoal production and *A. decurrens* wood biochar

The results showed that *in situ* charcoal production and soil amendment with *A. decurrens* wood biochar are useful in ameliorating soil acidity, restoring soil fertility and improving crop performance. After charcoal production, the remains of finer charcoal materials can be incorporated into the soil at kiln sites and in the surrounding areas resulting in improvements in soil fertility and crop performance of a degraded acidic agricultural land (Amare et al., 2022; Kim et al., 2022). A single addition of acacia wood biochar improved soil properties and crop performance and the residual effect might extend for two or more cropping seasons indicating the advantage of *in situ* charcoal production and soil amendment with acacia wood biochar over the conventional farming practice where only one crop harvest in two years is possible due to severe land degradation. Cropland area was impacted and hence the associated benefits on soil properties and crop performance by charcoal production practice can be increased through spreading charcoal fragments (biochar) beyond kiln sites (Dubiez, et al., 2019) and repeated rotations which increase the density of kiln sites. The results can be used in the management of the new cropping system towards sustainable farming practices.

Soil fertility and crop yield benefits of *A. decurrens*-based fallowing

In the study area, there is a rapid expansion of converting crop fields into an acacia fallow system. However, the sustainability of the fallow system could depend on the degree and duration of soil fertility and crop yield benefits. In this study, positive and significant soil quality and crop performance improvements were observed under the acacia fallow system. The fallow system improved soil chemical properties and *teff* performance in two successive rotations that represent 5 and 10 years of continuous fallow duration and for two subsequent production years. The marked improvements in soil properties and *teff* performance in the fallow system could be associated with the effect of the *A. decurrens* trees, addition of charcoal fragments to the soil amid *in situ* charcoal production from *A. decurrens* wood, farmers' best residue management

practices and a low level of disturbance. In the conventional farming practice, however, disturbance by frequent tillage, crop residue removal and prolonged use and increased application of inorganic fertilizer can deteriorate soil conditions and thereby reduce crop yields (Goulding, 2016; Ketema & Yimer, 2014). The results suggest that fallowing with *A. decurrens* can provide increased economic (Nigussie et al., 2020) and environmental benefits by improving soil properties, increasing crop yields, sustaining two or even three crop harvests between repeated rotations and reducing the need for chemical fertilizer application by half. We can conclude by highlighting the significance of the fallow system to sustainably enhance soil properties and crop performance and the need to plant *A. decurrens* on degraded acidic agricultural lands as a soil ameliorant. However, acacia woodlots could have negative impacts on crop production at adjacent croplands by modifying light conditions. Shading effects extending up to 10 m distance in the crop-woodlot interface contributed to reduced growth and yield of the *teff* crop.

Carbon storage benefits of the short-rotation *A. decurrens* woodlot system

After a five-year growth period, we observed SOC stock of 120 – 138 t ha^{-1} at 0–40 cm soil depth in *A. decurrens and E. camaldulensis* woodlots compared to 81 t ha^{-1} in continuously cultivated cropland. Higher SOC content in the woodlots than in the cropland is consistent with the common observation that agroforestry practices have a positive effect on SOC content than crop monoculture (Muchane et al., 2020; Shi et al., 2018). The loss of SOC in the cropland could be attributed primarily to reduced input of organic matter and increased disturbance by frequent tillage operations (Nair et al., 2010). The results also showed that woodlots of *A. decurrens* had greater effects on organic carbon stocks of a degraded cropland than *E. camaldulensis*, which is in line with the general observation that characteristics of planted species and tree density are known to influence carbon storage. Thus, it appears that *A. decurrens* woodlot provides greater total carbon stock (261 t ha^{-1}) than *E. camaldulensis* woodlot (177 t ha^{-1}). The marked increase in total carbon stock achieved over a short period by the *Acacia and Eucalyptus* woodlots underscored the importance of afforestation of degraded agricultural lands with fast-growing trees in carbon storage in the highlands of Northwestern Ethiopia.

7.2 Conclusions

This study highlights the significance of the inclusion of *A. decurrens* in the cropping system, a new development introduced by the local farmers, on its merits in terms of changes in soil acidity problems, soil fertility, carbon storage and crop performance. The results showed the positive contribution of integrating short rotation *A. decurrens* fallows in the cropping system, *in situ* charcoal production and soil amendment with *A. decurrens* wood biochar as locally available management options for the sustainable use and management of acidic soil in the highlands of Northwestern Ethiopia. The results revealed the benefits of farmers' innovations for agricultural sustainability in degraded agricultural lands. Listed below are the most important conclusions drawn from the results of this study:

In this study, short-term practice of *in situ* charcoal production and application of *A. decurrens* wood biochar as a soil amendment were found effective in reducing soil acidity, improving nutrient contents and crop performance. Farmers' practice of making the kilns right in the field inevitably altered the soil properties in these sites. As a result, better growth and grain yields were obtained from annual crops grown on these sites. In addition *in situ* charcoal production helped farmers earn increased economic benefits by reducing the need for inorganic fertilizer application. Biochar addition persistently improved soil properties and crop performance over two years and the effects were greater at higher application rates. The results suggest the potential use of non-commercial by-products of traditional charcoal production (biochar) as a soil amendment on its merits in terms of agricultural sustainability on a degraded acidic soil in a smallholder farming system.

Conversion of croplands into *A. decurrens*-based fallowing led to better soil fertility and higher *teff* performance than the sole *teff* cropping system and the effects were greater in the second rotation than in the first rotation. Moreover, improved soil conditions by the acacia fallows can increase the benefits of farmers by reducing the need for inorganic fertilizer application by half and sustaining two to three successive crop harvests unlike one harvest in the conventional practice in two years. However, tree-crop

interactions in *teff – Acacia decurrens* woodlot system resulted in a reduction in *teff* performance in adjacent croplands due to shading effects.

The conversion of croplands to woodlot systems led to increases in SOC storage during the first five years. Croplands had lower SOC than the woodlot systems. Comparison of carbon stocks of the woodlot systems showed greater carbon storage capacity of *A. decurrens* woodlot than *E. camaldulensis* woodlot. The results confirmed the benefits of establishing short-rotation woodlot systems on degraded acidic agricultural lands in mitigating climate change through increased carbon accumulation.

7.3 Recommendations and Suggestions for Further Studies

The study found that the practice of *in situ* charcoal production in the study area is a promising locally available management option to reclaim degraded acidic soils. The practice had environmental and economic benefits by improving soil properties, reducing the need for chemical fertilizer and enhancing crop performance. These benefits can be maximized by distributing charcoal fragments (biochar) beyond the charcoal production sites (kiln sites). Examining the residual effects of *in situ* charcoal production on soil biota and with different chemical fertilizer application rates, multiple rotations and over two or more production years is required to determine the amount of fertilizer required and better understand the role of the practice for sustainable agricultural production. Moreover, introducing efficient methods for biomass carbonization for the efficient charcoal production process and for minimizing health and environmental hazards and assessing the economics of biochar application are needed.

In the study area, a significant amount of biochar can be obtained from *A. decurrens* wood. And acidic soil treated with *A. decurrens* wood biochar in the field sustained crop production at least for two consecutive production years. The results implied the potential use of locally available *A. decurrens* wood biochar as an alternative management strategy to improve soil properties of degraded acidic agricultural soil for sustainable crop production. To improve nutrient management and for the large-scale implementation of *A. decurrens*-derived wood biochar to agricultural soils in the study area or somewhere else in the country where soil acidity problem prevails, further studies

need to address biochar effects on soil biota, the combined application of biochar and inorganic fertilizer, biochar addition at rates higher than 20 t ha^{-1} and testing at multiple locations over three or more cropping seasons.

This study also found that short-rotation *A. decurrens*-based fallowing is a promising locally available management option for the remediation of soil acidity, nutrient restoration and improved crop performance in degraded acidic agricultural soils. However, *A. decurrens* woodlots, especially at the age of four years or above, can reduce crop performance at adjacent crop fields through competition for light. Future studies that consider three or more rotations and production years are required to evaluate the sustainability of the fallow system on a long-term basis. Proper agroforestry design, including optimum planting density and stand establishment at a similar time, has to be considered to reduce the shading effects of acacia woodlots on adjacent croplands.

We have used widely applicable empirical equations to estimate biomass production and the associated carbon stock for the *A. decurrens* woodlot system. Due to the heterogeneity of agroecologies and management practices validation and calibration of these models by directly measuring through destructive sampling or developing species-specific allometric equations have to be part of the future research work. Moreover, carbon stock assessments in woodlots of various ages and multiple rotations, litterfall and understory vegetation should be addressed.

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SUPPLEMENTARY MATERIALS

List of supplementary tables

Table S3.1 Characteristics of kiln sites and biochar produced from *A. decurrens* wood as a byproduct during charcoal production and incorporated into soil at kiln sites.

Characteristics	Unit	kiln site	Biochar
Kiln type		Earth mound kiln	
Density	number ha^{-1}	33	
Diameter	m	7	
Duration of pyrolysis	day	5[†]	
Heating temperature	^oC	400-450[‡]	
Frequency of use for charcoal production	number	Only once	
Age since their establishment	month	1-12	
Charcoal produced (2750 kg wood)	t $kiln^{-1}$	0.552[†]	
Charcoal fragments (biochar) produced	t ha^{-1}	11[§]	
Depth of charcoal fragments incorporated	cm	10-15[¶]	
Successive use for crop production	year	1 - 2	
Crops commonly grown		*Teff*, barley and wheat	
pH			9.63
Total P	g kg^{-1}		38[§]
Total K	g kg^{-1}		380[§]
Total N	%		0.51

[†]Tazebew et al. (2023); [‡]Emrich (1985); [§]Kim et al. (2022); [¶]Amare et al. (2022).

Table S3.2 Correlation coefficients of growth and grain yield of *teff* with selected soil chemical properties at kiln sites and reference sites (n=18)

Soil properties	**Crop characteristics**			
	Biomass	Grain	Leaf area	Plant height
pH	0.95	0.91	0.92	0.93
SOC	0.88	0.83	0.92	0.86
P_{av}	0.96	0.93	0.85	0.91
Ex. Mg^{2+}	0.70	0.73	0.63	0.69
Ex. K^{+}	0.93	0.89	0.89	0.90
Ex. Acidity	-0.90	-0.86	-0.95	-0.90
Ex. Al^{3+}	-0.88	-0.85	-0.94	-0.89

All show significant correlations at $P < 0.01$.

List of supplementary figures



Figure S4.1 Illustrating *A. decurrens*-based fallow system: (a) *A. decurrens* woodlot (4-year-old); (b) heap of *A. decurrens* wood logs forming a kiln; (c) bags of charcoal for marketing; (d) *A. decurrens* saplings with remaining stalks of intercropped *teff* crop harvested last season. Farmers sow *teff* by broadcasting and plant acacia seedlings in rows as intercrop



Figure S6.1 Five-year-old *A. decurrens* (top) and *E. camaldulensis* (bottom) woodlots in Amesha Shinkuri kebele, Fagita Lekoma district

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Born on 15 May 1976 in North Mecha district of Amhara Region, Desalegn Tadele Awoke received his BSC degree in Biology in 1999 from Addis Ababa University. He was then employed and working for two years as a school teacher in the Education Bureau of Afar Region. In 2001, he was admitted to pursue his postgraduate study in Botany at Addis Ababa University, Science College. In 2004, he completed his MSc degree in Botany and was recruited at a post of lecturer at Bahir Dar University, Department of Biology. And he advised students, presented papers in conferences, and published seven articles: six in reputable journals and one in a book chapter. In September 2017, he commenced his PhD study in Soil Science at Bahir Dar University, College of Agriculture and Environmental Sciences and produced four articles of which two were published in a peer-reviewed, reputable journal. Now he is a candidate for the Degree of Doctor of Philosophy (PhD) in Soil Science in 2025 at Bahir Dar University, College of Agriculture and Environmental Sciences.

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