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Market driven afforestation

Trajectories in environmental sustainability under land use intensification

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Cover: A photo compilation showing a man from Fagita Lekoma district planting *A. mearnsii* seedlings in a production field, alongside a landscape view of the study area. From left to right: photos by Erik Karltun and Getachew G Tiruneh.

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Abstract

Biomass production using fast growing tree species presents a sustainable energy pathway for developing countries with high dependence on biomass as an energy source. A rapid land use change from cropland to short rotation forestry (SRF) using black wattle (*Acacia mearnsii* De Wild.) has taken place in northwest Ethiopia. The driver is the increasing market demand for charcoal in urban areas and the economic opportunities this presents for farmers. *Acacia mearnsii* is a fast growing, nitrogen (N) fixing tree, and native to Australia. This thesis investigated the extent of the land use change to SRF and the environmental sustainability of the SRF production system compared to the teff (*Eragrostis tef* (Zucc.) Trotter.) production system it replaced. The analysis was done using a combination of methods, including satellite imagery analysis, soil and biomass samples analysis, and review of data from published studies. By 2022, 60% of the fields under crop cultivation in 2005 had been converted to SRF. The landscape carbon (C) budget showed a net CO_2 sink due to C sequestration in biomass. However, despite the C sequestration and N fixation in tree biomass, successive rotations had lower soil C and N stocks. Nutrient budget estimates suggest that this is likely due to mineralization of soil organic matter to mobilize organically bound phosphorus and sulfur. The SRF resulted in the export of large amounts of base cations in harvested biomass, leading to higher soil acidification compared to the teff production system. Despite these concerns in the long term, biomass production reduced the pressure on natural forest for exploitation of charcoal and firewood. The findings highlight the need for improved management practices, including retaining nutrient dense residues in the field, phosphorus and sulfur fertilization, and liming to neutralize the soil acidity.

Keywords: *Acacia mearnsii*, short rotation forestry, land use change, charcoal, fuelwood, carbon sequestration, nitrogen fixation, nutrient budget, soil health, sustainability.

Marknadsdriven beskogning: miljömässig hållbarhet vid intensifierad markanvändning

Sammanfattning

Biomassaproduktion med hjälp av snabbväxande trädarter är ett potentiellt hållbart energialternativ i utvecklingsländer med hög användning av trädbränsle. I nordvästra Etiopien har det skett en snabb förändring i markanvändning från jordbruksmark till odlingar av snabbväxande *Acacia mearnsii* De Wild., ett snabbväxande, kvävefixerande träd som är härstammar från Australien. Drivkraften bakom markanvändningsförändringen är en ökande marknad för träkol i urbana områden och de ekonomiska möjligheter som detta erbjuder för bönderna. I avhandlingen kvantifieras markanvändningsförändringen till energiskog och den miljömässiga hållbarheten i odlingssystemet jämförs med teff (*Eragrostis tef* (Zucc.) Trotter.), den mest odlade jordbruksgrödan. Resultaten bygger på en kombination av metoder, inklusive satellitbildanalys, kemisk analys av jord- och biomassaprover samt genomgång av data från publicerade studier. Mellan 2005 och 2022 konverterades 60% av åkermarken i området till A. mearnsii odlingar. En kolbudget i landskapsskala visade på en netto CO_2-sänka för odlingssystemet på grund av ackumulation av kol i biomassa. Trots kolinbindning i biomassan och en hög kvävefixering hade marken efter tre rotationer lägre kol- och kväveinnehåll än åkermarken som används till teffodling. Beräkningar av odlingssystemets näringsbalans indikerar att det beror på mikrobiell mineralisering av markens organiska material för att mobilisera organiskt bunden fosfor och svavel i A. mearnsii-odlingarna. Energiskogsodlingarna resulterade i export av stora mängder baskatjoner i den skördade biomassan, vilket ledde till ökad markförsurning i A. mearnsii-odlingarna jämfört med teffodlingarna. Den ökade biomassaproduktionen minskade behovet av att hämta ved från omgivande skogar, vilket ledde till en återhämtning av trädvegetationen i naturskogen. Resultaten visar på behovet av att förbättra odlingsmetoderna, till exempel genom att i högre grad återföra näringsrika skörderester till marken, gödsla med fosfor och svavel, samt att kalka för att neutralisera markens ökade surhet.

Nyckelord: *Acacia mearnsii*, energiskog, markanvändningsförändring, kol, biobränsle, kolinbindning, kvävefixering, näringsbalans, markhälsa, hållbarhet.

Preface

Growing up, all I wanted was to avoid becoming a farmer. I was raised in a village surrounded by poor farmers. Although my parents were not farmers themselves, our lives were only a little better than those around us. For me, farming and village life were synonymous with poverty, and I always aimed at escaping. So, education was the only means of doing so.

I genuinely liked learning, but more than a desire for knowledge, it was my hatred of poverty that drove me. When I started middle secondary school, life got even harder. I was 13 and had to walk 20 kilometers every day to and from school since there was not one in my village. It was physically tough (I was so fit back then!), but it felt like my most likely escape route. I am grateful to the older students who ensured my safety on the road.

I am not unique. In fact, I was fortunate that my parents moved to what I now call my hometown, reducing the distance to school to just a 10-minute walk.

After high school, I had no interest in studying agriculture. In fact, I was not even aware it was a university discipline. Back then, students chose broad fields like natural or social sciences instead of specific programs. I chose natural sciences, only to find myself assigned to an agricultural university. Ironically, I ended up in the very field I had tried to escape. Over time, I grew to love it, especially soil science, thanks in part to my teachers. The field I once rejected ultimately reshaped my life in ways I never could have imagined, and for that, I am truly grateful.

After university, I had the privilege to work closely with farmers. They gave me so much wisdom, food and drinks even when they barely had enough for themselves - a testament to their generosity. Although this work gave me a deep satisfaction, a long-held dream of pursuing research also lingered. Since childhood, scientific methods and discoveries have fascinated me. Back then, I learned about discoveries and breakthroughs by listening to the radio. I often wished to be part of it. However, the opportunity never presented itself easily, and I eventually set that dream aside for financial stability. Given my background, it felt like a practical choice. When I got this chance, I faced a tough decision: Should I prioritize financial security or finally make space for my curiosity? It was a hard choice, and many questioned it, but I have never regretted taking this opportunity. The path was not easy, and I faced doubts, but I am still grateful I took the risk.

Dedication

To Ethiopian farmers, who receive little support yet bear the burden of feeding the nation.

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Tiruneh, G.G., Alemu, A., Barron, J., Yimer, F., Karltun, E. (2025). Short rotation forestry expansion drives carbon sequestration in biomass but not in soil. *GCB Bioenergy*, 17, 7. https://doi.org/10.1111/gcbb.70054

II. Tiruneh, G.G., Alemu, A., Barron, J., Yimer, F., Karltun, E. (2025). Nutrient budgets in short rotation black wattle (*Acacia mearnsii*) stands for charcoal production as compared with teff (*Eragrostis tef*) cultivation. *Forest Ecology and Management*, 588, 122762. https://doi.org/10.1016/j.foreco.2025.122762

III. Tiruneh, G.G., Alemu, A., Barron, J., Yimer, F., Karltun, E. Effects of intensive *Acacia mearnsii* cultivation on soil acidity and fertility indicators. (manuscript)

All published papers are reproduced with the permission of the publisher.

The contribution of Getachew Gemtesa Tiruneh to the papers included in this thesis was as follows:

I. Conceptualization, planning fieldwork, sampling, data analysis, formal analysis, visualization, and manuscript writing.

II. Conceptualization, planning fieldwork, sampling, data analysis, formal analysis, visualization, and manuscript writing.

III. Conceptualization, planning fieldwork, sampling, laboratory analysis (except biomass nutrient analysis), data analysis, visualization, and manuscript writing.

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Abbreviations

AGB	Above ground biomass
AIC	Akaike information criterion
BGB	Below ground biomass
DBH	Diameter at breast height
DRC	Democratic republic of Congo
FAM	Former *Acacia mearnsii* field later converted to cropland
ICP-SFMS	Inductively coupled plasma sector-field mass spectrometry
ISO	International Organization for Standardization
LRS	Leaf retained on site
NMA	National meteorology agency
NDC	Nationally determined contribution
LULC	Land use and land cover
SOC	Soil organic carbon
SOM	Soil organic matter
SRF	Short rotation forestry
WBH	Whole biomass harvest

1. Introduction

Sustainable charcoal production through competitive agroforestry systems is crucial for Ethiopia's future energy supply and environmental objectives. Despite multibillion dollar investments in expanding electricity generation capacity (Abtew and Dessu, 2019; UNDP, 2025), biomass remains the dominant energy source, with over 90% of the population relying on it for domestic energy needs (Sanbata *et al.*, 2014; Benti *et al.*, 2021; Tofu *et al.*, 2022). In urban areas, this demand is largely met by charcoal, which is used as the main cooking fuel by 85% of households (Johnson and Mengistu, 2013; Benka-Coker *et al.*, 2018; Getahun *et al.*, 2024).

Ethiopia is currently the second largest global charcoal producer, with an estimated annual production of 5.1 Mt in 2023 (FAOSTAT, 2023). The demand for charcoal is projected to increase due to population growth and rapid urbanization (Bekele and Girmay, 2014; Silva *et al.*, 2019). Ethiopia is the second most populous country in Africa (Hailemariam, 2017) with an estimated population of over 120 million (UN, 2024), and is projected to increase to 225 million in 2050 (UN, 2024; WHO, 2025). Therefore, the country's energy landscape will continue to be shaped by its growing population and dependence on biomass fuels.

Continued dependence on charcoal presents a significant environmental challenge, as its production is associated with logging in natural forests and deforestation (Bekele and Girmay, 2014; Hido *et al.*, 2023). As a measure to mitigate the negative impact on natural forests, charcoal production and sale have been legally restricted through the introduction of a licensing regime (FDRE, 2007). However, due to strong urban demand for charcoal, the economic gains it provides for rural populations, and the limited institutional capacity to enforce the restrictions, illegal charcoal production has continued (Bekele, 2011; Ayana, 2020).

Agroforestry has been promoted as a sustainable solution that simultaneously addresses biomass production and environmental conservation (Birhane, 2014). However, these efforts have often fallen short of intended outcomes. A primary reason was farmers' hesitancy to invest in long-term projects on the land where they lack secure tenure arrangements (Bishaw, 2001; Birhane, 2014). In addition, while policies advocated for tree planting, they simultaneously restricted farmers from harvesting the trees they had planted (Kassa *et al.*, 2011; Birhane, 2014). Such barriers have disincentivized smallholder farmers from allocating land to forestry, as the delayed returns and regulatory uncertainties fail to align with immediate livelihood needs (Abdul-Salam *et al.*, 2022).

Recent legislative reforms have sought to address these barriers and recognized the rights of private individuals and communities to manage and benefit from forest, while they also introduced incentives (Evans, 2018). However, the most notable successes have emerged from farmer-led initiatives. In recent years, small-scale afforestation practices rooted in farmers' own experience have emerged without institutional support. These initiatives are market driven and prioritized quick income generation through cultivation of fast growing exotic tree species such as eucalypt (Alemayehu and Melka, 2022; Belachew and Minale, 2025), thereby better aligning with livelihood strategies. Recently, black wattle (*Acacia mearnsii* De Wild.) has emerged as an alternative species to eucalypt in the northwest (NW) highlands of Ethiopia, which has resulted in a significant land use change from crop production to short rotation forestry (SRF) (Wondie and Mekuria, 2018). This market oriented SRF involved planting *A. mearnsii* on five-to-six-year rotations and subsequently converting the wood into charcoal for urban markets. Charcoal production has provided farmers with an increased source of income (Chanie and Abewa, 2021). It has also created employment opportunities for youth and unemployed individuals along the value chain (Belay *et al.*, 2024). This helps reduce deforestation pressure and aligns with climate change mitigation strategies that increasingly promote nature based solutions as climate smart alternatives (Iiyama *et al.*, 2014). However, the scale and speed of this land use change carry significant social and environmental implications that require careful examination. Therefore, this thesis focused on understanding the spatial extent of the land use change, its impact on carbon (C) budgets, long-term soil nutrient management and sustainability of the production system over multiple rotations.

2. Background

2.1 Land use change in northwest Ethiopia

A common perception in Africa and tropical countries is that the economic incentive generated by high charcoal demand promotes the unsustainable logging in natural forests, thereby accelerating deforestation (Chidumayo and Gumbo, 2013). However, a case in NW Ethiopia presents a contrast to this, where charcoal demand is associated with afforestation. A rapid land use change from crop production to SRF has taken place in this region over the last two decades (Worku *et al.*, 2021). This change is attributed to the widespread establishment of small-scale plantation forestry using *A. mearnsii*, for charcoal production.

The traditional cropping system in the area was dominated by the cultivation of teff (*Eragrostis tef*) (Zucc.) Trotter, followed by barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.) and potato (*Solanum tuberosum* L.) (Nigussie *et al.*, 2017). However, since the introduction of *A. mearnsii*, farmers have adopted an agroforestry system that integrated *A. mearnsii* with an annual crop. During the first year of seedling establishment, *A. mearnsii* is intercropped with teff (Figure 1). In the second year, farmers harvest the understory grass for fodder. By the third year, the *A. mearnsii* stand forms a closed crown cover, which reduces understory yield. The tree is typically harvested for charcoal production when the stand reaches an age of five to six years (Bazie *et al.*, 2020), after which a new cycle of intercropping with annual crops resumes.

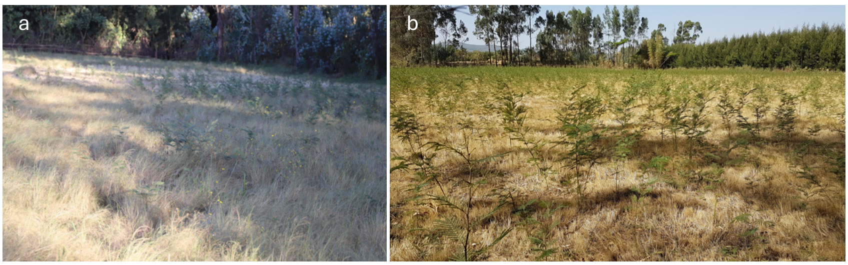

Figure 1. Intercropping of *A. mearnsii* with teff in the seedling establishment phase: a) teff crop with *A. mearnsii* seedlings and b) *A. mearnsii* after the teff crop was harvested, with the remaining straw visible underneath.
Picture credit: Erik Karltun

Studies have reported significant increases in vegetation cover in the area over the last two decades. Wondie and Mekuria (2018) reported a 25% increase in forest cover from 1995 to 2015, while Worku *et al.* (2021) showed a 16% increase between 2000 and 2017. A recent study by Mulu *et al.* (2024) showed an increase of plantation cover from 2.5% to 19% between 2009 and 2020. Studies based on smaller watersheds showed even higher increases, with Berihun *et al.* (2019b) and Berihun *et al.* (2019a) reporting a 260% and 400% increase from 2006 to 2017 and 2012 to 2017, respectively. Despite differences in quantification, study periods, and spatial scales, the studies showed a significant land use change from crop production to SRF.

The widespread conversion of cropland to small-scale forestry deviates from typical land management practices in Ethiopia. Although plantation forestry using fast-growing trees such as eucalypt is common (Jagger and Pender, 2003), these plantations are typically established on degraded or marginal lands. Recent studies have reported the expansion of eucalypt onto agricultural land. However, this is also mainly occurring in NW Ethiopia (Tesfaw *et al.*, 2022; Molla *et al.*, 2023), and at a less extensive scale than that of *A. mearnsii*.

Comparable sequential agroforestry systems using *Acacia* species have been reported in East African countries such as Democratic Republic of Congo (DRC) and Tanzania. However, unlike the present study, these initiatives were institutionally supported by international organizations including UN agencies, the World Bank and European funders (Kimaro *et al.*, 2011; Kachaka *et al.*, 2020; Ehrenstein, 2023). Despite the support, the plantation in DRC reportedly provided only 1% of the urban fuelwood consumption after twenty-five years (Ehrenstein, 2023). In contrast, estimates suggest charcoal production in the NW Ethiopia accounts for 3% of Ethiopia's annual charcoal production[1].

The land use change to SRF for charcoal production in NW Ethiopia represents, to the best of my knowledge, a unique land use change that has not been observed on a comparable scale elsewhere in the continent. It provides a potentially more sustainable pathway of charcoal production in comparison to the common charcoal production from natural forests.

[1] The estimate is based on unpublished data obtained from the value chain study conducted as part of the overall project.

2.2 From crop fields to plantations: the rise of *Acacia mearnsii*

2.2.1 Introduction and expansion of *A. mearnsii* in the northwest Ethiopia

Acacia mearnsii was first introduced to the NW highlands of Ethiopia in the 1980s to address firewood shortages and land degradation (Nigussie *et al.*, 2017; Chanie and Abewa, 2021). Farmers were initially hesitant to cultivate the tree widely and only planted it along roadsides and farm boundaries as live fencing (Chanie and Abewa, 2021; Biresaw *et al.*, 2023). However, the discovery of its potential for charcoal production by a local entrepreneur led to its expansion into main agricultural fields (Tamirat and Wondimu, 2019). *A. mearnsii* is a fast growing, evergreen leguminous tree that can grow up to a height of 11 m in 5-6 years in the Ethiopian highlands (Mekonnen *et al.*, 2006). The tree is native to Australia and mainly produced as a commercial source of tannin or firewood (Griffin *et al.*, 2011). It is also recognized as invasive species in south Africa (de Wit *et al.*, 2001).

2.2.2 Drivers of the land use change

The main driver of the land use change to SRF using *A. mearnsii* is the market demand for charcoal in urban areas and the significant economic return it generates (Nigussie *et al.*, 2017). Studies conducted in the area have reported that charcoal production provided significantly higher income than annual crop cultivation (Nigussie *et al.*, 2017). Kessie (2015, as cited by Nigussie *et al.*, 2017) reported that farmers earned five times more income from charcoal sales than annual crop production. This income was obtained from the same unit of land with reduced labor requirement and no need for fertilizer input.

The Fagita Lekoma district's strategic location along the main road connecting the major cities of Addis Ababa and Bahir Dar, with populations of 3.9 million and 338,000 respectively (ESS, 2022), has played a role in facilitating access to urban charcoal markets. This proximity facilitated efficient charcoal distribution to major markets (Figure 2), thus increasing the economic viability of its production. Moreover, the charcoal based economy also generated employment opportunities for previously unemployed individuals and urban youth who had limited prospects within the traditional agricultural sector, thereby maintaining production momentum through broader economic participation (Nigussie *et al.*, 2017; Endalew and Anteneh, 2022).

Figure 2. The charcoal production and marketing process: a) Harvested *A. mearnsii* tree; b) The tree stems are arranged for the charring process; c) Produced charcoal is loaded onto a lorry; d) Lorries loaded with charcoal leave the Fagita Lekoma district town for market in Addis Ababa. Picture credit: Erik Karltun

In addition to market forces, the agronomic compatibility of *A. mearnsii* with existing agricultural practices has further contributed to its widespread cultivation (Nigussie *et al.*, 2017). Farmers can intercrop *A. mearnsii* seedlings with the staple food crop teff during the seedling establishment and harvest understory grasses for livestock in subsequent year (Nigussie *et al.*, 2020). This integrated practice has increased the benefit per unit area. In addition, studies have indicated that crop cultivated following the harvest of *A. mearnsii* showed increased yield due to the nitrogen (N) fixing ability of the tree (Tadele *et al.*, 2024). As a result, farmers did not apply N fertilizer in the subsequent year, which reduced the cost of production (Alem *et al.*, 2020) and potentially contributing to the wider adoption of *A. mearnsii* in the area. Furthermore, the possibility of easily reverting to crop production, often with increased yields, provided farmers flexibility and security over land use decisions (Wondie and Mekuria, 2018; Chanie and Abewa, 2021).

2.2.3 Taxonomic confusion and disease outbreak

There was initial confusion about the tree species planted in SRF in the area. Early studies on the resulting land use change identified the species as green wattle (*A. decurrens* (J.C.Wendl.) Willd.) (Nigussie *et al.*, 2017; Wondie and Mekuria, 2018; Berihun *et al.*, 2019a). This remained the dominant reference in literature as recently as 2024. However, a disease outbreak that began in early 2020 prompted an expert investigation into both the host tree's taxonomy and the pathology of the disease (Agena *et al.*, 2023).

The host species was identified as *A. mearnsii* by the experts based on its distinctive leaf structure. This conclusion was further supported by the identification of *Uromycladium acaciae*, a fungal disease, which is less known to affect *A. decurrens* (Agena *et al.*, 2023; Pham *et al.*, 2024). However, local farmers referred to the disease as "corona". This was due to the temporal overlap between the disease outbreak and the onset of the COVID-19 pandemic. Due to the timing and extensive media use of the term "corona" at the time, local farmers began referring to the plant disease by the name.

2.2.4 Socio-economic impact

Prior to the adoption of *A. mearnsii*, farmers in the area faced economic challenges due to low crop yields caused by soil degradation and acidity (Wondie and Mekuria, 2018). As a result, many young people migrated to Addis Ababa and neighboring regions in search of better economic opportunities (Amsalu, 2018).

The introduction of charcoal production has since offered a more stable and profitable source of income, creating employment opportunities that were previously unavailable (Afework et al., 2024). The charcoal based economy has played a central role in alleviating poverty in the area (Nigussie *et al.*, 2021). Youths and landless individuals are now employed across various stages of the charcoal value chain, including nursery management, tree planting and harvesting, charcoal production, and trade (Worku *et al.*, 2021).

In addition to the economic benefits, the cultivation of *A. mearnsii* has had significant social impacts. In rural Ethiopia, women will have to collect firewood two to three times per week, with each trip requiring an average of three to five hours (Scheurlen, 2015; Birhanea *et al.*, 2019). This physically exhausting task involves not only gathering the wood but also transporting by carrying it on their heads or backs (Scheurlen, 2015). The availability of firewood near their homes has reduced the burden on women (Nigussie *et al.*, 2021).

2.3 Land use and afforestation in climate change mitigation

Land use plays a significant role in achieving the large-scale negative emissions required to meet global climate mitigation goals (Dooley *et al.*, 2024). Forest based mitigation is recognized as a cost-effective strategy for climate change mitigation, with the sector offering up to one-third of the necessary global emission reductions (UN-REDD, 2022). In recognition of this potential, most of the parties to the Paris agreement have included afforestation and reforestation as key components of their Nationally Determined Contributions (NDC) (Brack, 2019). To implement these commitments, countries are adopting a range of land use strategies tailored to regional and socio-economic contexts. Along efforts aimed at reducing deforestation and forest degradation, increasing emphasis has been placed on expanding agroforestry systems and afforesting marginal or low-productivity agricultural lands (Rämö *et al.*, 2023). In the northern hemisphere, for example, abandoned arable lands are repurposed for SRF to generate biomass feedstock (Tullus *et al.*, 2013), providing a sustainable land use alternative (Campbell *et al.*, 2008). In low-income countries, sequential agroforestry systems with N fixing trees are promoted as dual purpose strategies that increase C sequestration while reducing dependence on expensive synthetic N fertilizers in annual cropping systems (Kwesiga and Coe, 1994; Lahtinen *et al.*, 2025). However, the role of afforestation in C sequestration and subsequent climate change mitigation is a subject of considerable debate. The following sections explore the key discussions most relevant to this thesis.

2.3.1 Soil organic carbon in SRF

Land use change from agriculture to afforestation increases C stocks due to significant C sequestration in tree biomass (Amichev *et al.*, 2012; Krause *et al.*, 2022). Fast growing and N fixing trees are often preferred for SRF due to their rapid biomass accumulation. For example, *Acacia auriculiformis* A.Cunn. ex Benth. agroforestry system in the DRC sequestered 50.3 Mg C ha^{-1} over seven years, corresponding to 7.2 Mg C ha^{-1} y^{-1} (Reyniers, 2019). Similarly, *Acacia nilotica* L. and *Acacia crassicarpa* A. Cunn. ex Benth.

plantations in Tanzania showed a sequestration rate of 2.3 Mg C ha^{-1} y^{-1} and 5.1 Mg C ha^{-1} y^{-1}, respectively (Kimaro, 2009). However, increased biomass C accumulation following afforestation may not result in the same effect in the soil.

Most studies report a decline in soil C stocks during the initial decade after afforestation (Paul *et al.*, 2002; Li *et al.*, 2012; Hou *et al.*, 2020). Studies quantified this depletion at 5-10% of the initial soil organic C (SOC) during the first 10 years (Laganiere *et al.*, 2010; Li *et al.*, 2012).This is because C inputs from young tree stands are insufficient to offset the decomposition of SOC inherited from prior agricultural practices (Laganiere *et al.*, 2010).

Long-term studies show that SOC can recover and eventually increase with time. This transition to net C accumulation is due to mechanisms including: (1) physical protection due to cessation of tillage (Laganiere *et al.*, 2010; Don *et al.*, 2011); and (2) increased organic matter inputs from maturing tree stands through litterfall and root turnover (Li *et al.*, 2012). Studies show SOC gains of 5-26% of the initial SOC (Laganiere *et al.*, 2010; Harris *et al.*, 2015), with annual accumulation rate of 0.5-1.0 Mg C ha^{-1} y^{-1} after 30-50 years of afforestation (Don *et al.*, 2011; Li *et al.*, 2012).

The use of natural abundant stable C isotopes ($\delta^{13}C$) provides a robust method to trace soil C dynamics in land use changes that involve converting vegetation with different photosynthetic pathways (e.g., C_3 and C_4 plants) (Zhang *et al.*, 2015). A study conducted in southwestern Ethiopia applied this technique to quantify soil C sequestration resulting from land use involving the conversion from a C_4 plant maize (*Zea mays*) to afforestation with C_3 tree species (Lemma *et al.*, 2006). The study found that afforestation with exotic tree species *Pinus patuala* Schiede ex Schltdl. & Cham. and *Cupressus lusitanica* Mill. over 20 years period accumulated 29.3 Mg C ha^{-1} (1.47 Mg C ha^{-1} y^{-1}) and 69.6 Mg C ha^{-1} (3.48 Mg C ha^{-1} y^{-1}), respectively, to a soil depth of 50 cm. Similar land use change from maize cultivation to N fixing *Gliricidia sepium* (Jacq.) Kunth ex Walp. and *Erythrina poeppigiana* (Walp.) O.F.Cook alley cropping systems in Costa Rica resulted in no measurable SOC gain after 10 years. However, after 19 years, SOC increased significantly (Oelbermann *et al.*, 2006). The authors attributed this increase to C inputs from tree pruning. The isotopically confirmed net gain in SOC was equivalent to 0.27 Mg C ha^{-1} y^{-1} and 0.66 Mg C ha^{-1} y^{-1} to a 40 cm depth in *Erythrina poeppigiana* and *Gliricidia sepium* respectively (Oelbermann *et al.*, 2006). However, it is yet unclear whether land use change to SRF with

A. mearnsii has similar effects on SOC as the land use changes examined in these studies.

2.4 Land use change to SRF and soil health

Soil organic C regulates soil physical, chemical and biological properties that support essential ecosystem services (Murphy, 2015). However, the total SOC is largely a stable pool, with changes often taking many years to become apparent, making it not an optimal tool for monitoring short-term management effects (Weil *et al.*, 2003). Therefore, indicators that are sensitive enough to reflect management effects but stable enough to show cumulative impacts over time are needed (Islam and Weil, 2000). Measurements related to the microbially active portion of SOC can serve as indicators of soil health change (Lucas and Weil, 2021). These include permanganate oxidizable C (POXC) (Weil *et al.*, 2003) and phosphatase enzyme activity (Sinsabaugh *et al.*, 2008). POXC represents the biologically active fraction of SOC and is sensitive to changes in soil management practices (Culman *et al.*, 2012). Change in this SOC faction provides an early indication of soil degradation or improvement in response to management practices (Weil *et al.*, 2003). Similarly, phosphatase enzymes activity is a sensitive biological indicator of management change (Margalef *et al.*, 2021). Phosphatase is a group of enzymes that play a crucial role in the P cycle in the soil. They hydrolyze organic P compounds into forms that are available for plants and microorganisms (Nannipieri *et al.*, 2011; Margalef *et al.*, 2017). The general trend of these two indicators after land use change to afforestation is an increase due to higher organic input from trees (Zhang *et al.*, 2020a; Huang *et al.*, 2022).

2.5 Land use change to SRF and soil acidification

Land use change from crop production to SRF perturbs the biogeochemical processes and soil properties. Afforestation may lead to soil acidification due to the redistribution of base cations from the soil to biomass (Jobbágy and Jackson, 2004), the release of organic acids (Fujii, 2014) and acidity due to microbial and root respiration (Lükewille and Alewell, 2008). A study by Berthrong *et al.* (2009) reported a 0.3 unit decrease in soil pH following afforestation. Nitrogen fixation represents an additional acidification pathway, as N fixing species take up excess cation over anion (Bolan *et al.*, 1991). Furthermore, assimilation of the fixed N results in the release of 0.1 to 0.2 H^+ per N assimilated in temperate and tropical regions, respectively (Raven and Smith, 1976). These processes are particularly important for the study area where the N fixing *A. mearnsii* is cultivated. The repeated biomass harvesting in short rotation cycles exports the base cations from the production site, potentially intensifying the existing soil acidity.

Some studies suggest that afforestation can neutralize acidity. Hong *et al.* (2018) reported mechanisms contributing to this effect over long-term: (1) the inhibition of nitrification in acid soils promotes ammonification of mineralized N, resulting in an increase in soil pH; (2) aluminum contributes to buffering capacity in acidic soils and functions as a base cation; and (3) trees address base cation deficiencies in surface layers of acid soils by taking up cations from deeper soil layers. Moreover, increased evapotranspiration will reduce the leaching loss of base cations. However, these mechanisms are dependent on specific conditions. Inhibition of nitrification does not always result in a buildup of ammonium, as plants take up ammonium in acidic soil, and ammonia formation occur at pH higher than 7.5 (Bronson, 2008). The formation of aluminum organic complexes is necessary for aluminum to function as a base cation (Skyllberg, 1999). Furthermore, planted trees must be deep rooted to access cations from deeper soil layers (Collier and Farrell, 2007).

2.6 Controversies in biomass cultivation for energy

Biomass energy is expected to play a significant role in the future sustainable energy supply (Rose *et al.*, 2014). However, the cultivation of biomass for energy is a subject of debate due to the potential trade-offs. Biomass fuel is considered C neutral because the C released during burning was previously sequestered from the atmosphere and will be sequestered again through the regrowth of subsequent plantation cycles (Schulze *et al.*, 2020). However, the climate credentials of bioenergy are questioned due to the C footprint associated with its supply chain (Repo *et al.*, 2015; Booth, 2018). Moreover, the delayed payback period that could take decades to centuries is far too slow to be compatible with the urgency of the Paris agreement timetable (Norton *et al.*, 2019).

In food insecure countries, the main concern is that biomass production displaces food crops, leading to reduced food availability and increased food prices, thereby exacerbating food insecurity (Muscat *et al.*, 2020). The debate also extends to the environmental integrity of biomass sourcing. While proponents argue that biomass produced in SRF can relieve pressure on natural forests by supplying sustainably sourced biomass for energy (Paquette and Messier, 2010), critics warn that illegally produced charcoal could be rebranded as sustainably produced (Haag *et al.*, 2020).

Other concerns raised are the buildup of disease and pest due to monocropping practices (Bennett *et al.*, 2012). Market failure, resulting from a shift to alternative energy sources, is another potential concern (Howells *et al.*, 2010). Furthermore, repeated harvest of woody biomass in short rotations could increase nutrient export from the fields, potentially affecting long-term soil fertility (Thiffault *et al.*, 2011).

3. Aim and objectives

The overall aim of this thesis was to identify and describe positive and negative trajectories of land use change from crop production to SRF with *A. mearnsii* and evaluate the long-term sustainability under multiple rotations.

The specific objectives of the thesis were to:

- Evaluate spatial extent of land use change and C sequestration in biomass and soil at a landscape level.
- Quantify the nutrient budgets of teff and *A. mearnsii* cultivation systems and identify potential sustainability implications.
- Analyze the cumulative effects of repeated biomass harvest under short rotation intervals on soil acidity development and soil health indicators.

Fast growing woody trees sequester more C in their biomass than annual herbaceous crops (Poorter *et al.*, 2012). Furthermore, land use change to SRF reduce soil disturbance while increasing litterfall and root turnover that contributes to increased soil C (Rowe *et al.*, 2016; Georgiadis *et al.*, 2017). As N fixing species, *A. mearnsii* takes up excess cations over anions (Bolan *et al.*, 1991). This combined with its fast growth leads to higher base cation accumulation in its biomass compared to annual crop teff. Therefore, I hypothesize that *A. mearnsii* cultivation will significantly increase soil C and N compared to the teff cultivation system. However, repeated biomass harvesting will deplete soil nutrients and lead to an unsustainable production system compared to teff cultivation. Moreover, successive rotations with the N fixing *A. mearnsii*, coupled with repeated biomass harvesting, will significantly increase the risk of soil acidification compared to teff cultivation.

4. Materials and methods

4.1 Study approach

The temporal dynamics of the land use change were assessed using a space for time substitution approach. The sampled fields represented a chronosequence from cropland to successive rotations of *A. mearnsii* plantations, with stand ages ranging from three to six years. Teff cultivation was the predominant land use prior to the introduction of *A. mearnsii* and was therefore used as the baseline reference condition. The stand ages across rotations treated differed among the three studies. **Papers I** and **III** examined stands aged three to six years in each rotation, whereas **Paper II** focused on stands aged five and six years. This was because in **Paper II** the aim was to assess the nutrient budget of the production systems up until harvest. Previous studies in the area indicated that plantations are typically harvested at or after five years of age (Bazie *et al.*, 2020). In addition, fields formerly under *A. mearnsii* cultivation that had been reverted to teff cultivation (FAM), natural forest and open or grazing land were included. The FAM fields provided reference conditions for a post *A. mearnsii* plantation scenario, should cultivation be discontinued.

4.2 Study area

All the three studies summarized in this thesis were conducted in the Amesha watershed, located in Fagita Lekoma district, Awi zone, in the northwest of Ethiopian highlands (10° 57′ - 11° 11′ N and 36° 40′ - 37° 05′ E) (Figure 3). The elevation ranges from 1800 to 2900 m a.s.l and is characterized by undulating topography (Worku *et al.*, 2021). The climate of the area is classified as humid subtropical with a main rainy season (*meher*) lasting from May to October. The annual average rainfall and temperature of the area was 2110 mm and 18°C, respectively, for the period between 1997 and 2019 (NMA, 2020). The soils are predominantly Acrisols, characterized by a low pH (Regassa *et al.*, 2023).

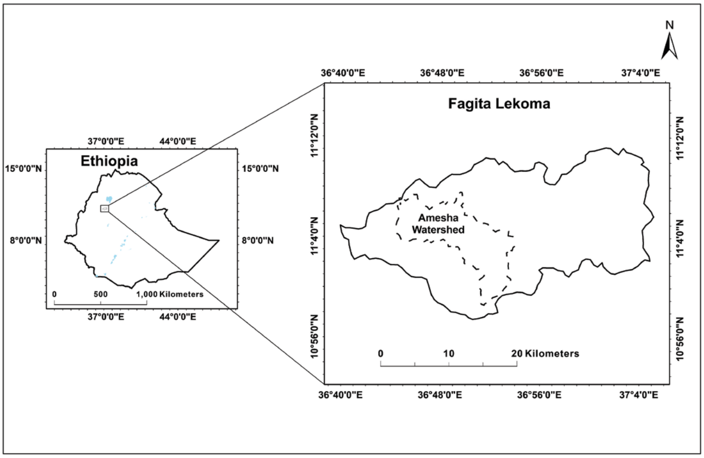

Figure 3. Map of the study area, Fagita Lekoma district, with the Amesha watershed indicated by the dotted line.

4.3 Sampling design

The Amesha watershed was delineated using the Shuttle Radar Topography Mission (SRTM) digital elevation model (USGS, 2022), obtained from www.usgs.gov. The digital elevation model was processed with the hydrology tool in ArcGIS 10.7.1. The watershed was divided into six subareas to ensure a spatially representative distribution of soil and biomass samples. A central coordinate within each subarea was marked as the starting point for field selection. The watershed map, with center of subareas marked, was subsequently uploaded to GPS devices for fieldwork navigation. Sampling teams started fieldwork by navigating to the marked center of each subarea. Sampling fields were selected using a systematic random sampling technique. Upon arrival at the marked center of each subarea, a walking path was established for field selection. The sampling team followed this path, and the first field encountered corresponding to the pre-defined land use categories was selected for sampling.

Soil samples were collected from a total of 96 fields representing 16 land uses categories (Figure 4), while biomass samples were collected from 24 fields representing stand age three to six years. Both biomass and soil samples were collected from a 10 m × 10 m sampling plots established in each selected field. However, the biomass and soil samples were collected from distinct fields, as the samples were collected by separate teams.

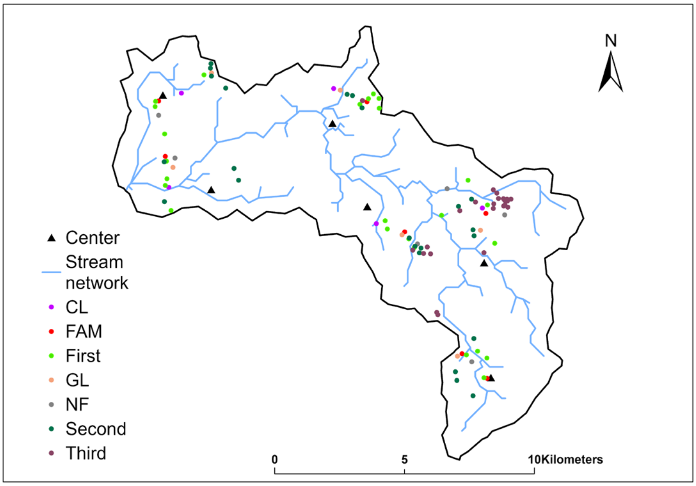

Figure 4. Map of Amesha watershed with drainage networks and soil sampling locations. Note: CL = cropland; FAM = former *A. mearnsii* field converted to cropland; GL = grazing land; NF = natural forest. First, Second, and Third represent the first, second, and third rotations of *A. mearnsii* plantation, respectively. Center - indicates the center of each subarea, used as a starting point for field selection.

Number of sampled fields by study:

- **Paper I** - a total of 96 fields representing 16 land use categories were sampled. These included 72 *A. mearnsii* fields stratified by rotation (1-3 rotations) and stand age (3-6 years), as well as 5 cropland, 6 open/grazing land, 6 natural forest, and 7 FAM fields.
- **Paper II** - a total of 49 fields representing 37 *A. mearnsii* plantation stratified by rotation (1-3 rotations) and stand age (5-6 years), 5 cropland and 7 FAM fields.
- **Paper III** - a total of 84 fields representing 72 *A. mearnsii* fields stratified by rotation (1-3 rotations) and stand age (3-6 years), 5 cropland and 7 FAM fields.

4.4 Soil and biomass sampling

Soil samples were collected at the four corners and the center of the sampling plot at two depth intervals: 0-15 and 15-30 cm. Samples from the same depth at the five spots were pooled to a composite sample for each depth. Additional soil cores were collected for bulk density determination at the same depths.

Biomass samples were collected from *A. mearnsii* fields with stands aged three to six years. In each sampling plot, the total number of trees was recorded, and the diameter at breast height (DBH) and height of twenty representative trees were measured. DBH was measured at 1.3 m above the ground using a digital caliper, and tree height was measured using a graded bamboo stick. A representative tree corresponding to the average DBH and height was selected and destructively sampled. The tree was then divided into its components - stem, branches, leaves, and roots - and subsamples were collected from each component for laboratory analysis. Stem wood and bark samples were obtained from disks cut at five evenly spaced intervals along the stem. Plantations younger than three years were not present due to an outbreak of *Uromycladium acacia,* which began in early 2020 (Agena *et al.*, 2023). The disease largely affected younger stands and led farmers to discontinue planting of new trees.

4.5 Allometric model for biomass estimation (Paper I)

Aboveground biomass (AGB) was estimated using an allometric model fitted with diameter at breast height (DBH) and tree heigh (H) as predictor variables. Model performances were evaluated using R^2, RMSE, and Akaike information criteria (AIC). Below ground biomass (BGB) was subsequently estimated by applying a model that used the AGB as a predictor.

For stands younger than three years, biomass and plant density per hectare were estimated by combining data from existing literature with field measurements from older stands (3-6 years old). The biomass weight of one year old stands was obtained from Mekonnen *et al.* (2006), and initial planting density was obtained from Chanie and Abewa (2021). These literature based data were interpolated with the measured data from older stands (3-6 years old) with respect to stand age. Litter and soil C stocks for younger stands were also interpolated, assuming zero initial litter and baseline soil C from cropland, given the land use change from cropland. The complete model outputs are presented in **Paper I**.

4.6 Land cover classification (Paper I)

Land use and land cover (LULC) changes from 2005 to 2022 were assessed using imagery from Google Earth Pro. LULC classification was assessed at four time points: 2005, 2014, 2017, and 2022. The analysis was based on 302 grid points generated at 1500 m × 1500 m across the Fagita Lekoma district. Visual interpretation of satellite imagery was supported by ground truthing. Land use proportions were calculated by dividing the number of points classified under a specific land use type by the total number of points assessed. A detailed description of the procedure is available in **Paper I**.

The overall landscape C stock for each of the time points was estimated by aggregating the C stocks of individual land use types. For *A. mearnsii*, the stand age determined from LULC assessment, was integrated with biomass and soil C data. Biomass C stock was assumed to be 50% of its dry matter content. The C stock for all other land use types was calculated based on their respective areas at each time point and the soil data.

4.7 Laboratory analysis

4.7.1 Sample processing

All soil samples were air dried and passed through a 2 mm sieve prior to laboratory analysis. Bulk density was determined by drying the core samples at 105°C for 24 hours. Biomass samples were dried at 65°C to constant weight, then ground and sieved through a 2 mm mesh. Laboratory analysis was performed on biomass samples from stands aged five and six years to quantify the nutrient content at the time of harvest.

4.7.2 Carbon and nitrogen analysis (Paper I and II)

The C and N content in the soil and biomass were determined through dry combustion according to ISO 10694 (1995) and ISO 13878 (1998), respectively, using an elemental analyzer (TruMac® CN, Leco Corp, St. Joseph, MI, USA), with a combustion temperature of 1350°C.

Abundances of the stable isotopes $\delta^{13}C$ and $\delta^{15}N$ were measured in 96 soil samples collected from the two sampled depth intervals, 0-15 cm and 15-30 cm. They comprised 24 soil samples each, from first-, second-, and third-rotation *A. mearnsii* plantations with stand aged of 5 and 6 years, as well as 10 from croplands and 14 from FAM. Similarly, abundances of the stable isotopes $\delta^{13}C$ and $\delta^{15}N$ were measured in 49 biomass samples. These comprised 24 *A. mearnsii* leaf samples, representing stands aged three to six years, and one leaf sample from a non-N fixing reference species, *Croton macrostachyus*. In addition, six samples each of stem, bark, root, and branch collected from stand aged six years were analyzed.

The stable isotope values $\delta^{13}C$ and $\delta^{15}N$ were expressed in parts per thousand (‰) relative to the Vienna Pee Dee Belemnite (VPDB) standard for $\delta^{13}C$ and to the atmospheric N for $\delta^{15}N$:

$$\delta^{13}C_{(‰)} = (\frac{R_{sample}}{R_{standard}} - 1)1000 \qquad \text{Eq. 1}$$

$$\delta^{15}N_{(‰)} = (\frac{R_{sample}}{R_{standard}} - 1)1000 \qquad \text{Eq. 2}$$

where R denotes the ratio of $^{13}C/^{12}C$ and $^{15}N/^{14}N$ in sample and standard.

The $\delta^{15}N$ values were used to estimate the proportion of N derived from biological N fixation by *A. mearnsii* using equation by Shearer and Kohl (1986) as follows:

$$\%Ndfa = \frac{\delta^{15}N_{Rp} - \delta^{15}N_{AM}}{\delta^{15}N_{Rp} - B} 100 \qquad \text{Eq. 3}$$

where:

%Ndfa = the percentage of plant N derived from atmospheric N,
$\delta^{15}N_{Rp}$ = the ^{15}N value of the non-N fixing reference plant,
$\delta^{15}N_{AM}$ = the ^{15}N value of *A. mearnsii*,
B = the $\delta^{15}N$ value of *A.mearnsii* grown in an N free medium obtaining its entire N from N fixation.

Due to absence of locally determined B value, a value of -1.76 was used in this study, based on the recommendation by Unkovich *et al.* (2008). The percentage of soil C and N derived from *A. mearnsii* were based on the mean values presented in Table 5. The decision criteria for $\delta^{13}C$ and $\delta^{15}N$ were a minimum $\delta^{13}C$ difference of 15‰ between the C_3 *A. mearnsii* and C_4 teff (Balesdent and Mariotti, 1996), and a statistically significant difference in $\delta^{15}N$ between the reference plant and *A. mearnsii* (Forrester *et al.*, 2007). A statistically significant difference between the reference cropland soil and the soil under *A. mearnsii* cultivation was used to confirm the presence of C and N derived from *A. mearnsii*. If the $\delta^{13}C$ values did not differ significantly between cropland soil and soil under successive *A. mearnsii* cultivation, but the $\delta^{15}N$ values showed a significant difference, then the C:N ratio was used to estimate the proportion of C derived from *A. mearnsii*, based on the quantified N contribution from *A. mearnsii*.

4.7.3 Chemical extraction (Paper II and III)

The concentrations of plant available nutrients in the soil samples were determined using the Mehlich-3 extraction procedure (Mehlich, 1984). All soil samples were extracted, and the concentration of phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), and sulfur (S) in the extract was measured using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES).

Nutrient concentrations in biomass samples were determined after digesting in a mixture of nitric acid and hydrogen peroxide with trace amount of hydrogen fluoride according to a standard procedure of SS-EN 13805:2014. The solution obtained was analyzed for the concentration of P, K, Mg, Ca, and S using Inductively Coupled Plasma Sector Field Mass Spectroscopy (ICP-SFMS).

Soil pH was measured in 0.01 M $CaCl_2$ in a 1:5 soil to solution ratio after shaking the mixture for 1 hour. Exchangeable acidity was determined after extracting the soil in 1M KCl solution. A 10 mL aliquot of the extract was diluted to 25 mL and titrated to a pH endpoint of 7 using 0.02 M NaOH.

4.7.4 Enzyme assay and permanganate oxidizable carbon analysis (Paper III)

Acid phosphatase enzyme activity was determined as described by Tabatabai and Bremner (1969), with optimization recommended by Margenot *et al.* (2018). All assays were performed in triplicate, with the third replicate used as control. Each assay mixture comprised of 1 g of air-dried soil mixed with

4 mL of modified universal buffer (MUB) at pH 6.5 and 1 mL of *p*-nitrophenyl phosphate (PNP) solution prepared in the same MUB solution. The mixture was incubated for 1 h at 37°C, after which the reaction was terminated by adding 4 mL of 0.2 M NaOH and 1 mL of 2 M $CaCl_2$. For the control samples, the PNP solution was added after the reaction was terminated. The mixtures were filtered, and the absorbance of the resulting filtrates was measured colorimetrically at 410 nm. The activity was expressed as µmol p-nitrophenol released per gram of soil per hour (µmol pNP g^{-1} soil h^{-1}).

Permanganate oxidizable C (POXC) was measured as the colorimetric change from the reduction of the manganese in a 0.2 M $KMnO_4$ solution according to the protocol developed by Weil *et al.* (2003). For each sample, the soil was mixed with 18 mL of milli-Q water and 2 mL of 0.2 M $KMnO_4$ prepared in 0.1M $CaCl_2$. The mixture was manually shaken for 2 minutes and then allowed to settle for 8 minutes. A 0.5 mL aliquot of the supernatant was then diluted with 49.5 mL of Milli-Q water. The absorbance of the remaining MnO_4^- in the diluted supernatant was then measured at 550 nm using a spectrophotometer. The POXC was calculated using a calibration curve built from the absorbance values of standard permanganate solutions (**Paper III**).

4.8 Nutrient stock calculations (Paper II and III)

Nutrient stocks of N, P, K, S, Ca, and Mg were estimated for both biomass and soil. Stocks of nutrients in biomass were estimated as the product of nutrient concentration in each biomass component and the corresponding dry matter weight (Eq. 4). Stocks of nutrients in soil were calculated as the product of bulk density, sampling layer thickness, and nutrient concentration within the respective soil depth (Eq. 5). The bulk density of the soil was corrected for the coarse fraction and subsequently adjusted according to the method specified by Fowler *et al.* (2023).

$$NS_t = \sum(DM_i \times N_i) \qquad \text{Eq. 4}$$

where:

NS_t = total nutrient stock in the tree in kg ha^{-1},
DM_i = dry matter of tree component *i*,
N_i = nutrient concentration of tree component *i*.

$$NS_s = \sum(\rho_i \times t_i \times C_i) \qquad \text{Eq. 5}$$

where:

NS_s = soil nutrient stock,

ρ_i = soil density at the i^{th} depth,

t_i = thickness of the layer at i^{th} depth,

C_i = nutrient concentration in the soil at the i^{th} depth.

4.9 Nutrient and acid budget estimation (paper II and III)

The nutrient budget was determined as the net difference between total inputs and outputs. Inputs included fertilizer application to teff, biological N fixation by *A. mearnsii*, ash return from on-site charcoal production in *A. mearnsii* and atmospheric deposition. Outputs included nutrient removal through teff crop harvest, litterfall and woody biomass harvest of *A. mearnsii* for charcoal and firewood, and leaching, erosion, and gaseous losses in both production systems. Two biomass management scenarios were considered for *A. mearnsii*: whole biomass harvest (WBH) and leaf retained on site (LRS). WBH represented the current dominant harvesting practice, where leaves and twigs are removed from the field before subsequent agricultural activities. Conversely, LRS is a potential alternative that involves returning the nutrients in the leaves to the soil.

Fertilizer input data were based on Elias (2017) and ESS (2022). Atmospheric deposition data were obtained from two separate studies. Data for N were obtained from Mulualem *et al.* (2024), who conducted measurement in an area near the study watershed. Deposition data for all other elements were obtained from Ashagrie and Zech (2010), based on their measurements in the Rift Valley region of Ethiopia. Nitrogen fixation by *A. mearnsii* was quantified using Eq. 3. Ash input was estimated using a mass balance approach based on laboratory determined ash content in *A. mearnsii* wood, the ash content of *A. mearnsii* charcoal presented by Cromarty *et al.* (2023), and the charcoal conversion efficiency of traditional kilns reported by Tazebew *et al.* (2023).

Nutrient export through teff grain and residue harvest was quantified using data synthesized from published studies (presented in **Paper II**). Nutrient export from *A. mearnsii* fields was estimated based on nutrient stocks in biomass at stand age five and six years (Eq. 4). Loss in erosion was estimated using soil loss estimate from different land uses in the area presented by Ter Borg (2020), with additional proxy data from Erkossa *et al.* (2015) and pedotransfer functions recommended by Smaling *et al.* (1993). Nutrients in litter layer were estimated using the measured litter layer mass and nutrient resorption ratios of senesced leaves relative to fresh leaves. Due to the lack of mineral weathering and organic matter mineralization rates data, their contributions to the nutrient budget were estimated as the unexplained input required to balance total outputs. A nutrition budget, where the output exceeded known inputs, was considered to indicate soil organic matter (SOM) mineralization. Conversely, a budget where output was lower than input was considered to indicate immobilization.

An acid budget was estimated using the same input and output data as for the nutrient budget. The budget was calculated as net H^+ flux from nutrient uptake by biomass, atmospheric deposition, leaching, litter decomposition, and ash from charcoal making. The net acidity produced from nutrient uptake was calculated using proton production and consumption fluxes according to the principles of mass conservation and electro-neutrality (Bredemeier, 1987). Cation uptake contributed to proton production, whereas anion uptake resulted in proton consumption as follows:

$$\text{Net } H^+ = (NH_4^+ + K^+ + Ca^{2+} + Mg^{2+} + Na^+) - (H_2PO_4^- + SO_4^{2-})$$

Nitrate (NO_3^-) was excluded from the anion term because N uptake either as ammonium (NH_4^+) or NO_3^-, which has been nitrified from NH_4^+, results in a net production of one H^+. The phosphate anion is represented as dihydrogen phosphate ($H_2PO_4^-$), which is the dominant form of available phosphorus in acidic soils (Tan, 2010). Although N fixation by itself is not an acidifying process (Van Breemen *et al.*, 1983; Binkley and Richter, 1987; Bolan *et al.*, 1991), the subsequent assimilation of fixed N results in 0.1 to 0.2 H^+ per N assimilated in temperate and tropical regions, respectively (Raven and Smith, 1976). Given that the study area is a subtropical climate (Fazzini *et al.*, 2015), the average of these two values was applied in this study. The N fixation rate of *A. mearnsii* was based on Eq. 3, while major nutrient uptake was estimated based on Eq.4. For teff, nutrient uptake was based on detailed data presented in **Paper II**.

4.10 Statistical analysis

All statistical analyses were conducted in R version 4.2.3 (R Core Team, 2023). Mixed effects models were fitted to assess the effects of land use on soil parameters, with land use as fixed effect and subareas as a random effect. The models were fitted using the *lme* function from the *nlme* package. When model assumptions were violated, response variables were transformed into logarithms or square root values, depending on which best fulfilled the assumptions. Post-hoc comparisons were performed using the *emmeans* package with Tukey adjustment for multiple comparisons. All results are presented as means ± 95% confidence intervals. The confidence interval for aggregated means represents the cumulative uncertainty propagated from individual components. Statistical significance was evaluated at p=0.05.

5. Results

5.1 Land use change (Paper I)

Land use land cover change between 2005 and 2022 was characterized by a significant expansion of *A. mearnsii* cultivation at the expense of cropland. While cropland covered more than 65% of the district area in 2005, this decreased to below 30% in 2017. Imagery analysis using Google Earth Pro showed that SRF cultivation increased by more than 28,000 ha between 2005 and 2017, accounting for over 40% of the total area of the district. However, the pace slowed after 2017 with only 5% of cropland from prior period converted to new plantations. In contrast, a reversal trend emerged, with 18% of the land formerly under *A. mearnsii* was converted back to cropland (FAM). By 2022, the area under cropland, including FAM, accounted for 50% of the total area, while *A. mearnsii* covered 25%. Between 2005 and 2022, 60% of the fields originally under cropland in 2005 had been planted with *A. mearnsii* at least once over the period. Additionally, 7% of open/grazing land was converted to *A. mearnsii* during the period.

5.2 Dry matter yield (Paper I and II)

The average total dry matter biomass yield of *A. mearnsii* at expected harvest age was 151 Mg ha^{-1}, with woody stems and branches accounting for 62% and 15% of the total mass, respectively (Table 1). Barks, roots and leaves with twigs accounted for smaller proportions. The average annual accumulation rate is seven times higher than that of teff (3.77 Mg ha^{-1} y^{-1}), based on a teff yield of 980 kg ha^{-1} (Nigussie *et al.*, 2020) and an average harvest index of 0.26, compiled from different studies presented in **Paper II**.

Table 1. Dry matter weight of *A. mearnsii* biomass components in Mg ha^{-1} at the expected harvest age.

Component	Sample size	Dry matter weight	Annual accumulation
Stem	12	93.4 ± 22.0	17.0 ± 4.00
Bark	12	13.0 ± 6.24	2.36 ± 1.13
Root	12	11.6 ± 3.17	2.11 ± 0.58
Branch	12	22.1 ± 5.20	4.02 ± 0.95
Leaf	12	10.7 ± 2.28	1.95 ± 0.41
Sum		151 ± 31.3	27.5 ± 5.69

Note: Values are mean ± confidence interval (95%). Reproduced from **Paper II**.

5.3 Carbon and nitrogen in biomass (Paper I and II)

The total C stock in biomass and the litter layer increased from 20.8 ± 8.3 Mg C ha^{-1} at age three to 98.3 ± 14.7 Mg C ha^{-1} by age six (Figure 5). At the typical harvest age, stand aged five and six years, the average C stock is 78.9 ± 22.4 Mg C ha^{-1}.

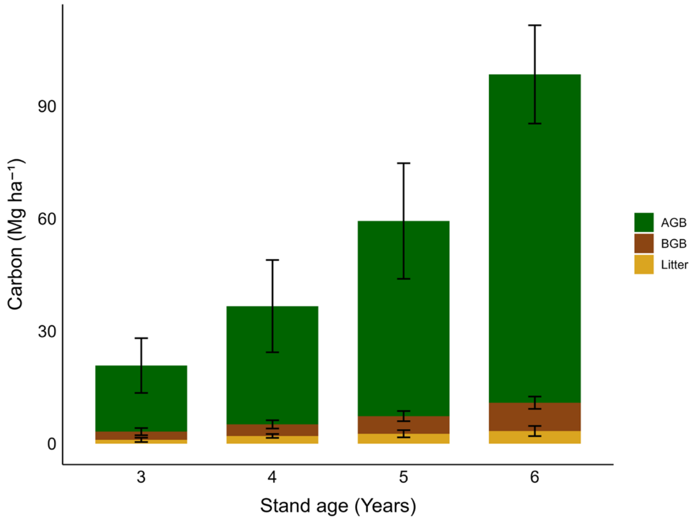

Figure 5.Total C stock in above and below ground biomass and litter layer by stand age in Mg ha^{-1}.
Note: Bars indicate mean ± CI (95%). Reproduced from **Paper I**.

At the typical harvest age, fine roots constituted 47% of the BGB with an average C stock of 2.89 Mg C ha^{-1} (Table 2), while the litter layer represented an average of 3.00 Mg C ha^{-1} (Figure 3). This corresponds to annual C inputs of 0.53 Mg C ha^{-1} y^{-1} from fine roots and 0.54 Mg C ha^{-1} y^{-1} from litter, resulting in a total potential in field C retention of 1.07 Mg C ha^{-1} y^{-1}. The biomass in coarse roots is not recycled to the soil for reasons discussed in Section 6.3.

Table 2. Estimated C in BGB of *A. mearnsii* by size class and soil depth at the typical harvest age in Mg ha^{-1}.

Stand age	Depth	Fine roots C	Coarse roots C
5	0-20	1.56 ± 0.45	1.80 ± 0.52
	20-40	0.67 ± 0.19	0.67 ± 0.19
6	0-20	2.27 ± 0.49	2.78 ± 0.60
	20-40	1.28 ± 0.28	1.21 ± 0.26
Mean	0-20	1.91 ± 0.67	2.29 ± 0.80
	20-40	0.98 ± 0.34	0.94 ± 0.33

Note: Values indicate mean ± CI (95%). Fine roots (< 5 mm diameter) and coarse roots (> 5 mm diameter). Adopted from paper I.

Table 3 presents the proportion of N derived from atmospheric N fixation by different biomass components of *A. mearnsii*, along with the corresponding quantity of N fixed over a rotation period. At the typical harvest age, *A. mearnsii* had fixed 960 kg N ha^{-1} over the rotation, equivalent to 175 kg N ha^{-1} y^{-1}. Stems exhibited the highest %Ndfa, whereas leaves and twigs accounted for the largest absolute N contributions.

Table 3. $\delta^{15}N$ and proportion of N derived from atmospheric N fixation by *A. mearnsii* in different biomass components over a rotation period.

	N	$\delta^{15}N$ ‰	%Ndfa	N_2 fixed in kg ha^{-1}
Acacia mearnsii				
Stem	6	-2.34 ± 0.95	100%	201 ± 23.6
Bark	6	-0.52 ± 0.97	79%	125 ± 10.8
Branches	6	-1.15 ± 0.81	90%	173 ± 18.7
Roots	6	-0.65 ± 1.15	81%	47.1 ± 6.18
Leaves	24	-1.05 ± 0.25	83%	256 ± 9.30
Litter fall				158 ± 12.4
Total			87%	960 ± 36.1
Croton macrostachyus[2]	1	4.08		

Note: The N fixed in the litterfall was estimated as the product of N concentration in fresh leaves, the proportion of N not resorbed prior to senescence as presented by Railoun *et al.* (2021), measured litter dry matter, and the proportion of N derived from atmospheric N fixation (%Ndfa). Values indicate mean ± CI (95%). The detailed analysis is presented in **Paper II**.

5.4 Nutrient accumulation in biomass (Paper II)

The annual nutrient accumulation rate in biomass components of teff crop and *A. mearnsii* stand is presented in Table 4. The accumulation rate of base cations in *A. mearnsii* was more than three times higher than in teff crop while the N accumulation was five times higher. However, P and S accumulation rates were comparable to teff. Among the biomass components, leaves had the lowest dry matter weight but contained the highest nutrient stock, followed by bark.

[2] Reference plant

Table 4. Average nutrient accumulation in standing biomass of teff and *A. mearnsii* at harvest (kg ha^{-1} y^{-1}).

		N	P	K	S	Ca	Mg
Teff	Grain	15.3	4.10	3.97	1.60	1.52	1.87
	straw	15.7	3.24	29.3	4.10	9.20	5.30
	Total	**31.0**	**7.35**	**33.2**	**5.69**	**10.7**	**7.15**
A. mearnsii	Stem	36.5	2.67	26.4	2.05	17.8	4.49
	Bark	28.7	0.97	8.67	0.97	19.1	3.02
	Root	5.82	0.38	1.95	0.61	2.69	0.44
	Branch	35.1	2.18	19.5	1.91	15.9	3.75
	Leaf	56.0	2.45	15.1	2.96	17.3	4.00
	Total	**162**	**8.65**	**71.6**	**8.51**	**72.7**	**15.7**

Note: adopted from **Paper II**. Values for *A. mearnsii* were converted to annual accumulation rates using an average rotation length of 5.5 years. For detailed information, including error terms associated with the reported means, refer to Table 3 in **Paper II**.

5.5 Carbon and nitrogen in soil (Paper I and II)

Figure 6 and 7 present the soil C and N stock in cropland and successive *A. mearnsii* rotations. Although C and N stock increased with stand age within each rotation, the stocks were lower in successive rotations when compared to the one preceding it. The average C stock in the third rotation was significantly lower than in the first rotation (Figure 7a). At the typical harvest ages, the C stock in third rotation was 37.7 Mg ha^{-1} lower than in the first at the same age. This corresponds to an annual average decrease of 3.43 Mg C ha^{-1} y^{-1} between the two rotations. Similarly, successive rotations had lower N stocks, with the second and third rotations in the 0-15 cm layer showing significantly lower N stocks compared to the first (Figure 7b).

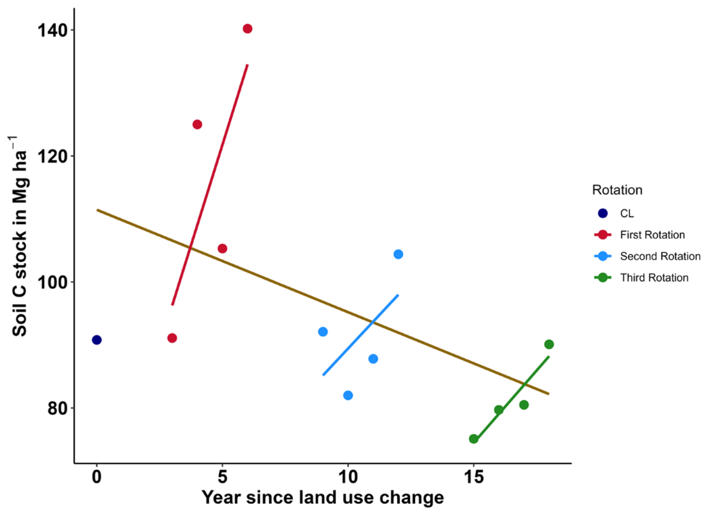

Figure 6. Soil C stocks (Mg ha^{-1}) by stand age across successive rotations.
Note: CL refers to cropland and represents the initial (year zero) soil C stock. Each point within the respective rotations corresponds to stand ages between three to six years. The dark yellow regression line represents the general trend of C stock change over successive rotations.

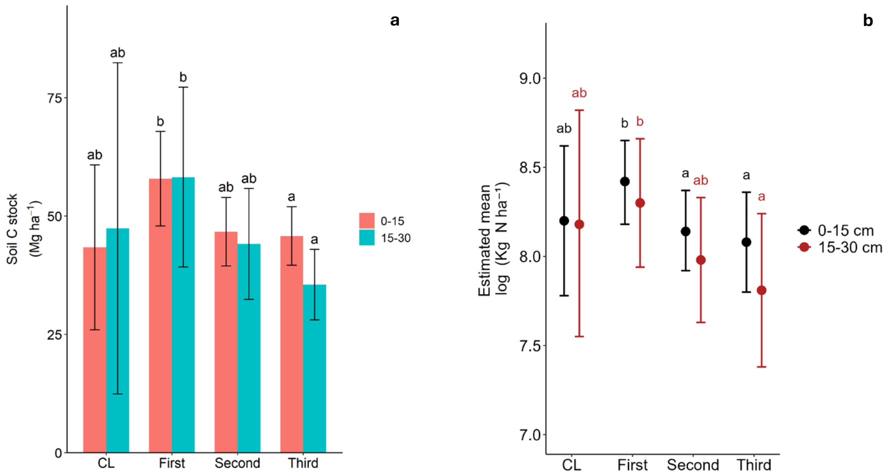

Figure 7.(a) Average soil C stocks by rotation and (b) soil N stocks by rotations.
Note: Values indicate mean ± CI (95%). Mean values sharing the same letter are not significantly different. In plot b, values presented are on a natural logarithmic scale. The plots are reproduced from **Paper I** and **II**, respectively.

Soil $\delta^{15}N$ values in the 0-15 cm layer were significantly lower in the second and third rotation of *A. mearnsii* plantations compared to cropland (Table 5). However, $\delta^{15}N$ values did not differ significantly between cropland and first rotation *A. mearnsii* and FAM soils. Similarly, no significant differences in $\delta^{15}N$ were observed at the 15-30 cm layer. For C, $\delta^{13}C$ values did not differ significantly between cropland and *A. mearnsii* rotation cycles. As a result, isotopic fractionation method could not be used to estimate C derived from *A. mearnsii*. However, in soils where $\delta^{15}N$ depletion was observed, the C:N ratio was used as an alternative approach and the C input from *A. mearnsii* was estimated to be 1.27 Mg ha^{-1} y^{-1} and 0.87 Mg ha^{-1} y^{-1} in the second and third rotations, respectively, with an average of 1.05 Mg C ha^{-1} y^{-1}.

Table 5. Average $\delta^{15}N$ ‰ and $\delta^{13}C$ ‰ values of soil under cropland and different rotation of *A. mearnsii* cultivation and corresponding estimates of N and C derived from *A. mearnsii*.

Land use	Depth	$\delta^{15}N$ ‰	%N fixed	N fixed kg N ha^{-1} y^{-1}	C:N ratio	$\delta^{13}C$ ‰	C derived from AM Mg ha^{-1} y^{-1}
CL	0-15	6.83 ± 1.54			12.2	-18.6 ± 1.1	
	15-30	6.93 ± 1.46			12.0	-18.1 ± 1.3	
FAM	0-15	6.42 ± 1.02			12.7	-19.1 ± 1.0	
	15-30	6.80 ± 0.82			12.8	-17.8 ± 1.4	
First rotation	0-15	5.67 ± 0.61			12.4	-19.5 ± 0.8	
	15-30	6.09 ± 0.70			12.2	-18.8 ± 0.8	
Second rotation	0-15	4.63 ± 1.62*	26%	84	13.2	-20.4 ± 1.6	1.27
	15-30	5.72 ± 1.02			12.8	-18.4 ± 1.5	
Third rotation	0-15	4.78 ± 1.44*	24%	54	13.4	-20.2 ± 1.2	0.83
	15-30	5.61 ± 1.26			12.9	-18.4 ± 1.4	

Note: Values indicate mean ± CI (95%). Mean values followed by different letters are statistically different at $p < 0.05$. The annual N derived from *A. mearnsii* were calculated by dividing the total N attributed to *A. mearnsii* by 5.5, 11, and 16.5 for the first, second, and third rotations, respectively. These values correspond to the cumulative years since land use change for each rotation, based on a typical harvest age of 5 to 6 years and an average rotation length of 5.5 years. Annual C derived from *A. mearnsii* were estimated using soil C:N ratios following confirmation of N fixation through significant $\delta^{15}N$ depletion compared to cropland soils. Abbreviation: AM – *A. mearnsii.* The asterisk (*) indicates a statistically significant difference.

5.6 Landscape carbon stock balance

Figure 8 presents the net C sequestered for the respective years, along with the area under *A. mearnsii* cultivation. Although soil C stocks were lower in successive rotations, the total landscape C stock increased by 1.41 Tg, representing a 21% increase compared to the initial total landscape C stock in 2005. This increase is driven by C accumulation in *A. mearnsii* biomass.

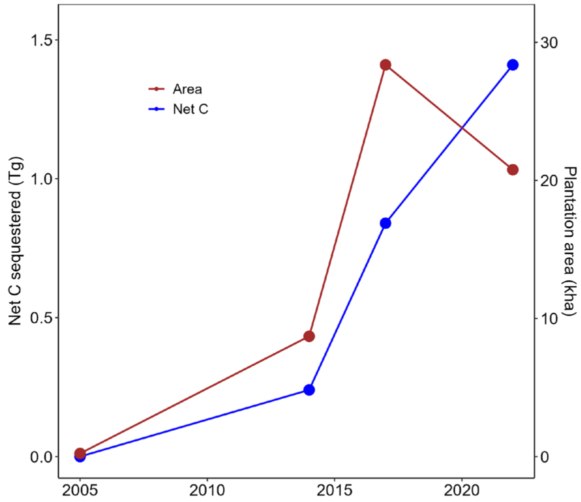

Figure 8. Change in area under *A. mearnsii* plantation and the corresponding net C sequestered in Fagita Lekoma between 2005 and 2022.
Reproduced from **Paper I**.

5.7 Nutrient and acid budget (Paper II and III)

A comparative analysis of nutrient budgets between *A. mearnsii* under the two harvest scenarios and the traditional teff production system showed that both systems resulted in soil nutrient depletion. The depletion was higher in *A. mearnsii* than teff, with all measured nutrients, N, P, K, S, Ca, and Mg showing depletion under both harvest scenarios. Under the current harvest regime (WBH) for *A. mearnsii*, N and base cation depletion rates were 3.5 and 2.5 times higher, respectively, than in the teff cultivation system. The depletion of N is after accounting for the contribution of biological N fixation. In contrast, under the LRS scenario, N depletion reduces to 1.5 times higher than teff, whereas base cation depletion is twice as high as teff. While teff maintains a near steady state P and S budget, *A. mearnsii* results in depletions of 10-13 kg P ha^{-1} y^{-1} and 7-10 kg S ha^{-1} y^{-1}. The cumulative nutrient depletion from teff production over 17 years is equivalent to the nutrient depletion from a single *A. mearnsii* rotation.

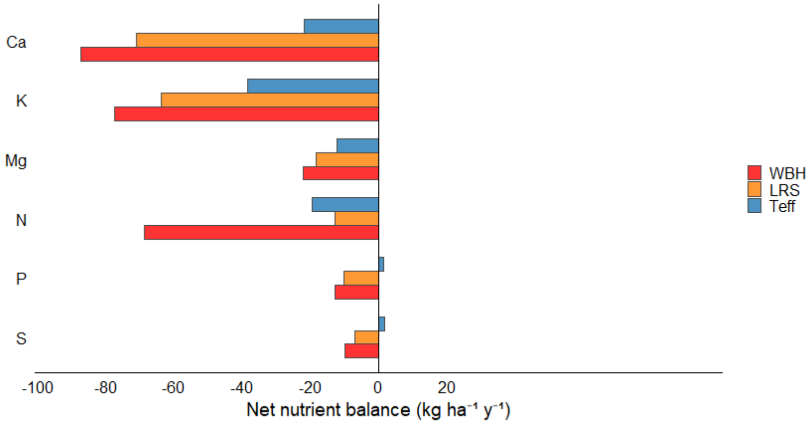

Figure 9. Net nutrient balance in teff and *A. mearnsii* cultivation systems under two harvest scenarios.
Note: the vertical axis represents the steady-state nutrient level, with values to the left indicating nutrient depletion and values to the right indicating nutrient immobilization. WBH and LRS in the legend represent whole biomass harvest and leaf retention on the production site, respectively.

The proton budget analysis also showed that the annual acid load in soil under *A. mearnsii* was 60% higher than under teff cultivation. The dominant source of acidity was nutrient uptake by biomass, producing 9.14 kmol H^+ ha^{-1} y^{-1} in *A. mearnsii* and 3.7 kmol H^+ ha^{-1} y^{-1} in teff. In *A. mearnsii*, the major acidifying process during nutrient uptake is the excess uptake of base cations over anions, due to N fixation, which is then followed by N assimilation into biomass. Nitrogen uptake is the dominant acidifying process among nutrient uptake in teff cultivation.

Average soil pH values in the 0-15 cm layer were lower in successive rotations compared to the cropland, with differences of -0.1, -0.14, and -0.1 units for the first-, second-, and third rotations, respectively (Table 6). Similarly, in the 15-30 cm soil layer, average pH values were lower in successive rotations compared to the cropland, with difference of -0.02, -0.07, and 0.02 units, for the first, second, and third rotations, respectively. However, none of these differences were statistically significant. Corresponding with the pH trend, the average exchangeable soil acidity in the 0-30 cm layer increased by over 70%, from 31.7 kmol ha^{-1} under cropland to 54.5 kmol ha^{-1} in the third rotation of *A. mearnsii* (Table 6).The highest increase was observed at 0-15 cm layer. However, these increases were not statistically significant.

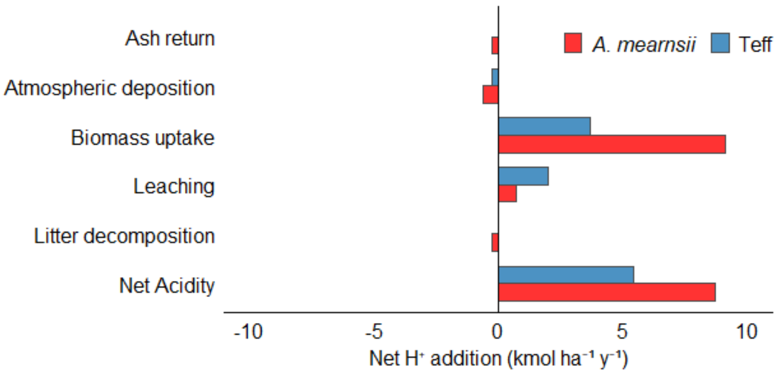

Figure 10. Acid producing and consuming biogeochemical processes, with corresponding net acidity produced and consumed in kmol ha^{-1} y^{-1}.
Note: the left side of the plot indicates net acid consuming process, while the right side indicates net acid producing processes, along with the net total acidity from all processes.

5.8 Soil biological processes (Paper III)

Land use change did not significantly affect phosphatase enzyme activity at either the 0-15 cm or 15-30 cm soil layer (Table 6). The relationship between phosphatase enzyme activity and SOC varied among the studied land uses. While no clear relationship was observed in cropland and FAM, a positive relationship between SOC and acid phosphatase activity was observed at both depths in natural forest soils, as presented in Figure 11. Conversely, a negative and statistically significant relationship was observed at soil depth 15-30 cm between SOC and phosphatase activity under the three rotations of *A. mearnsii*. A significant negative correlation was observed between phosphatase activity and available soil P at both depths (Figure 12). Conversely, the activity increased with an increasing pH across the measured range (Figure 13).

Table 6. Soil pH, total soil acidity, POXC concentration and phosphatase enzyme activities in soil under cropland and three different rotation cycles of *A. mearnsii* cultivations at the 0-15 and 15-30 cm soil layers.

	Depth	pH	Total acidity (kmol ha^{-1})	POXC (g C kg^{-1} soil)	Phosphatase (µmol p-NP g^{-1} soil h^{-1})
CL	0-15	4.68 ± 0.48	13.6 ± 16.3	0.68 ± 0.11[a]	1.81 ± 0.34[a]
	15-30	4.66 ± 0.52	18.1 ± 24.4	0.59 ± 0.11[ab]	1.57 ± 0.38[a]
First	0-15	4.57 ± 0.10	20.0 ± 8.08	0.72 ± 0.06[a]	1.96 ± 0.16[a]
	15-30	4.61 ± 0.12	20.3 ± 9.64	0.63 ± 0.06[b]	1.63 ± 0.19[a]
Second	0-15	4.51 ± 0.11	26.1 ± 9.76	0.66 ± 0.06[a]	1.81 ± 0.15[a]
	15-30	4.54 ± 0.13	28.1 ± 11.2	0.54 ± 0.05[a]	1.52 ± 0.17[a]
Third	0-15	4.41 ± 0.07	30.1 ± 6.92	0.67 ± 0.06[a]	1.90 ± 0.15[a]
	15-30	4.48 ± 0.08	24.4 ± 7.36	0.52 ± 0.06[a]	1.69 ± 0.18[a]

Note: First, second and third refer to the corresponding *A. mearnsii* successive rotations. Values presented are mean ± 95% CI. POXC concentrations are presented on a natural logarithm scale, while phosphatase activities are on a square root scale. Mean values followed by different letter indicate significant differences (p<0.05).

Permanganate oxidizable C in the 0-15 cm layer did not differ significantly from cropland. Although a significant difference was observed at 15-30 cm, this difference disappeared in pairwise comparisons between cropland and subsequent rotations. However, within the rotations, the second and third rotations showed significantly lower POXC than the first rotation (Table 6).

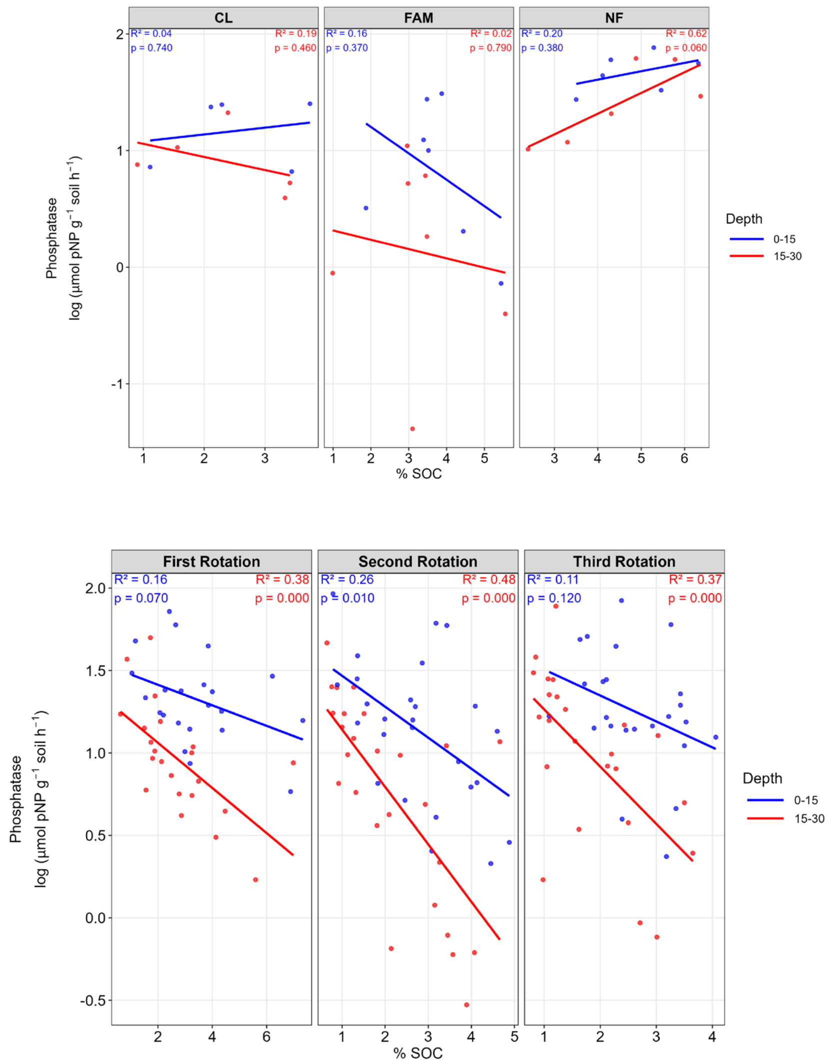

Figure 11. The relationship between SOC and phosphatase enzyme activity in soils under different management practice.

Note: phosphatase activity is presented on a logarithmic scale. CL = cropland; FAM = Former *A. mearnsii* field reverted to cropland; NF = natural forest; First, Second, and Third rotations = *A. mearnsii* fields under respective rotations.

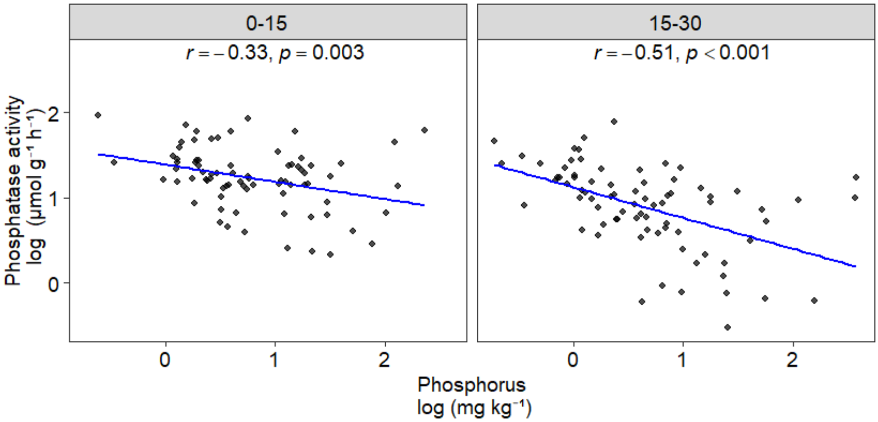

Figure 12. The relationship between acid phosphatase activity and Mehlich-3 extracted soil available phosphorus at 0-15 cm and 15-30 cm.
Note: both acid phosphatase activity and available phosphorus concentrations are presented on natural logarithm scale, and the *r* value indicates Pearson's correlation coefficient. The plots represent all soil samples under cropland and *A. mearnsii* cultivation.

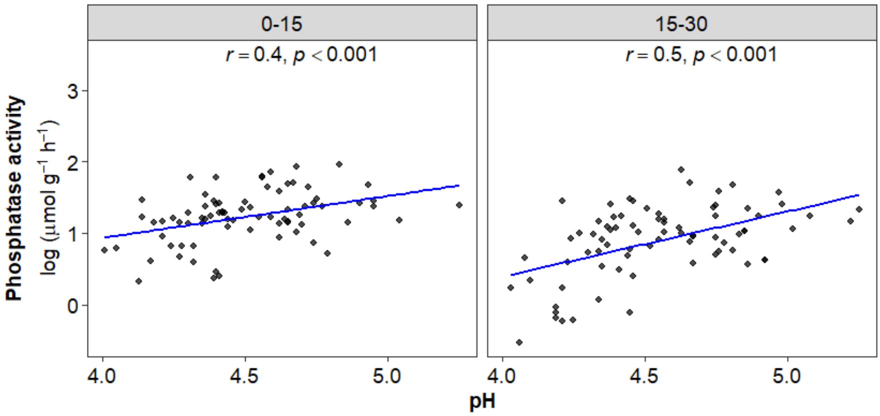

Figure 13. Acid phosphatase activity and soil pH correlation at 0-15 and 15-30 cm layers.
Note: Acid phosphatase activity is presented on natural logarithm scale, and the *r* value indicates Pearson's correlation coefficient. The plots represent all soil samples under cropland and *A. mearnsii* cultivation.

6. Discussion

6.1 Increased land use change from cropland to SRF

The main land use change observed in the area was the conversion of cropland to *A. mearnsii* plantation. Only 40% of the original cropland remained under cropland in 2022 while 60% had at least one plantation cycle between 2005 and 2022. Despite the expansion of the charcoal based economy in the area (Wondie and Mekuria, 2018), natural forest areas remained unaffected. Temporal satellite imagery showed increasing natural forest density, indicating that SRF plantation may have mitigated the deforestation pressure. However, SRF expansion was not sustained beyond 2017, as a reversal trend emerged. Between 2017 and 2022, approximately 25% of the area previously under *A. mearnsii* cultivation was converted back to cropland or left fallow. This was primarily driven by a fungal disease outbreak that affected the plantations since the beginning of 2020 (Agena *et al.*, 2023; Pham *et al.*, 2024). The disease mainly affected younger stands, leading farmers to discontinue establishment of new plantations.

I used a methodological approach to LULC change analysis that differed from conventional techniques. Traditional pixel based LULC classification approaches struggle to distinguish between natural forests and plantations due to spectral overlap (Ordway, 2015). This can confound interpretations of land cover change and introduce bias into area estimations. The use of high-resolution imagery in Google Earth Pro enables an accurate classification through manual visual interpretation (See *et al.*, 2013), thereby addressing the limitations of conventional methods. Historical imagery mosaics available through Google Earth Pro (Google, 2024) also play an important role in past land use classification. This functionality enables temporal assessment of LULC change, thereby allowing for the determination of past land cover types, the planting or harvesting dates of specific fields, the stand age of plantations, and the subsequent estimation of corresponding C stocks. This detailed field level analysis can then be aggregated to estimate the total C stock within a larger landscape. The free accessibility of this data, combined with the fact that its basic interpretation requires minimal specialized training, makes it a suitable tool for land use change monitoring for a wide array of users in low-income countries.

6.2 Biomass yields and organic input to the soil

The dry matter accumulation rate of *A. mearnsii* at the typical harvest age (27.5 Mg ha^{-1} y^{-1}) is comparable to a study by Kumar (2008), who reported an average between 22 and 27 Mg ha^{-1} y^{-1} for the species under little external input. The stem accounted for 62% of the total biomass weight corroborating the results by Kumar (2008) and Caldeira *et al.* (2014) who reported 60% and 64%, respectively. Although *A. mearnsii* showed high AGB accumulation, its BGB was proportionally low. Unlike the typical 15-25% reported for most tree species (Harris *et al.*, 1979), the BGB of *A. mearnsii* accounted for only 8% of the total biomass. However, the result is comparable to Kumar (2008) and Caldeira *et al.* (2014), who reported similar proportions of 4-6% and 11%, respectively.

Woody components of *A. mearnsii* are primarily used as feedstock for charcoal production, whereas components unsuitable for this purpose, such as stumps and large root systems, are also removed from the production site and used as firewood (Nigussie *et al.*, 2020; Kim *et al.*, 2022). Therefore, in addition to the relatively low proportion of BGB, a large portion, 53% of the BGB at the typical harvest age, is removed from the field. The intensive harvesting results in reduced organic inputs into the soil. Although the stand fixes significant amounts of C and N, most of these elements are removed from production sites in firewood and charcoal. As a result, fine roots represent the main soil C input that remain in the field under *A. mearnsii* cultivation.

6.3 Soil carbon stock

Despite significant C sequestration in the biomass, no corresponding increase in soil C stock was observed in the fields under *A. mearnsii* cultivation compared to cropland. One potential explanation for this discrepancy, highlighted in **Paper I** and **II**, is the limited BGB. The BGB of *A. mearnsii* is small and below the average reported for many woody plants (Harris *et al.*, 1979). While root derived C has a longer residence time and is the main driver of C buildup in soil (Rasse *et al.*, 2005), the relatively small proportion of *A. mearnsii*'s BGB limits this process. This is further compounded by harvesting practices that removes significant portion of the root biomass at harvest (Kim *et al.*, 2022), reducing organic inputs to the soil.

The low organic input is incompatible with the high nutrient demand of a fast-growing tree. *A. mearnsii* produces 27.5 Mg ha^{-1} y^{-1} of biomass compared to 3.77 Mg ha^{-1} y^{-1} for teff. However, unlike teff, the *A. mearnsii* production system receives no fertilizer input. The dominant soil type in the area is Acrisols (Regassa *et al.*, 2023) characterized by limited weatherable minerals and poor chemical properties (Driessen *et al.*, 2001). While biological N fixation meets most of the N demand (87%), and the stock of available base cations is sufficient (**Paper II**), P and S emerge as limiting nutrients. The concentrations of P and S in the studied soils are lower than those generally found in other Ethiopian highland soils (Melese *et al.*, 2015). Notably, these highland soils are themselves characterized by low levels of plant available organically cycled nutrients (Agegnehu *et al.*, 2015; Negash *et al.*, 2017). As a result, the tree must meet its P and S demand by mineralizing organically bound P and S from the SOM pool. This was evaluated based on net C mineralization data (**Paper I** and **II**), C:P (Spohn, 2020) and C:S ratios (Solomon *et al.*, 2001). The theoretical P and S released from SOM mineralization, 14 kg P ha^{-1} y^{-1} and 8.64 kg S ha^{-1} y^{-1}, closely matched the unexplained P and S input calculated for the *A. mearnsii* production system (10 - 13 kg P ha^{-1} y^{-1} and 7 -10 kg S ha^{-1} y^{-1}; **Paper II**). This indicates that SOC depletion is a result of SOM mineralization induced by roots or microbes to obtain P and S. It is possible that root exudates from *A. mearnsii*, coupled with microbial activity, stimulated SOM decomposition through a priming effect (Berg and Matzner, 1997; Dijkstra *et al.*, 2021).

The dynamics of SOC showed a contradiction when comparing trends within and between rotations. Within individual rotations, SOC increased as stands aged from three to six years, yet each new rotation started with lower initial SOC than at the end of the preceding rotation. This contradiction is best explained by a methodological artifact related to fine root fragments (Kuzyakov *et al.*, 2001). Although soil samples were passed through a 2 mm sieve, the possibility of fine root fragments remaining in the samples, and thereby inflating organic matter content, cannot be dismissed. Fine root density increased with stand age and was concentrated in the 0-20 cm soil layer (66%), where the apparent increase in organic matter also occurred. It is likely that the measurement included a considerable amount of fine root fragments. Stable isotope data of $\delta^{13}C$ and $\delta^{15}N$ supports this interpretation. The $\delta^{13}C$ values indicated no significant addition of new C to the soil, as there was no significant difference between *A. mearnsii* rotations and cropland.

However, indirect estimates based on $\delta^{15}N$ suggested that the average amount of "new C" added to the soil closely matched the average amount of C expected from fine roots and litter. Therefore, the within rotation increase likely indicates the accumulation of undecomposed biomass, whereas the decrease between rotations shows a genuine loss of stable SOC.

This methodological limitation may extend to other recent studies in the region that reported SOC gains under *A. mearnsii* plantations (Amare *et al.*, 2022; Kim *et al.*, 2022). While these studies similarly observed increased SOC in mature stands, their analyses did not integrate SOC development across stand age and over successive rotations. As a result, they likely missed detecting the long-term net soil C loss.

A review of existing literature shows a mixed result regarding SOC dynamics following plantation establishment on agricultural land. While some studies reported an increase (Dimitriou *et al.*, 2012; Berhongaray *et al.*, 2017), others showed a decrease (Cook *et al.*, 2016; Sabbatini *et al.*, 2016), and some found no net change (Lockwell *et al.*, 2012; Walter *et al.*, 2015). However, a consistent theme in the literature is the importance of management practices and the duration since land-use change. My review of literature showed that studies reporting significant SOC increases typically involved plantations that remained unharvested for two to three decades (Kasongo *et al.*, 2009; Nave *et al.*, 2013; Dubiez *et al.*, 2019; Zhang *et al.*, 2020b). Therefore, despite the favorable subtropical climate and N fixing ability of *A. mearnsii*, often associated with SOC accumulation (Paul *et al.*, 2002; Rytter and Rytter, 2020), the SOC was rather lower in successive rotations. Its limited BGB, the repeated short rotation harvesting and the mineralization of existing SOM limit the potential for long-term SOC accumulation.

6.4 Landscape carbon stock

Although soil C stocks were lower in successive rotations under *A. mearnsii*, the overall landscape functioned as a net C sink between 2005 and 2022. During this period, a total of 1.41 Tg of C was sequestered. This represented a 21% increase compared to the 2005 base year and was driven by C accumulation in biomass. This is equivalent to a removal of 5.17 Mt of CO_2 with an annual average sequestration rate of 0.3 Mt of CO_2. This sequestration took place in an area representing 0.17% of Ethiopia's total arable land in

2021(World Bank, 2021) and offset 2.3% of Ethiopia's fossil fuel emissions for the same year. The figure does not account for additional CO_2 sequestered from natural forest regeneration associated with SRF expansion (Figure 14). Forest density increased between 2005 and 2022 as pressure on natural forests for charcoal and firewood decreased.

Figure 14. Google Earth Pro satellite imagery showing the increase in natural forest density between 2005 (left panels) and 2024 (right panels).

6.5 Soil nitrogen

The estimated N fixation rate of 175 kg N ha^{-1} y^{-1} is comparable to the 200 kg N ha^{-1} y^{-1} previously reported for *A. mearnsii* in tropical regions (Orchard and Darb, 1956; Dreyfus *et al.*, 1987). However, this input did not result in a net accumulation of N in the soil, as total N was lower in successive rotations (Figure 7b). Soil δ^{15}N signatures only began to differ from the baseline cropland after the second rotation and only in the 0-15 cm layer (Table 5), indicating a 7 to 12 years lag before fixed N become detectable in the soil. Similarly, FAM fields, most of which had undergone only a single rotation, remained isotopically similar to cropland, suggesting that input from one rotation is not enough to change the isotopic signature of soil N. Despite the fact that N derived from *A. mearnsii* continued to be detected in the third rotation, the absolute amount was smaller than in the second rotation, because the total soil N was smaller than in preceding rotations. This implies that either less N fixation occurred in successive rotations, or that fixed N (low in $\delta^{15}N$) from earlier rotations was rapidly mineralized and reassimilated by the trees. It is likely that the former is more probable than the latter because the biochemical composition of *A. mearnsii* litter did not appear to result in rapid mineralization (section 6.8). A possible explanation for reduced N fixation is that the mineralization of existing SOM, to supply P and S, simultaneously released N. Nitrogen fixing trees would preferentially use the available mineralized N, as it is energetically less costly than fixing atmospheric N (Pearson and Vitousek, 2001). Another contributing factor is the P limitation observed in the soil in later rotations (**Paper II**). Given that P is a critical element for the energy intensive N fixation process (Binkley *et al.*, 2003; Batterman *et al.*, 2013), its limited availability in succussive rotations may have limited further N fixation.

The fixed N was only detectable on the top 0-15 cm soil layer. Even after three rotations (15-18 years), fixed N was only isotopically detectable within the upper 15 cm of the soil, suggesting a limited N input from *A. mearnsii* to deeper layers. This contrasts with Kim *et al.* (2022) who reported increased C accumulation down to a depth of 1 m.

The absence of a corresponding buildup in total N in the soil, despite N fixation, again shows limited organic input. This observation is consistent with de São José *et al.* (2024), who reported that although N fixation contributes to N nutrition in *A. mearnsii* stands, it is generally insufficient to meet the entire demand during the production cycle. Consistent with this, the isotopic signature of the N stock in *A. mearnsii* biomass showed that 87% was acquired from N fixation. Thus, the deficit is met through other N inputs or nutrient mining from the soil.

The N fixation estimate may be underestimated due to the conservative $\delta^{15}N$ value used in the %Ndfa calculation. Previous studies have used $\delta^{15}N$ value of -1.3 (Forrester *et al.*, 2007) and -1.56 (Tye and Drake, 2012) for *A. mearnsii* in Australia and South Africa, respectively. In the absence of a local B value, a value of -1.76 reported for *Sesbania sesban* (L.) Merr. in Kenya by Gathumbi *et al.* (2002) was used based on the recommendation provided by Unkovich *et al.* (2008).

6.6 Nutrient balance

The comparative nutrient budget analysis showed that short rotation *A. mearnsii* plantation is more nutrient depleting than the teff cultivation system it replaced. Although N fixation is a key aspect of *A. mearnsii* cultivation, the amount fixed was not sufficient to meet the demand over a full rotation, as discussed above. As the trees matured from stand age three to six years, the proportion of N demand met from the soil increased from 6% to 22% (**Paper II**). This reliance on SOM mining extends to P and S. The excess supply required to balance the output of P and S in the *A. mearnsii* system is currently met by the mineralization of the existing SOM pool. In contrast, teff cultivation maintains a balance for P and S due to fertilizer application. The difference between the systems is more pronounced for base cations. The annual removal of K, Ca, and Mg in harvested biomass is 110% (LRS) to 155% (WBH) higher compared to teff.

The long-term consequences of these differing depletion rates are considerable. The cumulative nutrient export from 17 years of continuous teff production is equivalent to the nutrient loss from a single rotation of *A. mearnsii* under the WBH. During this same period, *A. mearnsii* undergoes three rotations, resulting in considerably higher nutrient depletion.

In summary, the production system is limited by organically recycled nutrients (N, P, and S). While the current available base cation stocks are sufficient to support needs for several rotations (**Paper II**), future demands will require additional input due to low weathering rates of Acrisols (Driessen *et al.*, 2001). Both teff and *A. mearnsii* production systems face potential nutrient limitations in the future. However, the *A. mearnsii* based system is likely to reach critical thresholds sooner due to higher nutrient exports.

Several assumptions were made to estimate the nutrient budget of the production systems due to low availability of data. Empirical formulas, for example, were used to estimate inputs and outputs where measured data were unavailable. The empirical formulas for leaching and gaseous loss, for example, were based on rainfall and did not account for soil type, which may have led to over or underestimation. In some cases, the available measured data were from studies conducted in locations distant from the study area in the Rift Valley region of Ethiopia (Ashagrie and Zech, 2010). However, the assumptions were based on widely accepted methodologies, and the use of data from other part of Ethiopia provides a reasonable approximation, allowing a fair overview of the nutrient dynamics within the two production systems.

6.7 Soil acidity

The land use change from traditional teff cultivation to SRF with *A. mearnsii* drives a progressive soil acidification process. The proton budget analysis showed that the *A. mearnsii* system generated 60% higher net annual acid load to the soil compared to teff cultivation. The main cause of this increase is the excess cation uptake relative to anions. As an N fixing species, *A. mearnsii* takes up a higher ratio of cations to anions as compared to non N fixing plants (Bolan *et al.*, 1991). This process requires the plant to release protons (H^+) into the soil to maintain its internal charge balance. The process contributed to 70% of the proton production within the *A. mearnsii* system. In natural ecosystems, protons generated during biomass growth are neutralized upon decomposition, as base cations are released back into the soil. However, this natural process is disrupted in managed forestry systems. The removal of harvested biomass in these systems leads to export of cations from the production field, resulting in net soil acidification (Van Breemen *et al.*, 1983). In the teff cultivation system, soil acidification is driven by N input through fertilizer application and its subsequent removal through leaching, and harvest of grains and straw.

The calculated proton surplus is reflected in measured soil properties. Soil pH was lower in successive rotations, although this was not statistically significant. Also, a 57% increase in exchangeable acidity over successive rotations was observed (**Paper III**). This highlights a trade-off between biomass production and soil fertility management. The C sequestration benefits of this forestry system come at acidification cost of 0.64 kmol H^+ for every megagram of C sequestered. This value is at the higher end of the range reported in comparable studies (Fujii *et al.*, 2012). Given that the soils in the study area are already acidic with limited natural buffering capacity, this additional acid load poses a risk to long-term soil productivity. The acidity generated by *A. mearnsii* production requires almost double the lime required to neutralize the acidity in the teff production system (**Paper III**).

6.8 Soil biological processes

Acid phosphatase activity increased with decreasing soil available P and was, on average, higher in *A. mearnsii* cultivated fields than in cropland. However, these differences were not statistically significant despite decreasing soil available P in successive rotations (**Paper II**). The probable explanation is the quantity and quality of substrate in successive rotations. Studies show that the availability of organic P is more important in determining phosphatase activity than the level of P deficiency (Janes-Bassett *et al.*, 2022). Since SOC and POXC were lower in successive rotations, there was a limited organically bound P from legacy SOC to stimulate higher enzyme production. As a result, the depletion of legacy SOC may have reduced the expected phosphatase response to P deficiency. Furthermore, the biochemical properties of the newly added litter from *A. mearnsii* provide complementary explanation. Phosphatase activity is expected to increase with SOC to increase mobilization of organically bound P in P limited soils (Margalef *et al.*, 2017). The result in natural forest soils is consistent with this expected relationship. However, soils under *A. mearnsii* plantations presented a contradiction, showing a strong inverse relationship between acid phosphatase and SOC. Studies suggest that N fixing plants can enhance phosphatase activity because phosphatase is an N rich molecule, and biological N fixation provides a source of N for enzyme synthesis (Olander and Vitousek, 2000). This mechanism was suggested to provide a competitive advantage to N fixing trees in acquiring P from organic compounds in P limited soils, particularly in tropical regions (Li *et al.*, 2021). Despite this potential advantage, the strong inverse relation observed suggests that another possible factor is overriding the anticipated enzymatic response. The biochemical composition of *A. mearnsii* litter, particularly its high tannin concentration, may provide a possible explanation (Griffin *et al.*, 2011). Studies indicate that while low tannin concentrations enhance phosphatase enzyme activity, high concentrations (0.4% condensed tannins and 2% tannic acid) can reduce the activity by over 40% (Joanisse *et al.*, 2007; Adamczyk *et al.*, 2017). Although the bark is recognized as the primary source of tannin in *A. mearnsii*, its leaves also contain high concentrations (Xiong *et al.*, 2016). Therefore, the inhibitory effect of tannins on phosphatase enzyme activity may explain the absence of a significant increase in phosphatase activity, despite P limitation in successive rotations. The lack of SOC and phosphatase enzyme activity relationship in FAM and cropland was likely due to the absence of active cropping during the sampling. This means there was not a high demand for P mobilizing enzyme. Despite weak, however, the relationship in FAM soils is negative indicating a legacy effect of *A. mearnsii* derived SOM inputs on the enzyme activity.

The progressive soil acidification under *A. mearnsii* cultivation also creates less favorable conditions for phosphatase activity (Herbien and Neal, 1990; Fraser *et al.*, 2024). Previous studies by Herbien and Neal (1990) and Fraser *et al.* (2024) have shown that the optimum pH for acid phosphatase activity is around pH 5.0. Consistent with this, the result showed a significant linear increase in phosphatase activity with increasing soil pH (range: 4.01-5.25). Therefore, the lower soil pH observed under successive *A. mearnsii* rotations may have suppressed acid phosphatase activity.

The conventional sample treatment protocol for the phosphatase enzyme assay was not applied, which may have also influenced the result. The assay traditionally requires fresh or frozen soil samples, but this protocol could not be implemented due to the unavailability of reagents and a cold storage facility at the sampling location. As a result, soil samples were air dried and analyzed three months later. Air drying is reported to reduce phosphatase enzyme activity (Turner and Romero, 2010; Peoples and Koide, 2012). However, other studies found higher activity in tropical regions during dry seasons (Smith *et al.*, 2015; Schaap *et al.*, 2023). Given that all samples were treated identically and originated from a dry subtropical area, where extended dry seasons are common, the results should remain valid for comparative analysis.

Contrary to the expectation, SRF with *A. mearnsii* did not increase the POXC. It is likely that as the legacy C is mineralized and depleted over time, the newly added C has a smaller fraction of labile C available for microbial use due to its high tannin concentration (Triebwasser *et al.*, 2012). The lower POXC concentration with successive rotations indicates an early sign of SOC loss. This may potentially trigger a negative feedback loop, whereby reduced microbial activity limits nutrient availability and, in turn, limit tree growth in subsequent rotations.

6.9 Sustainable management

A sustainable forest production system requires a balance where inputs offset outputs to ensure long-term productivity (Ranger and Turpault, 1999). Considering this, the current system of short rotation biomass production for charcoal and firewood operates on an unsustainable basis. The WBH represents the most intensive nutrient depleting scenario. Although the possible alternative proposed, LRS, does not entirely solve the problem, with only a 7% reduction in harvested biomass, it can reduce depletion by 30%. Additionally, removing bark before making charcoal could further decrease exported nutrients by 20%. However, this depends on the development of a practical bark removal method.

Acidity and nutrient stock in the FAM soil remained closer to those under the *A. mearnsii* plantation than to long-term cropland values (**Paper II and III**). This shows that removing the tree alone is not sufficient to reverse the soil's nutrient status and acidification trajectory. As a result, in addition to less intensive harvesting practice, management practice should include external nutrient inputs to maintain productivity across multiple rotations. Particularly, P and S fertilization can help mitigate future production limitations. This could also promote increased plant growth and biomass production, potentially leading to increased C storage in soil over time. Furthermore, the application of lime is required to neutralize the acidity generated in these soils.

The disease outbreak that affected the plantation between 2020 and 2022 highlights the risks associated with the monoculture practices. This event exposed the vulnerability of the production system and the need for diversification. A future large-scale outbreak could result in the failure of livelihoods for a considerable number of people in the area who rely on the *A. mearnsii* value chain. Given the growing interest among local farmers in tree cultivation, policymakers must explore and promote alternative tree species for planting to mitigate these risks. If managed properly, the afforestation could simultaneously contribute to the preservation of remaining natural forests by supplying charcoal and fuel wood, act as a long-term CO_2 sink, and provide a sustainable income source for the smallholder farmers.

6.10 Study design limitation

The chronosequence approach assumes that spatial gradients represent long-term temporal changes (Johnson and Miyanishi, 2008). A potential limitation of this method is the influence of historical land-use decisions, wherein farmers may have progressively expanded *A. mearnsii* cultivation into more productive areas. As a result, the findings from the successive rotation might reflect historical land use decisions rather than the direct effects of land use change to *A. mearnsii* cultivation.

7. Conclusions

A significant land use change has taken place in the northwest of Ethiopia, where annual crop production has been replaced by SRF using *A. mearnsii*. This resulted in the conversion of 60% of fields under cropland in 2005 to SRF plantations by 2022.

The expansion of *A. mearnsii* cultivation in the area led to increased C sequestration in biomass. However, this was not followed by a corresponding increase in soil C. In contrast, successive rotations showed a lower soil C stocks, with the third rotation showing a significantly lower C stock than the first rotation. The main cause of C loss is probably root or microbial driven nutrient mining. This process depletes SOC and, consequently, undermines the long-term sustainability of the production system. However, the loss of C in soil is offset by high C accumulation in biomass, and the net sink corresponds to 2.3% of Ethiopia's fossil fuel emissions for the year 2021. Furthermore, the expansion of *A. mearnsii* has reduced the dependence on natural forests for charcoal and firewood production.

Despite N fixation by *A. mearnsii*, no corresponding increase in total N was observed in the soil. Subsequent rotations had lower N than the first with the third rotation significantly lower than the first. Although *A. mearnsii* fixes N, the fixed amount provided only 87% of the N demand of the trees over a rotation cycle.

The SRF systems acidify the soil more than teff production, due to assimilation of fixed N and a large base cation export from the field during harvest.

Given that the cultivation of *A. mearnsii* will continue as a livelihood option, proactive management practices are essential for long-term sustainability. These include retaining nutrient dense residues such as leaves, bark and twigs on the field. Additionally, distributing ash from charcoal production sites and returning ash from domestic fire use to the production site are crucial for replenishing important nutrients. Furthermore, applications of P and S fertilizer and lime are necessary to address current nutrient limitations and mitigate soil acidity.

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Popular science summary

Global energy demand continues to increase due to increasing population and economic growth. According to the International Energy Agency, developing economies were responsible for over 80% of the increase in global energy demand in 2024. However, a large part of this increase is met by fossil-fuel based energy systems and leads to greenhouse gas emissions and subsequent global warming. Balancing the increasing energy needs against climate mitigation targets presents a challenge.

Biomass based energy is a nature-based solution to climate change. When managed sustainably, biomass can be carbon neutral because the carbon dioxide released during burning is offset by the carbon dioxide taken up by the plants during their growth.

For many developing countries, including Ethiopia, biomass is already the main energy source, supplying more than 90% of the energy needs. However, the current biomass production in many regions depends on the unsustainable harvesting of forests. This accelerates environmental degradation and undermines climate goals. Cultivation of biomass in managed plantations offers a potentially more sustainable alternative.

In northwestern Ethiopian highlands, a large area of cropland has been converted to short rotation forestry in the last two decades. This change has been driven by a high urban demand for charcoal and the profit the charcoal production presents to the farmers. The tree cultivated is black wattle (*Acacia mearnsii*), a fast-growing species native to Australia. It is harvested in five-to-six-year cycles and converted to charcoal. Parts of the tree that are unsuitable for charcoal are used as firewood. The system has increased income for farmers and created job opportunities for youth and unemployed individuals at various stages of the value chain. It has also reduced the burden on women who previously walked long distances to collect and carry heavy loads of firewood. Although economically beneficial, the long-term environmental sustainability of this system requires careful assessment.

This thesis examined the environmental sustainability of the land use change to short rotation forestry by comparing it to the teff production system it replaced. The main finding is that the large-scale black wattle cultivation has increased the carbon stock in the landscape. The short rotation forestry sequestered carbon dioxide equivalent to 2.3% of Ethiopia's annual fossil fuel emissions and fixed 175 kg of nitrogen per hectare per year.

Despite this, the gains in biomass did not translate into gains in soil quality. Soil carbon and nitrogen did not increase as expected but rather declined over successive rotations. This is because the tree roots, in collaboration with microorganisms, break down soil organic matter to obtain nutrients like phosphorus and sulfur. It also takes up large quantities of base cations, which are removed from the field during harvest. As a result, the practice increases soil acidification in an area that already has problems with soil acidity.

In conclusion, the production system requires management intervention to become sustainable in the long term. These include retaining harvest residues on production sites to recycle nutrients back into the soil. In addition, application of phosphorus and sulfur fertilizers is essential to address the observed nutrient deficits, while lime application is necessary to counteract soil acidification. Despite the need for these management interventions, the cultivation of black wattle has reduced dependence on natural forest for charcoal and firewood production, which has led to the recovery of natural forest in the area.

Populärvetenskaplig sammanfattning

Energibehovet i världen fortsätter att öka på grund av växande befolkning och ekonomisk tillväxt. Enligt International Energy Agency stod utvecklingsländerna för över 80% av ökningen i den globala energiefterfrågan under 2024. En stor del av denna ökning sker genom ökat användande av fossila bränslen, vilket leder till utsläpp av växthusgaser och global uppvärmning. Det är en utmaning att balansera de ökande energibehoven mot klimatmålen.

Biomassabaserad energi kan minska växthusgasutsläppen. När den förvaltas på ett hållbart sätt kan den genererade energin bli nära koldioxidneutral eftersom den koldioxid som släpps ut vid förbränning motsvaras av den koldioxid som växterna tagit upp under sin tillväxt. För många utvecklingsländer, inklusive Etiopien, är ved och träkol den viktigaste energikällan och står för mer än 90% av energibehovet. Det nuvarande uttaget av trädbiomassa baseras på ett ohållbart uttag av brännved. Detta påskyndar avskogning och undergräver klimatmålen. Odling av energiskog erbjuder ett potentiellt mer hållbart alternativ.

Under de senaste två decennierna har stora arealer jordbruksmark omvandlats till energiskog med korta omloppstider i de nordvästra delarna av det etiopiska höglandet. Drivkraften bakom markanvändningsförändringen är en hög efterfrågan på träkol som skapat möjligheter för bönderna att tjäna pengar på träkolstillverkning. Trädet som odlas är garvakacia (*Acacia mearnsii*), en snabbväxande trädart från Australien. Det skördas i cykler på fem till sex år. Efter skörd gör man träkol av veden. De delar av trädet som är olämpliga för kolning används lokalt som brännved. Systemet har ökat böndernas inkomster och skapat många arbetstillfällen, också för kvinnor och ungdomar. Odlingarna har också minskat arbetsbördan för många kvinnor, som tidigare gick långa sträckor för att samla och bära brännved till hushållet. Trots att odlingen och träkolstillverkningen är ekonomiskt fördelaktiga, måste den långsiktiga hållbarheten av odlingssystemet analyseras.

I denna avhandling analyseras den miljömässiga hållbarheten i övergången från traditionell växtodling till energiskogsodling genom jämförande studier av energiskogsodlingen med odlingen av teff (*Eragrostis tef*) som är den dominerande jordbruksgrödan i området. Den storskaliga odlingen av garvakacia har ökat kolinlagringen i landskapet. Energiskogen i det studerade distriktet fångade under varje år in koldioxid motsvarande 2,3 % av Etiopiens årliga utsläpp av fossila bränslen och fixerade 175 kg kväve per hektar per år från atmosfären.

Trots den kraftigt ökade produktionen av biomassa och den stora kvävefixeringen ledde odlingarna inte till förbättrad markhälsa. Markens kol- och kväveinnehåll ökade inte som förväntat, utan minskade över tid med ökande antal energiskogsrotationer. Det beror förmodligen på att mikroorganismer, i symbios med träden, bryter ner jordens organiska material för att få tillgång till näringsämnen som fosfor och svavel som det råder brist på. Trädbiomassan tar också upp stora mängder baskatjoner, som sen försvinner när den skördade biomassan förs bort. Detta driver på markförsurningen, något som redan är ett problem i området.

Sammanfattningsvis kräver produktionssystemet anpassningar för att bli hållbart på lång sikt. Det inkluderar att lämna kvar skörderester på åkrarna för att återföra näringsämnen till marken, samt att tillföra fosfor- och svavelgödsel i odlingarna. Marken kan också behöva kalkas för att motverka den försurningen av marken som odlingen orsakar. Odlingen av garvakacia har minskat beroendet av att hämta brännved i de omgivande skogarna, vilket har lett till en återhämtning av naturskogarna i området.

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RESEARCH ARTICLE OPEN ACCESS

Short Rotation Forestry Expansion Drives Carbon Sequestration in Biomass but Not in Soil

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Keywords: *Acacia mearnsii* | afforestation | charcoal | fuelwood | land use change | landscape | SOC | sustainable

ABSTRACT

A significant land use change from cropland to short rotation forestry (SRF) has taken place in the northwestern (NW) Ethiopian highlands where a fast-growing tree species, *Acacia mearnsii*, is cultivated to produce charcoal for urban markets. We investigated the extent of this land use change, its impact on the landscape carbon (C) budget, and its implications for climate change mitigation by combining field studies with remote sensing. We analyzed land use and land cover changes between 2005 and 2022 using Google Earth Pro imagery and validated the result with ground truthing through field observations. We estimated C stocks using soil and biomass samples collected from *A. mearnsii* plantation fields managed by smallholder farmers across three rotations and stand ages, as well as from cropland and other major land use types. Between 2005 and 2022, 60% of the cropland in the studied district was converted to *A. mearnsii* plantations. Our analysis showed that *A. mearnsii* cultivation had the highest spatial cover in 2017. However, a disease outbreak in 2020 resulted in a 40% reduction in cultivated area by 2022 compared to 2017 levels. The expansion of *A. mearnsii* cultivation increased total landscape C stocks by 21%, equivalent to a net sequestration of 0.3 Mt CO_2 year^{-1} in the study district. This corresponded to 2.3% of Ethiopia's total annual fossil fuel emissions in 2021. The observed gain was due to C accumulation in standing biomass. In contrast, soil C stock showed a declining trend with successive rotations, though this change was not statistically significant. The main contribution of *A. mearnsii* based SRF in NW Ethiopia to the C budget is its potential to reduce dependence on natural forest for charcoal and firewood production.

1 | Introduction

Unsustainable use of fuelwood and charcoal is a major driver of forest degradation and loss, and contributes to climate change (Wassie 2020). An estimated 27%–34% of pantropical fuelwood extraction is unsustainable, with East Africa one of the hotspots (Bailis et al. 2015). In Ethiopia, more than 90% of households rely on fuelwood and charcoal for cooking (Sime et al. 2020; Yalew 2022). While much of the fuelwood is sourced close to the homesteads of the users (Dresen et al. 2014), both fuelwood and, particularly, charcoal are traded in domestic markets. The demand is substantial, and Ethiopia ranks as the second largest charcoal producer globally, following Brazil, with a production of 5.1 million tons of charcoal in 2023 (FAOSTAT 2023). A study by Alem et al. (2010) estimated that Addis Ababa alone receives 69,000 metric tons of charcoal annually.

Historical accounts suggest that forests once covered approximately 40% of the country and up to 90% of the highlands (EFAP 1994; Young et al. 2020). By 1950, natural forest cover had declined to 16% (Thomas and Bekele 2003), and further decreased to less than 4% by the 1980s (Hurni 1988). One of the major drivers for this deforestation is the illegal production of charcoal (Teketay 2001). In recent years, the trend of forest cover loss has been reversed in some parts of Ethiopia, particularly due to plantation of eucalypts on cropland or grazing land in short rotation forestry (SRF) (Alemneh et al. 2019).

The use of fast growing SRF species has the potential to contribute to renewable energy production and climate change mitigation (Djomo et al. 2013). These production systems can be regarded as close to carbon (C) neutral if negative trends in wood biomass and soil organic carbon (SOC) can be avoided. A review by Don et al. (2012) showed that SRF established on former arable land in the European Union (EU) sequestered 0.44–0.66 Mg soil C ha^{-1} y^{-1}. However, other studies have reported mixed results regarding SOC changes. Walter et al. (2015) found no significant SOC changes, while Sabbatini et al. (2016) observed a decrease in SOC following the conversion of cropland to SRF for biomass energy production. This pattern of C accumulation in biomass with limited impact on SOC is also observed in tropical regions (Lewis et al. 2019). In the Democratic Republic of Congo, SOC initially increased after land use change to *Acacia auriculiformis* A. Cunn. ex Benth. plantations but remained unchanged over successive rotations (Dubiez et al. 2019). SRF, in general, has been shown to reduce pressure on natural forests for fuelwood and contribute to mitigate greenhouse gas emissions (Makundi 2001).

A rapid land use change from traditional crop production to SRF has taken place in the Awi zone of northwest (NW) Ethiopian highlands. This change is driven by the market demand for charcoal in urban areas (Wondie and Mekuria 2018; Nigussie et al. 2020). The species cultivated is a wattle tree native to Australia. While previous studies reported the species as green wattle (*Acacia decurrens* Willd.) (Wondie and Mekuria 2018; Chanie and Abewa 2021), a recent study has reclassified it as black wattle (*Acacia mearnsii* De Wild.) (Agena et al. 2023). *A. mearnsii* is a fast-growing, evergreen leguminous tree that can grow up to a height of 11 m in 5–6 years in the Ethiopian highlands (Mekonnen et al. 2006). Its fast growth and adaptability to various environmental conditions (Midgley and Turnbull 2003) make it a suitable source of biomass for charcoal production.

The conversion of croplands to *A. mearnsii* based SRF has significantly changed the land cover in the NW part of the Ethiopian highland over the past two decades. Several studies conducted using satellite imagery analysis have reported considerable increases in vegetation cover. Wondie and Mekuria (2018) reported a 25% increase in forest cover from 1995 to 2015, while Worku et al. (2021) observed a 16% increase between 2000 and 2017. Watershed-based studies reported even higher increases, with Belayneh et al. (2020) reporting a 256% increase between 2003 and 2017 and Berihun et al. (2019) reporting a 400% increase between 2012 and 2017.

The rapid land use change from cropland to SRF alters the C dynamics of the landscape. Biomass accumulation contributes to C sequestration, with roots turnover and litterfall eventually contributing to soil C stocks. However, these gains may be offset by greenhouse gases (GHGs) emissions from charcoal production and microbial decomposition of organic matter (OM). Therefore, the overall climate impact of land use change is determined by the net C balance between sequestration and GHG emissions.

Previous studies on the *A. mearnsii* afforestation in the Awi zone of NW Ethiopia have shown considerable variation in the extent of land use change and often focused solely on afforestation rates without distinguishing between natural forest and *A. mearnsii* plantation. Furthermore, they have not separately estimated the C pools of soil and biomass. To assess the climate impact of the charcoal produced from these plantations, we need a quantitative estimate of the C stock dynamics in the landscape. Therefore, in this study, we aimed (1) to quantify the extent of land use change since the introduction of *A. mearnsii* based SRF and (2) to estimate the C sequestration in biomass and soil in a landscape perspective. Fast-growing woody trees, such as *A. mearnsii*, sequester more C in biomass than annual herbaceous crops like teff (*Eragrostis tef* (Zucc.) Trotter) (Poorter et al. 2012). Furthermore, reduced soil disturbance and increased litterfall and root turnover in tree cultivation systems contribute to increased soil C stocks (Rowe et al. 2016; Georgiadis et al. 2017). Consequently, we hypothesized that *A. mearnsii* would significantly increase both soil and biomass C stocks compared to the annual, rain-fed, *E. tef* cultivation practiced in the area.

2 | Methods

2.1 | Study Area

The study was conducted in the NW highlands of Ethiopia, in the Fagita Lekoma district (Figure 1). The district is located between 10°57′–11°11′ N and 36°40′–37°05′ E and is characterized by an undulating, sometimes steep, topography with elevations ranging from 1800 to 2900 m a.s.l (Worku et al. 2021). The main rainy season (*meher*) lasts from May to October. The annual average rainfall and temperature of the area is 2110 mm and 18°C, respectively, for the period between 1997 and 2019 (NMA 2020). The annual average temperature and rainfall data are provided in Figure S1. The soils are predominantly Acrisols, characterized by a low pH (Regassa et al. 2023).

Historically, land use in the area has been dominated by the common food crop teff (*E. tef*) cultivation, followed by barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), and potato (*Solanum tuberosum* L.) (Nigussie et al. 2017). However, since the introduction of *A. mearnsii*, farmers have adopted an agroforestry system with the intercropping of *A mearnsii* and annual crops. During the initial year of seedling establishment, *A. mearnsii* is interplanted with teff. The second year the farmers harvest grass for fodder from the plantation. From the third year on, the *A. mearnsii* stands have reached a crown cover that prevents intercropping due to shading of the ground. After 5–6 years, the trees are harvested for charcoal production (Nigussie et al. 2017; Wondie and Mekuria 2018), after which a new rotation of intercropping with annual crops resumes.

2.2 | Study Approach

A space for time substitution method was used to simulate temporal dynamics associated with the land use change. The fields

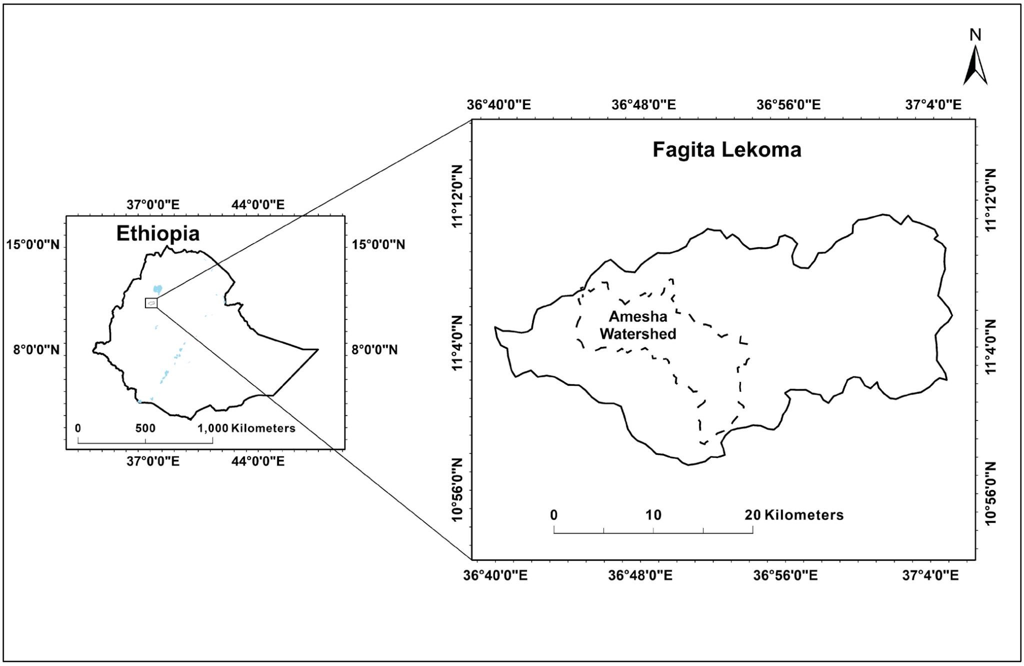

FIGURE 1 | A map of study area, Fagita Lekoma district, with the Amesha watershed delineated by dotted lines.

selected represented a chrono-sequence from cropland through successive rotations of *A. mearnsii* plantations, with stand ages ranging from three to sixyears. This approach aimed to evaluate the cumulative effects of continuous *A. mearnsii* cultivation over time. *E. tef* cultivation on cropland was the predominant land use prior to the introduction of *A. mearnsii* and represented the baseline condition. These were compared with *A. mearnsii* fields under the first, second, and third successive rotations. Additionally, fields formerly under *A. mearnsii* cultivation that had been converted back to *E.tef* cultivation (FAM), as well as natural forest and open/grazing land, were included. The FAM fields provided insights into the potential future condition of fields currently under *A. mearnsii* plantations, should cultivation be discontinued.

2.3 | Sampling Design

Soil and biomass samples were collected within the Amesha watershed in Fagita Lekoma district in April and May 2022. The watershed was delineated prior to fieldwork using the Shuttle Radar Topography Mission's (SRTM) digital elevation model from www.usgs.gov (USGS 2022) with the Hydrology tool in ArcGIS 10.7.1. This approach was adopted to fulfill the requirements of a simultaneous study within the same research project. The area of the watershed is 119 km^2.

Sampling fields were selected using a systematic random sampling technique. The delineated watershed was divided into six subareas to ensure even distribution of soil and biomass sampling. A coordinate in the center of each subarea was marked as a starting point for field selection. The resulting watershed map was subsequently uploaded to GPS devices for fieldwork navigation. Sampling teams started fieldwork by navigating to the marked center of each subarea. Upon arrival, a transect was established, and the first encountered field representing one of the predefined land use categories was selected for sampling.

Soil samples were collected from a total of 96 fields representing 16 land use categories (Figure 2). They included 72 *A. mearnsii* fields, stratified by first, second, and third rotations, and stand ages three to six. Sampling fields corresponding to each stand age and rotation were gathered from the six subareas. Fields representing the third rotation were only found near the epicenter of the early establishment of *A. mearnsii* plantations. As a result, their distribution is geographically aggregated as they were unavailable in the other subareas of the watershed. Additional samples were collected from cropland, open/grazing land, natural forest, and fields from former *A. mearnsii* plantations that have been converted back to cropland (FAM). The number of sampled fields per land use type and their corresponding definitions are provided in the Table S1.

2.4 | Soil Sampling and Analysis

In the sampling fields, a 10 m × 10 m square plot was established, and soil samples were collected from the four corners and the center of the plot at two depth intervals: 0–15 and 15–30 cm. Soil samples from the same depth at the five spots were pooled to a composite sample for each depth. Additional soil cores were collected for bulk density determination at the same depths.

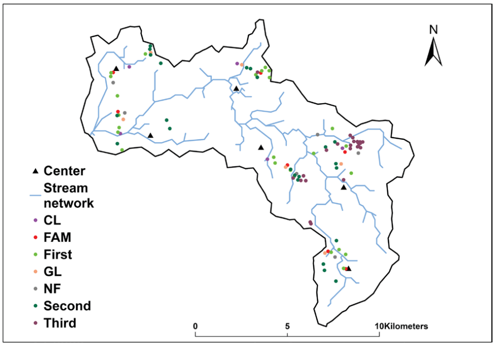

FIGURE 2 | Map of Amesha watershed with drainage networks and soil sampling locations. CL, cropland; FAM, former *Acacia mearnsii* field converted to cropland; GL, grazing land; NF, natural forest; and first, second, and third, first, second, and third rotation *A. mearnsii* plantations. Center indicates the center of each subarea marked as a starting point for field selection.

The sampled soils were air dried and crushed with a mortar and subsequently sieved through a 2 mm mesh sieve. The coarse fraction retained on the 2 mm sieve was used to calculate the coarse fraction percentage. An additional 1 g of soil was milled into fine powder using a ball mill for stable isotope analysis.

The C and nitrogen (N) content in the soils were determined through dry combustion according to ISO 10694 (1995) and ISO 13878 (1998), respectively, using an elemental analyzer (TruMac CN, Leco Corp, St. Joseph, MI, USA), with a combustion temperature of 1350°C. Soil bulk density was determined by oven drying samples at 105°C for 24 h. The bulk density was calculated by dividing the dry weight by the volume of the core sampler.

Stable isotope ratios for ^{13}C:^{12}C were determined using an isotope ratio mass spectrometer coupled with an elemental analyzer (EA-IRMS) at the stable isotope laboratory of Swedish University of Agricultural Sciences (SLU) in Umeå, Sweden. The value of the stable C isotope ratio ($^{13}C/^{12}C$) was expressed using the standard delta (δ) notation ($\delta^{13}C$) in parts per thousand (‰) relative to the Vienna Pee Dee Belemnite (VPDB) standard;

$$\delta^{13}C_{(‰)} = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right)1000 \quad (1)$$

where R is the ratio of $^{13}C/^{12}C$ in the sample and standard.

The natural abundance of $\delta^{13}C$ was used to quantify the proportion of soil C derived from *A. meanrsii*, a C3 plant introduced following land use change, and *E. tef*, a C4 crop cultivated prior to the land use change. The proportional contribution of each source to the soil C pool was calculated using the equations by Balesdent and Mariotti (1996):

$$C_{\text{New}} = \left(\frac{\delta^{13}C_N - \delta^{13}C_O}{\delta^{13}C_{AM} - \delta^{13}C_O}\right)100 \quad (2)$$

$$C_{\text{New}} = \left(\frac{\delta^{13}C_N - \delta^{13}C_O}{\delta^{13}C_{AM} - \delta^{13}C_T}\right)100 \quad (3)$$

where C_{New} = proportion of C derived from *A. mearnsii* plantation in %, $\delta^{13}C_N$ = isotopic ratio of the soil under *A. mearnsii* cultivation, $\delta^{13}C_O$ = isotopic ratio of the soil under *E. tef* crop cultivation, $\delta^{13}C_{AM}$ = isotopic ratio of *A. mearnsii* biomass, and $\delta^{13}C_T$ = isotopic ratio of *E. tef* crop.

The $\delta^{13}C$ value of the *E. tef* crop (−12‰) was obtained from Krampien (2015), while the $\delta^{13}C$ values for *A. mearnsii* biomass and the soil samples were determined through laboratory analysis. Equation (3) corrects for isotopic fractions due to decomposition (Balesdent and Mariotti 1996). We report results from both equations to provide a range of potential estimates of soil C derived from *A. mearnsii*.

The soil C stock was calculated as:

$$CS_i = \frac{SOC_i \rho_i Z_i (1 - CF_i)}{1000} 10 \quad (4)$$

where CS_i = C stock in Mg ha^{-1}, SOC_i = soil organic C (g kg^{-1}), ρ_i = soil bulk density (kg m^{-3}), Z_i = layer thickness (m), CF_i = coarse fraction > 2 mm at layer i.

Prior to C stock estimation calculation, the bulk density of the soil was adjusted according to the method specified by Fowler et al. (2023). The stock in the 0–30 cm soil depth interval was determined by summing the stock in the 0–15 and 15–30 cm layers.

2.5 | Biomass Sampling and Processing

Biomass samples were collected from *A. mearnsii* stands aged three to six in each subarea of the watershed. Plantations younger than 3 years were not present due to the impact of *Uromycladium acacia* since the beginning of 2020 (Agena et al. 2023), which led farmers to discontinue planting new trees.

In each sampling field, a 10 m × 10 m square sampling plot was established. The total number of trees within the sampling plot was recorded. Stem diameter at breast height (DBH) and tree height were measured on 20 representative trees within the sampling plot. The DBH was measured at 1.3 m above the ground using digital caliper, and tree height was measured using a graded bamboo stick. A representative tree, corresponding to the average DBH and height within the plot, was selected from each plot and destructively sampled. The tree components were separated into stem, branch, leaf, and root fractions, and subsamples were collected from each component for further analysis in laboratory. Stem samples (wood and bark) were obtained from disks cut at 20% intervals along the height of the stem. Representative samples of various sizes were taken from roots, branches, and leaves. Litter samples were collected from a set of two 30 cm × 30 cm squares placed along the diagonal of the main 10 m × 10 m square plot. Below ground biomass (BGB) was determined by excavating sample trees to 40 cm depth, with separate samples taken from

0–20 cm and 20–40 cm depths. Collected roots were classified into three diameter classes: fine (< 2 mm), medium (2–5 mm), and coarse (> 5 mm) (FAO 1990).

Fresh weights of each component were measured on site, and the corresponding dry weights were determined after oven drying a weighed subsample at 65°C until a constant weight was achieved. The C content of the litter and biomass components (stem, branches, fine and coarse roots, and leaves) was analyzed using an elemental analyzer (TruMac CN, LECO). The estimated C stocks were then converted into CO_2 equivalents to calculate CO_2 sequestration in both biomass and soil.

2.6 | Allometric Model Fitting for Estimating Biomass

Several models were tested to predict aboveground biomass (AGB) using DBH and height as predictor variables. The performance of each model was evaluated using the coefficient of determination (R^2), the root mean square error (RMSE), and the Akaike information criterion (AIC). Models with the highest R^2 and the lowest RMSE and AIC values were selected as suitable allometric equations. The goodness of fit was assessed by plotting the predicted AGB values against the observed values. The best correlation, with an R^2 value of 0.89, was obtained with the following linear model:

$$\text{Ln(AGB)} = a + b\text{DBH} + cH \quad (5)$$

where AGB = aboveground biomass (kg), DBH = diameter at breast height (cm), H = tree height (m), and a, b, and c are model parameters equal to 0.34, 0.026, and 0.22, respectively.

The BGB is estimated from the AGB using the following linear model:

$$\text{BGB} = a + b\text{AGB} \quad (6)$$

where BGB = belowground biomass (kg), AGB = aboveground biomass (kg), and a and b are model parameters equal to 0.14 and 0.076, respectively.

Biomass data for stands younger than 3 years were estimated using models built from measured data for stands aged 3–6 years and existing literature. Plant density for this age group was estimated from initial planting density and seedling counts per hectare reported by Chanie and Abewa (2021). Aboveground biomass for 1 year old stands was reported by Mekonnen et al. (2006). Aboveground biomass for 2 year old stands was estimated using a model based on data by Mekonnen et al. (2006) for stand age one and our measured data for stands aged 3–6 years. The root biomass of these stand ages was estimated as a function of above ground biomass. Litter layer C for stands aged one and two were estimated by interpolating between litter data for stands aged 3–6 years and assuming zero initial litter at planting. Similarly, soil C stocks for these stands were estimated using a similar interpolation, assuming that the average soil C stock at planting (stand aged zero) was equal to that of cropland, as most land use change was from cropland to *A. mearnsii* plantations. The resulting models and their respective R^2 values are presented in the Table S2.

2.7 | Land Cover Classification

The temporal dynamics of land use land cover (LULC) change were analyzed over a 17-year period from 2005 to 2022 using Google Earth Pro imagery (version 7.3.6.9345; accessed March 2023). Prior to classification, a 1500 m × 1500 m grid was overlaid on the Fagita Lekoma district using ArcGIS, resulting in 302 grid intersection points for LULC assessment (Figure 3a). Land use was classified at four distinct time points: 2005 when *A. mearnsii* plantations began to emerge in the area, 2014, 2017, and 2022 (Figure 3). Due to incomplete coverage in 2005, imagery from 2002 was used to fill gaps and ensure comprehensive land use classification. Imagery from the

FIGURE 3 | (a) Grid points generated in ArcGIS for land use change assessment in Fagita Lekoma. Each point was assessed at four different times: 2005, 2014, 2017, and 2022, and the type of land use and stand development at these years was recorded. The percentage of each land use type for each year was calculated as the number of points under the land use type divided by the total number of points assessed (302). (b) Grid point 519 shows the land was under cropland cultivation in 2005. (c) By 2014, this same point had been converted to *Acacia mearnsii* cultivation. (d) The previous plantation was harvested, and the site was replanted with new seedlings in 2017. (e) By 2020, the replanted *A. mearnsii* had reached a stand age of 3 years.

corresponding years was validated with ground truth data collected during fieldwork. These ground truth data were used as reference training data for visual land use classification based on Google Earth Pro imagery. The percentage of each land use type for the years studied was calculated by dividing the number of points classified under a specific land use type in a given year by the total number of points assessed (302). Subsequently, the total area for each land use type in each year was calculated by multiplying the corresponding percentage by the total area of the district. The LULC categories and their corresponding definitions are presented in Table 1.

TABLE 1 | Land use land cover classification studied and their respective definitions.

LULC classification	Definition
Cropland	Fields used to produce annual crops including fallow areas
Open/grazing land	Field that is used for grazing, including open areas covered with grass that may or may not have been grazed
Natural forest	Natural vegetation areas, consisting of bushes, shrubs. and woodland, developed without human interference
Acacia mearnsii plantations	Fields covered by stands of different ages and rotation cycles of *A. mearnsii* cultivation
Water bodies	Rivers and wetlands
Settlement area	Built up areas and roads
Tree lines	Defined as linear array of woody vegetation used to form a field boundary within agricultural land or alongside roads
Bare land	A barren area with exposed bedrock, gully formations, and significant erosion caused by wind or water
FAM	Fields that were formerly planted *A. mearnsii* but have since been converted back to cropland or left fallow

2.8 | Statistical Analysis

The effect of land use changes on soil C stock was assessed using a mixed effect model in R using the *nlme* package (Pinheiro et al. 2025). Analyses of variance (ANOVA) were applied to examine the main effects of land use (stand age and rotation cycles for *A. mearnsii*), with site and soil depth included as a random effects. When model assumptions were not met, data were logarithmically transformed. Post hoc comparisons were performed using the *emmeans* package in R (Lenth et al. 2025) with Tukey's adjustment for multiple comparisons. Results are presented as means ± confidence intervals. The confidence interval for aggregated means represents the cumulative uncertainty propagated from individual components. Statistical significance was evaluated at $p = 0.05$.

3 | Results

3.1 | Land Use and Land Cover Change Between 2005 and 2022

Land use and land cover change between 2005 and 2022 is presented in Table 2. In 2005, cropland was the dominant land use, covering 67% of the district area, followed by open/grazing land at 19%. Other land uses collectively accounted for 14%. By 2014, both cropland and open/grazing land had decreased, while *A. mearnsii* plantations increased from 0.3% to 13% of the total area. Between 2005 and 2014, 16% of cropland and 9% of open/grazing land were converted to *A. mearnsii* plantations.

In the period between 2014 and 2017, *A. mearnsii* plantation continued to expand, primarily at the expense of croplands. By 2017, *A. mearnsii* plantations covered 42% of the total area, while cropland decreased to 29%. The conversion represented 55% of

TABLE 2 | Land use and land cover in the in Fagita Lekoma in 2005, 2014, 2017, and 2022 by area (ha) and percentage.

	2005		2014		2017		2022	
LULC	Area	%	Area	%	Area	%	Area	%
Cropland	45,351	67	37,978	56	19,436	29	17,202	25
Acacia mearnsii	223	0	8712	13	28,372	42	20,776	31
Open/grazing land	12,510	19	11,170	17	9159	14	7372	11
Natural forest	4691	7	4468	7	4245	6	4245	6
Water bodies	894	1	894	1	894	1	894	1
Settlement area	1117	2	1564	2	2010	3	2234	3
Bare land	894	1	894	1	894	1	1117	2
FAM					670	1	12,063	18
Tree lines	1787	3	1787	3	1787	3	1564	2

former cropland and 23% of former open/grazing land since the 2005 baseline (Table 3). Other land use categories experienced moderate changes during the period.

The period between 2017 and 2022 saw a slowdown in land use change to *A. mearnsii* plantations. Only 5% of cropland from prior periods was converted to new plantations (Table 4). Furthermore, this period marked a reversal in land use change, with areas previously under *A. mearnsii* cultivation reverted to cropland or left fallow. By 2022, 40% of the land under *A. mearnsii* plantations in 2017 had reversed back to crop production or was left as fallow (Table 4).

Between 2005 and 2022, the expansion of *A. mearnsii* plantations resulted in the conversion of over 28,000 ha of cropland to *A. mearnsii* plantation, representing 40% of the total area of the district (Tables 3 and 4). An additional 5000 ha of open/grazing land were also converted to *A. mearnsii* plantation. The area covered by *A. mearnsii* reached its maximum in 2017 and subsequently decreased. Despite the reduction in both cropland and open/grazing land, no natural forest areas were converted to *A. mearnsii* cultivation throughout the study period.

3.2 | Carbon Sequestration in Litter and Standing Biomass

The total C stock in *A. mearnsii* biomass and litter layer increased from $20.8 \pm 8.35\,\mathrm{Mg\,ha^{-1}}$ for stands aged three to $98.3 \pm 15.2\,\mathrm{Mg\,ha^{-1}}$ for stands aged six (Table 5). AGB accounted for the largest portion, with BGB accounting for 8.5% of the total dry matter for stands aged three to six. The average C stock in

TABLE 3 | Land use change matrix for land use class in 2005 and 2017 in the Fagita Lekoma district.

	2017									
2005	**CL**	**OGL**	**NF**	**AM**	**WB**	**ST**	**BL**	**FAM**	**TL**	**Total (2005)**
Cropland	19,212			25,021		447		670		45,350
Open/grazing land	223	9159		2904		223				12,510
Natural forest	0		4244	223		223				4691
Acacia mearnsii				223						223
Water bodies					894					894
Settlement						1117				1117
Bare land							894			894
FAM										—
Tree lines									1787	1787
Total (2017)	19,436	9159	4244	28,371	894	2011	894	670	1787	67,466

Note: Values are area in ha.
Abbreviations: AM, *A. mearnsii*; BL, bare land; CL, cropland; NF, natural forest; OGL, open/grazing land; ST, settlement; TL, tree line; WB, waterbodies.

TABLE 4 | Land use change matrix for land use class in 2017 and 2022 in the Fagita Lekoma district.

	2022									
2017	**CL**	**OGL**	**NF**	**AM**	**WB**	**ST**	**BL**	**FAM**	**TL**	**Total**
Cropland	17,176			2034		226				19,436
Open/grazing land		7372		1564			223			9159
Natural forest			4244							4244
Acacia mearnsii				16,978				11,393		28,371
Water bodies					894					894
Settlement						2011				2011
Bare land							894			894
FAM								670		670
Tree lines				223					1564	1787
Total	17,176	7372	4244	20,799	894	2237	1117	12,063	1564	67,466

Note: Values are area in ha.
Abbreviations: AM, *A. mearnsii*; BL, bare land; CL, cropland; NF, natural forest; OGL, open/grazing land; ST, settlement; TL, tree line; WB, waterbodies.

TABLE 5 | Total C stock in standing biomass and litter layer by stand age in $Mg ha^{-1}$.

Stand age	AGB	BGB	Total biomass	C stock in biomass	C in Litter layer	Total C in biomass and litter
3	35.1 ± 14.6	4.40 ± 1.90	39.5 ± 16.5	19.8 ± 8.24	1.01 ± 0.57	20.8 ± 8.35
4	62.9 ± 24.5	6.20 ± 2.20	69.0 ± 26.7	34.5 ± 13.4	2.05 ± 0.51	36.6 ± 13.7
5	104 ± 30.7	9.40 ± 2.70	113 ± 33.5	56.7 ± 16.7	2.64 ± 0.97	59.4 ± 16.4
6	175 ± 26.2	15.1 ± 3.30	190 ± 29.2	94.9 ± 14.6	3.36 ± 1.35	98.3 ± 15.2
Mean	94.2 ± 49.5	8.80 ± 5.20	103 ± 54.4	51.5 ± 27.2	2.26 ± 1.83	53.7 ± 13.6

Note: Values indicate mean ± CI.
Abbreviations: AGB, above ground biomass; BGB, below ground biomass.

TABLE 6 | Estimated C in BGB of *Acacia mearnsii* by size class and soil depth at the typical harvest age in $Mg ha^{-1}$.

Stand age	Depth	Fine root biomass	Coarse root biomass	Fine root C	Coarse root C
5	0–20	3.11 ± 0.90	3.60 ± 1.04	1.56 ± 0.45	1.80 ± 0.52
	20–40	1.34 ± 0.39	1.34 ± 0.39	0.67 ± 0.19	0.67 ± 0.19
6	0–20	4.53 ± 0.98	5.56 ± 1.20	2.27 ± 0.49	2.78 ± 0.60
	20–40	2.57 ± 0.56	2.43 ± 0.53	1.28 ± 0.28	1.21 ± 0.26
Mean	0–20	3.82 ± 1.33	4.58 ± 1.59	1.91 ± 0.67	2.29 ± 0.80
	20–40	1.95 ± 0.68	1.88 ± 0.65	0.98 ± 0.34	0.94 ± 0.33

Note: Values indicate mean ± 95% CI. roots (< 5 mm diameter) and coarse roots (> 5 mm diameter).

biomass and litter layer is 53.7 ± 13.6 $Mg ha^{-1}$. The litter layer represented 4.2% of the average C stock. At a typical harvest age of 5–6 years, fine roots constituted 47% of the BGB, with an estimated C stock of 2.89 Mg C ha^{-1} (Table 6). The litter layer, at the same harvest age, has an estimated C stock of 3.00 Mg C ha^{-1} (Table 5). Therefore, the total C potentially retained in the field from leaf litter and fine roots is estimated to be 1.07 Mg C ha^{-1} y^{-1}.

3.3 | Soil C Stock

The mean soil C stock of different LULC classes at two soil depths is presented in Figure 4. When combining the soil C stock for the two depths, the highest soil C stock was observed in soil under natural forest with 181 ± 54.7 Mg C ha^{-1} followed by open/grazing land and FAM with 142 ± 34.4 and 132 ± 42.7 Mg C ha^{-1}, respectively. The C stock in the reference land use, cropland, was 90.8 ± 51.1 Mg C ha^{-1}. The C stock in *A. mearnsii* cultivated soils decreased with subsequent rotation cycles but increased with stand age within each rotation (Figure 5). The average C stocks were 116 ± 28.0, 90.8 ± 18.3, and 81.3 ± 13.1 $Mg ha^{-1}$ in the first, second, and third rotations, respectively.

Statistical analysis revealed significant differences in soil C stock among the land uses studied. Post hoc comparisons showed that the soil under natural forest had a significantly higher soil C stock compared to all other land uses, whereas the third *A. mearnsii* rotation exhibited the lowest soil C stock among all land uses. Comparison between cropland soil and soil under the three *A. mearnsii* rotations also revealed that the third *A. mearnsii* rotation had significantly lower C stock compared to the first. However, no significant differences were found between cropland and any of the *A. mearnsii* rotations.

The average C stock in the 0–30 cm of the first rotation plantation was 25.2 ± 58.2 $Mg ha^{-1}$ higher than that of cropland. Subsequent rotations showed a lower level in C stock relative to the first rotation. The second had 25.2 ± 33.5 Mg C ha^{-1} lower and the third rotation had a further 9.50 ± 22.5 Mg C ha^{-1} lower stock (Figure 5). Consequently, the overall change in soil C stock from cropland to the third rotation cycle represents a net change of—9.46 Mg C ha^{-1}. The C change was more pronounced in the 15–30 cm layer as compared to the topsoil. The stock change at the anticipated harvest age of the first and third rotation cycles, stand ages five and six, showed a decline of 37.7 $Mg ha^{-1}$ from the first to the third rotation, that is, over 11 years. This corresponds to an average 3.43 Mg C ha^{-1} $year^{-1}$ decrease between the first and the third rotations.

Soil $\delta^{13}C$ values did not differ significantly between cropland and *A. mearnsii* rotation cycles ($p = 0.31$) (Table 7). The analysis showed the amount of C possibly derived from *A. mearnsii* biomass decreased with successive rotations. The estimated annual C derived from *A. mearnsii* using Equation (2) was 1.99, 1.02, and 0.58 Mg C ha^{-1} $year^{-1}$ for the first, second, and third rotations, respectively, with an average of 1.20 Mg C ha^{-1} $year^{-1}$ (Table 7). The estimates based on Equation (3) were 1.16, 0.59, and 0.34 Mg C ha^{-1} $year^{-1}$ for the respective rotations, with an average of 0.70 Mg C ha^{-1} y^{-1}.

3.4 | Landscape C Balance

When total biomass and soil C under SRF are summed, and C stocks for cropland, open/grazing land and natural forest are assumed to remain constant, the total C stock in the Fagita Lekoma district increased from 6.77 ± 2.37 Tg in 2005 to

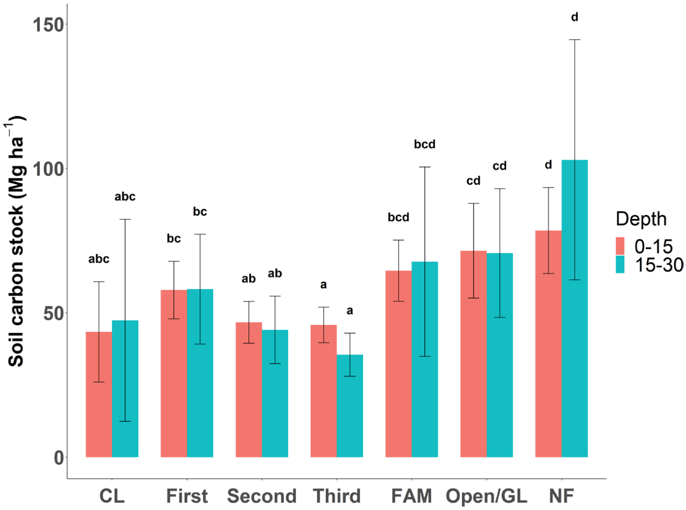

FIGURE 4 | Soil C stock at 0–15 and 15–30 cm depths across different LULC classes. First, second, and third represent the respective rotation cycles of *Acacia mearnsii*. CL, Open/GL, and NF refers to cropland, open/grazing land and natural forest, respectively. Values are mean C stock for the respective depth interval and LULC class and error bars indicate 95% confidence intervals. *A. mearnsii* rotation values are average C stock for stands aged 3–6 years. Means denoted by a different letter indicate significant differences between the land uses. The mean and CI are presented based on the orgianl data, whereas the analysis was perfomred on a logarithmic scale. Sample sizes: Cropland (5), first rotation AM (24), second rotation AM (24), third rotation AM (24), FAM (7), Open/grazing land (6), and Natural forest (6).

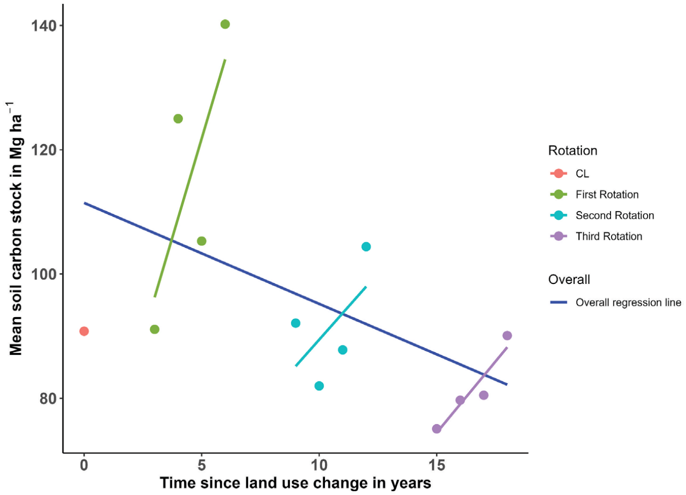

FIGURE 5 | Average soil C stock (Mg ha^{-1}) as a function of time since land use changed from cropland to *Acacia mearnsii* plantations. The organge colored point represents the average C stock of the cropland (CL) soil, serving as the initial reference soil C stock. Green points indicate the mean C stock of the first-rotation plantations with stand ages ranging from 3 to 6 years. Similarly, light blue and purple points represent the second and third rotations, respectively, with stand ages from 3 to 6 years. Regression lines for each rotation correspond to the colors of respective rotations. The blue line represents the overall regression line fitted across all stand ages since the land use conversion to *A. mearnsii* plantations. Sample sizes: Presented in Table S1; for first, second, and third rotations *A. mearnsii* plantations, each point represents a stand age of 3–6 years. Values were calculated as the average of samples per stand.

8.18 ± 1.59 Tg in 2022 with a net increase of 1.41 Tg (Figures 6 and 7). This corresponds to an overall increase of 21% between 2005 and 2022. The increase correlates with the areal expansion of *A. mearnsii* plantation, which increased from less than 1% of the area in 2005 to 42% of the area in 2017. At the same time, Google Earth Pro imagery revealed that the

TABLE 7 | $\delta^{13}C$‰ values of soil under cropland and different rotation of *Acacia mearnsii* cultivation and corresponding estimates of C derived from *A. mearnsii*.

Land use	Depth	$\delta^{13}C$ ‰	C stock $Mg\,ha^{-1}$	% C derived from AM (Equation 2)	C derived from AM $Mg\,ha^{-1}$ (Equation 2)	C derived from AM $Mg\,ha^{-1}\,year^{-1}$ (Equation 2)	% C derived from AM (Equation 3)	C derived from AM $Mg\,ha^{-1}$ (Equation 3)	C derived from AM $Mg\,ha^{-1}\,year^{-1}$ (Equation 3)
CL	0–15	−18.6 ± 1.1	43.4 ± 17.4						
	15–30	−18.1 ± 1.3	47.4 ± 35.0						
FAM	0–15	−19.1 ± 1	64.6 ± 10.6	5.9%	3.84 ± 0.63		3.4%	2.2 ± 0.36	
	15–30	−17.8 ± 1.4	67.7 ± 32.8						
First rotation	0–15	−19.5 ± 0.8	57.9 ± 10.0	10.7%	6.19 ± 1.07	1.12 ± 0.19	6.1%	3.53 ± 0.61	0.64 ± 0.11
	15–30	−18.8 ± 0.8	58.2 ± 19.0	8.1%	4.74 ± 1.55	0.86 ± 0.28	5.0%	2.91 ± 0.95	0.52 ± 0.17
Second rotation	0–15	−20.4 ± 1.6	46.7 ± 7.20	20.5%	9.59 ± 1.48	0.87 ± 0.13	11.8%	5.51 ± 0.86	0.50 ± 0.16
	15–30	−18.4 ± 1.5	44.1 ± 11.7	3.8%	1.67 ± 0.44	0.15 ± 0.04	2.3%	1.02 ± 0.27	0.09 ± 0.02
Third rotation	0–15	−20.2 ± 1.2	45.8 ± 6.20	18.2%	8.31 ± 1.13	0.50 ± 0.07	10.4%	4.76 ± 0.64	0.29 ± 0.04
	15–30	−18.4 ± 1.4	35.5 ± 7.50	3.5%	1.26 ± 0.27	0.08 ± 0.02	2.2%	0.78 ± 0.16	0.05 ± 0.01

Note: The annual C derived from *A. mearnsii* was calculated by dividing the total C attributed to *A. mearnsii* by 5.5, 11, and 16.5 for the first, second, and third rotations, respectively. These values correspond to the cumulative years since land use change, assuming a typical harvest age of 5–6 years and an average of 5.5 years per rotation.
Abbreviation: AM, *A. mearnsii*.

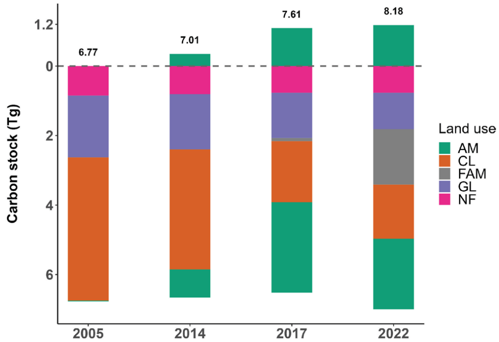

FIGURE 6 | Above- and below-ground C stocks in Fagita Lekoma from 2005 to 2022 in Tg C. The dotted zero line represents the soil surface. Bars above the dotted line indicate C stock in *Acacia mearnsii* biomass, while bars below the dotted line represent C stock in the soil. The values on the top of the bars represent the total C stock in soil and biomass for the respective years in the landscape. Note that biomass C represents only the C sequestered in *A. mearnsii* biomass. AM, land under *A. mearnsii*; CL, cropland; FAM, formerly under *A. mearnsii* plantation but reverted back to cropland; GL, open/grazing land; NF, natural forest.

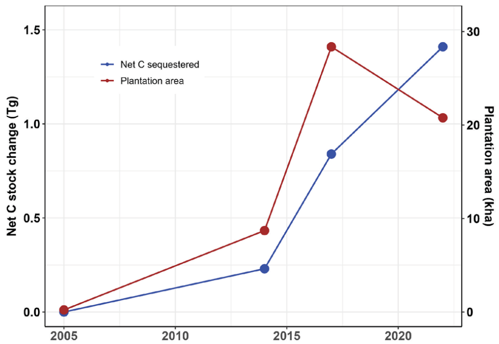

FIGURE 7 | Changes in area under *Acacia mearnsii* plantation and the corresponding net change in C stock in Fagita Lekoma between 2005 and 2022. The blue line shows the changes in net C stock in soil and biomass (left hand y-axis), and the brown line represents the area under *A. mearnsii* plantation (right hand y-axis).

forest density in areas under natural forest cover increased between 2005 and 2022 (Figure 8).

4 | Discussion

4.1 | Land Use Land Cover Change

The predominant LULC change observed during the study period was the conversion of cropland to SRF with *A. mearnsii* plantations. Based on the analysis of land use change matrix, only 38% of the initial cropland area remained cropland. Hence, 62% of the original cropland area have had at least one cycle of *A. mearnsii* plantation between 2005 and 2022. The rapid rate of conversion to plantations occurred between 2014 and 2017. This trend is likely attributable to the influence of early adopters, whose success in the prior period demonstrated the economic viability of charcoal production over food crop, thereby triggering a cascade of emulative land use decisions (Admassie and Ayele 2010). In contrast to the changes observed in cropland and open/grazing land; the natural forest areas remained unaffected throughout the study period. Although the area under natural forest did not increase, signs of recovery were observed, with forest density increasing compared to the baseline year. This suggests that *A. mearnsii* plantations are the primary source of energy for domestic consumption, potentially mitigating deforestation pressure on natural forests.

Land use change from cropland to plantation reversed between 2017 and 2022. This reversion coincided with a disease outbreak that impacted *A. mearnsii* trees, prompting farmers to revert to crop cultivation. Informal interviews conducted by the fieldwork team revealed that the emergence of the disease coincides with the onset of the COVID-19 pandemic in 2020. Due to this temporal correlation and the widespread use of the term "corona" in the media at that time, farmers colloquially referred to the disease as "corona." A recent visit by a team of experts identified the disease as the wattle rust fungus, *U. acaciae* (Agena et al. 2023). Despite the reduction in plantation area due to the disease outbreak, *A. mearnsii* plantations remained the dominant land use in the district in 2022.

Inconsistencies in previous estimates of LULC change within the study area have posed challenges to understand the land use dynamics and quantify the associated C stock implications. The conventional land classification approaches often struggle to accurately distinguish between natural forests and plantations due to spectral overlap (Ordway 2015). The spectral similarity between natural vegetation and *A. mearnsii* plantations can confound interpretations of land cover change, potentially leading to bias in area estimation. Therefore, the accuracy of previous studies (Wondie and Mekuria 2018; Berihun et al. 2019; Belayneh et al. 2020; Worku et al. 2021) relying solely on remotely sensed data may warrant further scrutiny, particularly those employed coarser resolution imagery. Studies using Google Earth imagery have demonstrated better accuracy for land use classification in Ethiopia (See et al. 2013; Tilahun and Teferie 2015). This improved accuracy is likely due to Google Earth Pro imagery's integration of data from multiple sources, including satellite and aerial photography (Google 2024). Unlike single sensor satellite data, which often have coarser spatial resolutions, this approach provides access to high resolution mosaics (Potere 2008; Google 2024). Moreover, the use of visual interpretation in Google Earth Pro imagery allowed us to overcome the challenge of spectral overlap. It enables detailed visual interpretation of land cover features that automated methods often struggle to differentiate, thereby improving classification accuracy.

4.2 | Carbon Stock in *A. mearnsii* Biomass

There was increased biomass C accumulation with stand age in *A. mearnsii* stands, with c. 50% of the total C sequestered in the final

FIGURE 8 | Google Earth Pro satellite imagery showing temporal increase in natural forest density from 2005 to 2022. The left panels show images from 2005, while the right panels display the same areas with increased forest density in 2022.

years prior to harvest. A similar study by Mekonnen et al. (2006) showed a higher accumulation rate (77%) in the final 2 years prior to harvest (between 40 and 64 months of age). This difference may be explained by differences in soil type and disease incidence reported in our study area (Agena et al. 2023). Mekonnen et al. (2006) conducted their study under controlled conditions on more fertile Vertisols, whereas our data were collected from farmer managed fields established on nutrient poor Acrisols. These less favorable soil conditions may have contributed to the lower growth observed. Additionally, Pham et al. (2024) reported that the disease resulted in stunted growth, leading to overall low biomass production. Therefore, the lower biomass accumulation observed in our study is likely attributable to one or a combination of these limiting factors. Despite this variation, the rapid biomass accumulation observed in both studies between 5 and 6 years of age explains the practice of harvesting *A. mearnsii* for charcoal production within this age range.

The proportion of BGB in *A. mearnsii* is lower than that observed in most other tree species (Cairns et al. 1997; Qi et al. 2019). BGB have been shown to contribute more to SOC than AGB, and root derived C has a longer residence time in soils (Rasse et al. 2005). The low BGB observed in this study indicates a limited contribution to SOC through root turnover. Additionally, a significant portion of this BGB is removed during harvest as fuelwood (Chanie and Abewa 2021; Kim et al. 2022), while the AGB is harvested for charcoal production. The combination of low BGB litter input and intensive harvesting practices results in reduced organic inputs to the soil from both sources. As a result, fine roots remain the primary source of C input to the soil.

Despite biomass removal through harvest, expansion of *A. mearnsii* plantations resulted in C sequestration in the standing biomass. Between 2005 and 2022, a total of 2.63 Tg of C, equivalent to 9.64 Tg of CO_2, was sequestered in standing biomass. This accumulation was largely attributable to a large area under plantation in 2017 and the dominance of mature trees in 2022, which contained high C stocks, despite a decrease in plantation area between 2017 and 2022.

4.3 | Carbon Stock Change in Soil

Contrary to our hypothesis, the conversion of cropland to *A. mearnsii* plantation did not result in soil C accumulation. While first rotation plantations had higher soil C stock than cropland, successive rotations exhibited declining stocks, likely due to the export of the whole biomass of *A. mearnsii* for charcoal and firewood production (Nigussie et al. 2021).

The lack of statistical significance difference in δ^{13}C signatures between soil under *E. tef* cultivation and *A. mearnsii* plantations also suggests that the C3 *A. mearnsii* did not contribute a significant amount of new C to the soil previously cultivated with the C4 crop teff. However, the strength of this interpretation is limited by the lack of detailed historical land use data, and we cannot rely solely on δ^{13}C analysis. To complement this, we used data on δ^{15}N abundance that we presented in Tiruneh et al. (2025). This allowed us to quantify the N additions from the N fixing *A. mearnsii* by estimating the proportion of N derived from N_2 fixation. The soil δ^{15}N data revealed that 26% and 24% of the soil N in the second and third rotation in the 0–15 cm depth, respectively, originated from *A. mearnsii*. Through integration of this information with the soil C:N ratio, we estimated that *A. mearnsii* contributed 1.04 Mg C ha^{-1} $year^{-1}$ (Table S3), while the estimate based on $\delta^{13}C$ was 0.7–1.2 Mg C ha^{-1} y^{-1}. These estimates corresponded to the total C potentially retained in the field from leaf litter and fine roots turnover (1.07 Mg C ha^{-1} y^{-1}).

Despite this, our results showed no net C accumulation in the soil with successive rotations. Although C stock increased within each rotation as the stands aged from 3 to 6 years, subsequent rotations had lower initial C stocks compared to the average stock of the preceding rotation (Figure 5). This apparent contradiction may be attributed to the methodological challenges of excluding fine roots from soil samples (Kuzyakov et al. 2001). Although the soil samples were sieved through a 2 mm sieve prior to analysis, the possibility for some fine root biomass to remain and influence the results cannot be dismissed. Our results showed that 66% of fine roots were found in the 0–20 cm layer (Table 6), while Ceconi et al. (2008) reported an even higher proportion (86%). This high fine root density in the topsoil makes it likely that some fine root biomass was included in the soil samples, potentially resulting in an overestimation of soil C. The $\delta^{13}C$ and $\delta^{15}N$ analysis, which indicated a limited overall contribution of C but a higher proportion of *A. mearnsii* derived C in the 0–15 cm soil layer, supports the possibility of fine root inclusion. Therefore, the increase in C stocks within rotations likely reflects root biomass accumulation, whereas the decline over successive rotations indicates a genuine loss of stabilized SOC. Our argument is supported by the close correspondence between the amount of C potentially retained in the field and the estimates derived from $\delta^{13}C$ and $\delta^{15}N$ analysis. This indicates that the isotopically detected C is largely derived from root biomass rather than SOC. Thus, the soil C stocks, particularly in older stands with denser root systems, may be overestimated.

In addition to methodological factors, whole biomass harvest that results in low C input and the high litter quality of *A. mearnsii* (Xiang and Bauhus 2007), which increases the decomposition rate of legacy OM, may have played a significant role. Whole biomass harvest with repeated harvest cycles, removes essential plant nutrients, potentially leading to nutrient limitations in the soil (Dovey 2012). Studies show that nutrient limited plants secrete extracellular enzymes and organic compounds to enhance acquisition of phosphorus (P), sulfur (S), and other micronutrients (Dakora and Phillips 2002; Fujii and Hayakawa 2021). While this adaptive strategy allows plants to acquire essential nutrients, it leads to C loss through increased OM mineralization. We observed a higher BGB to AGB ratio in younger stands (Table 5), which suggests a prioritization of below ground growth during early developmental stages to enhance nutrient acquisition. This may also involve an increase in the production of root exudates and enzymes to obtain nutrients from organic sources. Our calculations demonstrated correspondence between the amount of P and S potentially mineralized from annual C mineralization (3.43 Mg C ha^{-1} y^{-1}) and the observed nutrient budget deficit for P and S in the *A. mearnsii* cultivation system (Tiruneh et al. 2025). This indicates that *A. mearnsii* cultivation may benefit from mining OM to mobilize P and S to support its growth.

Previous studies have shown that afforestation of former cropland can result in both an increase and a decrease of soil C stock, depending on the tree species and the climatic conditions of the area. Paul et al. (2002) suggested that the establishment of deciduous hardwoods or N-fixing species on cropland in tropical or subtropical regions leads to accumulation of soil C. However, litter quality from N fixing species, characterized by low C:N and C:P ratios, could potentially result in C loss (Manzoni et al. 2010; Mao et al. 2018). Studies by Chang et al. (2014) and reviews by Li et al. (2012) and Paul et al. (2002) indicate that soil C stock initially declines after afforestation of former croplands before a gradual return to the pre-afforestation level and subsequent increase. In this study, although the trend was weak ($p = 0.2$), we observed a decline in soil C stock with successive *A. mearnsii* rotations. It is possible that the soil C stock is still in a transitional phase, where steady-state and the subsequent accumulation period discussed by Li et al. (2012), Paul et al. (2002), and Chang et al. (2014) may not yet have been reached.

Soil under natural forest and open/grazing land had higher C stock exceeding both cropland and *A. mearnsii* plantations. This finding is consistent with previous research showing that undisturbed natural ecosystems have higher C stock (Poeplau and Don 2013; Assefa et al. 2017). FAM soils also had higher C stock compared to cropland and *A. mearnssii* plantation. However, given that *A. mearnsii* cultivation did not lead to an increase in soil C stock, the higher C stock observed in FAM soils cannot be attributed to the previous presence of *A. mearnsii*. This suggests that farmers may have prioritized reverting the field to cropland rather than maintaining it under *A. mearnsii* plantation, possibly because the soil has better agricultural productivity. This interpretation is supported by the observation that majority of the FAM fields had undergone only a single rotation. These fields were also not subject to SOC depletion associated with repeated harvest cycles. While the LULC change analysis showed that the natural forest area remained unaffected by SRF expansion, open/grazing land was the second most converted land use type to SRF after cropland during the study period.

Our finding differs from studies in the same area by Kim et al. (2022) and Amare et al. (2022), who reported a substantial increase in soil C stocks with *A. mearnsii* cultivation. Kim et al. (2022) observed an annual increase of 21 Mg C ha^{-1} y^{-1}, while Amare et al. (2022) reported an average increase of 40% in SOM after 4 years under plantation. Kim et al. (2022) analyzed soil samples collected from mature stands at harvest, while Amare et al. (2022) analyzed soil samples collected from stands ranging from newly planted to mature stands ready for harvest. These different sampling approaches limit the ability to analyze temporal C stock development within and across rotations. Kim et al. (2022) focused on mature stands, thereby missing C stock development with stand age, while Amare et al. (2022) missed evaluating long-term trends across successive rotations. Both studies, however, reported higher C stocks in mature stands compared to cropland. This is consistent with our result where all the mature stands in each rotation had higher C stock compared to cropland (Figure 5). However, given that they observed significant differences in mature stands but not in younger stands, we believe their results may also have been affected by the presence of fine roots in the soil samples. Furthermore, the high C sequestration rate of 21 Mg C ha^{-1} $year^{-1}$ in soil under *A.*

mearnsii cultivation reported by Kim et al. (2022) appears to be an overestimation. This value exceeds the average annual biomass C sequestered over a 6-year period in our study (16.4 Mg C ha^{-1} y^{-1}) (Table 5). Moreover, the finding by Kim et al. (2022) of a significant increase in soil C to a depth of 1 m appears unlikely, given the shallow root system of *A. mearnsii* observed in this study and corroborated by others. It is unlikely that such a substantial change in C stock to 1 m depth could appear within a three rotations period (12–16 years).

4.4 | Carbon Balance in a Landscape Perspective

Despite the observed average decrease in soil C stock with successive rotations, the large amount of C sequestered in biomass offsets the possible loss in the soil. The combined analysis of soil and biomass C stock in the Fagita Lekoma district indicated that there was an overall increase in C stock in the landscape. The increase corresponds to 5.17 Mt of CO_2 equivalent, translating to an annual CO_2 sequestration rate of 0.30 Mt. Although the district accounts for only 0.06% of the total land area of Ethiopia (UN 2024), its average annual CO_2 sink represented 2.3% of Ethiopia's total annual fossil fuel emissions for the year 2021(IEA 2022).

Our estimation of C stock changes did not account for the potential increase resulting from natural forest regeneration. The expansion of *A. mearnsii* plantations has contributed to natural forest conservation. A review of temporal imagery from Google Earth Pro showed a corresponding increase in forest density with the expansion of plantations. This suggests that the net increase in C stock in the district may be higher than estimated, considering the positive impact of the plantations on natural forest regeneration.

The main contribution of *A. mearnsii* based SRF in Fagita Lekoma to the C dynamics is its role in reducing reliance on natural forest resources for charcoal and firewood production. With biomass based energy constituting over 90% of household cooking energy source (Sime et al. 2020; Yalew 2022), the landscape's role as a C sink is expected to remain significant if cultivation continues to expand into new areas. However, long-term productivity of the production system depends on implementation of sustainable management practices (Tiruneh et al. 2025).

To the best of our knowledge, this study represents the first comprehensive landscape level analysis of C dynamics of *A. mearnsii* plantations in Ethiopia. Previous studies have primarily focused on field-scale comparisons of C stocks in cropland soils and those under *A. mearnsii* cultivation. However, while these field level studies offer valuable insights into localized C dynamics, they do not consider the spatial distribution of land use types or the temporal changes in land use patterns. Consequently, extrapolating findings from such studies to the landscape scale may result in under- or overestimations of C stock changes. We addressed this challenge by adopting a landscape level approach that integrates multiple land use types and temporal land use and land cover change over a 17-year period. This enabled us to assess not only the difference between specific land uses but also the broader impacts of land use change on C stock dynamics in the landscape.

5 | Conclusions

This study examined the impact of land use change from cropland to *A. mearnsii* based SRF on C stock dynamics. Land use and land cover change analysis showed a substantial change between 2005 and 2022, primarily from cropland to SRF. By 2017, *A. mearnsii* cultivation reached its peak, covering 42% of the area, while cropland decreased from 67% in 2005 to 25% in 2022. However, a reversal of this trend occurred after 2017, with 40% of former *A. mearnsii* planted areas reverted to cropland or left fallow, coinciding with a disease outbreak.

Conversion of cropland to *A. mearnsii* plantations did not lead to soil C accumulation. Although the initial conversion resulted in a modest increase in soil C stock, subsequent rotations showed a decline. However, these observed differences were not statistically significant, and C sequestered in biomass offsets the potential C losses in soil.

The landscape level analysis revealed an overall increase in C stock, driven by biomass C accumulation. The annual CO_2 sequestration rate of the *A. mearnsii* based SRF system in Fagita Lekoma represented 2.3% of Ethiopia's fossil fuel emission for the year 2021.

Author Contributions

Getachew Gemtesa Tiruneh: data curation, formal analysis, investigation, methodology, project administration, visualization, writing – original draft, writing – review and editing. **Asmamaw Alemu:** funding acquisition, investigation, methodology, project administration, writing – review and editing. **Jennie Barron:** funding acquisition, methodology, writing – review and editing. **Fantaw Yimer:** investigation, methodology, writing – review and editing. **Erik Karltun:** conceptualization, data curation, funding acquisition, investigation, methodology, project administration, supervision, visualization, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data that supports the finding of this study are openly available in Dryad at https://doi.org/10.5061/dryad.q573n5tvt.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

II

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Nutrient budgets in short rotation black wattle (*Acacia mearnsii)* stands for charcoal production as compared with teff (*Eragrostis tef*) cultivation

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ABSTRACT

A rapid land use change from cropland to short-rotation forestry (SRF) with black wattle (*Acacia mearnsii* De Wild.) has taken place in northwest Ethiopia. The market demand for charcoal in urban areas is the main driver of the SRF expansion. Farmers grow *A. mearnsii* in 5–6 years rotations and they use the wood for charcoal production and fuel wood. We investigated the sustainability of the land use change through comparing nutrient budgets for the *A. mearnsii* plantations with teff (*Eragrostis tef* (Zucc.) Trotter) cultivation. We considered two harvest scenarios for *A. mearnsii*: whole biomass harvest and leaves retained on site. The average symbiotic nitrogen (N) fixation in the *A. mearnsii* stands was 175 kg N ha^{-1} y^{-1}. However, we did not observe any net accumulation of total N in the soil. The results suggest that the *A. mearnsii* cultivation depends on soil organic matter mineralization to mobilize organically bound phosphorus (P) and sulfur (S), in order to sustain the biomass production. Furthermore, *A. mearnsii* cultivation increased the net excess export of base cations by 110 % compared to *E. tef,* even when leaves were retained on the site. This export further increased to 155 % under the whole biomass harvest scenario. Thus, the land use change to SRF will lead to an intensified soil acidification. The findings highlight the need for improved nutrient management practices. These include the recycling of biomass residues and ash and potentially P and S fertilization to ensure the long-term sustainability of *A. mearnsii* cultivation in the region.

1. Introduction

Fuelwood consumption for energy in Ethiopia has more than doubled since 1990, while forest cover has decreased by over 10 % in the same period (Moges et al., 2010; IEA, 2019; FAO, 2020). The main driver for the increased demand is the population growth. The Ethiopian population has doubled between 1998 and 2022 (UN, 2024), leading to increasing demand for biomass based fuels for cooking (Kasu, 2022). The increased pressure on resources has resulted in deforestation and environmental degradation (Daley, 2015).

Biomass fuel plays a crucial role in meeting the domestic energy needs for over 90 % of the population (Sanbata et al., 2014; Benti et al., 2021; Tofu et al., 2022). Urbanization has increased charcoal demand due to its higher energy density, better cooking environment, and ease of transport compared to firewood (Drigo and Salbitano, 2008; Terfa et al., 2019). Sub-Saharan Africa accounts for an estimated 65 % of the global charcoal production, with Ethiopia among the top producers with an annual production of 4.4 Mt (Mensah et al., 2022). Illegal charcoal production from primary and secondary forests is a driver for deforestation (Alem et al., 2013; Bekele et al., 2015). Charcoal produced from managed forest is an alternative and can, if fulfilling certain criteria, also be considered as carbon (C) neutral, since subsequent forest growth offsets the C released during production and combustion (Schulze et al., 2020).

The increased market demand for charcoal has stimulated interest in the establishment of small-holder plantations (Nigussie et al., 2021b; Tesfaw et al., 2022). This has led to a land use change from cropland to short rotation forestry (SRF) in some areas (Delelegn et al., 2017; Molla et al., 2022; Endalew and Anteneh, 2023). The change is particularly notable in the Fagita Lekoma district, where large proportions of cropland have been converted to SRF in a short period (Wondie and Mekuria, 2018; Lulie and Tesfaye, 2020; Nigussie et al., 2020). The farmers

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cultivate black wattle (*Acacia mearnsii* De Wild.), a fast growing species native to Australia. Initially identified as green wattle (*Acacia decurrens*) (Nigussie et al., 2017; Wondie and Mekuria, 2018), the *Acacia* species cultivated by local farmers was later reclassified as *A. mearnsii* (Agena et al., 2023).

Farmers primarily cultivate the tree for charcoal production, because charcoal sales generate higher income than cultivation of traditional food crops. According to Nigussie et al. (2020) and Chanie and Abewa (2021) the cultivation has more than doubled farmers' annual return on investment compared to the staple food crop, teff (*Eragrostis tef*) (Zucc.) Trotter). The activities around the charcoal value chain generated employment opportunities for men, women and rural and urban youth (Nigussie et al., 2020; Chanie and Abewa, 2021). The rapid land use change to SRF resulted in a 25 % increase in forest cover of the area between 1995 and 2015 (Wondie and Mekuria, 2018). By 2017, the forest cover had more than doubled compared to the 2003 baseline (Belayneh et al., 2020).

Plantation harvest in the Fagita Lekoma involves the removal of large amounts of aboveground biomass along with stumps and larger roots (Abebe et al., 2020). Given that the soils in the area are acidic and with a poor fertility (Nigussie et al., 2017; Wondie and Mekuria, 2018), this harvest practice could affect long-term soil fertility and sustainability. The removal of biomass in acidic and nutrient poor soils could further increase soil acidification and deplete plant nutrient stocks, particularly in soils with a limited capacity for nutrient replenishment (Nykvist and Rosén, 1985; Olsson et al., 1996; Temesgen et al., 2016) which raises concerns about the long-term sustainability of this practice.

Even though the SRF system using *A. mearnsii* is unique, it has similarities to other agroforestry systems, especially the sequential planting of fast growing, nitrogen (N) fixing trees or shrubs as part of a crop rotation. These systems are often referred to as improved fallows and have been promoted as a way of improving soil fertility and reducing the reliance on mineral fertilizer in resource constrained smallholder farming in sub Saharan Africa (Kwesiga et al., 2003). Most studies of these system focuses on biomass production and N input. They have shown a positive yield effect of improved fallows on subsequent maize harvests which has been attributed to the input of symbiotically fixed N (Kwesiga and Coe, 1994; Ståhl et al., 2002). Niang et al. (2002) studied the recycling of nutrients from the harvest of improved fallows for four different N_2 fixing species by looking at the nutrient input when all the foliage was incorporated into the soil at harvest of either 6 or 12 months after planting. They found that the input of N after 12 months varied between 133 and 239 kg N ha^{-1} as compared to 100 kg N ha^{-1} for a natural fallow. For phosphorus (P), the input ranged from 6.1 to 13.4 for the N_2 fixing species, with the natural fallow recycling more P (16.3 kg P ha^{-1}). Corresponding figures for potassium (K) was 25.7–116 kg K ha^{-1} with 140 kg K ha^{-1} for the natural fallow. The review by De São José et al. (2024) provided detailed quantitative data on nutrient export through *A. mearnsii* harvest. For example, they highlighted that although N_2-fixation contributes to N nutrition in *A. mearnsii* stands, the amount fixed is generally insufficient to meet the demand during the production cycle. A study by Gupta and Bhardwaj (2012) indicated considerable nutrient export due to harvest and suggested that even retaining the nutrient-rich leaves in the field may not offset the depletion. Although these studies indicated possible long-term nutrient depletion and advised on management practices, they did not provide a complete nutrient budget analysis. To the best of our knowledge, there are no published comprehensive nutrient budget studies from improved fallows with N_2 fixing species for other nutrients than N.

This study examined the impact of land use change from annual crop production to SRF for charcoal production. The aim was to quantify nutrient budgets for major plant nutrients in the *A. mearnsii* cultivation system under two different harvest intensities and to compare them with similar budgets for *E. tef* in order to identify potential sustainability implications on soil nutrient balances.

2. Materials and methods

2.1. Study area

The study was conducted in the Amesha watershed in Fagita Lekoma district, located in the north west highlands of Ethiopia (10° 57′ - 11° 11′ N and 36° 40′ - 37° 05′ E) (Fig. 1.). The area has an undulating topography with elevations ranging from 1800 to 2900 m.a.s.l. (Worku et al., 2021). According to the Köppen classification, the area falls within the moist subtropical climate zone (Worku et al., 2021), with an average annual precipitation of 2100 mm and mean annual temperature of 18°C for the period 1997–2019 (NMA, 2020). The main rainy season, in Amharic referred to as *meher*, lasts from May to October. The predominant soil type in this area is Acrisols (Regassa et al., 2023), which are characterized by low fertility and high soil acidity. Rainfed mixed crop-livestock farming is the principal agricultural production system in the area, with *E. tef*, wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and potato (*Solanum tuberosum*) being the primary crops cultivated (Nigussie et al., 2017).

2.2. Study approach

In this study, we used a space for time substitution approach to emulate temporal changes by comparing fields with different land use histories simultaneously. The compared fields represented different stages in the land use change trajectory, ranging from the baseline condition to successive plantation rotations. Teff fields were the predominant land use prior to the introduction of *A. mearnsii* and represented the baseline condition. These were compared with *A. mearnsii* fields under the first, second, and third successive rotations. This chronosequence was intended to evaluate the cumulative effects of continuous *A. mearnsii* cultivation over time. Fields formerly under *A. mearnsii* cultivation that had been converted back to *E. tef* cultivation (FAM) were included as an additional land use type. The FAM fields provided insights into the potential future state of the fields currently under *A. mearnsii* plantations if cultivation were to cease. The land use categories and their respective definitions are presented in Table 1.

2.3. Sampling design

Soil and biomass samples were collected within the Amesha watershed in Fagita Lekoma (Fig. 1) in April and May 2022. The watershed boundary was delineated using Shuttle Radar Topography Mission (SRTM) digital elevation model from www.usgs.gov (USGS, 2022) with the hydrology tool of ArcGIS 10.7.1 prior to fieldwork.

A systematic, random sampling technique was applied to select sampling fields. The delineated watershed was divided into six subareas to ensure even distribution of sampling across the watershed. The center of each subarea was marked to facilitate navigation to the different subareas within the watershed. The resulting map, with the subarea centers marked, was uploaded to GPS devices for fieldwork navigation. Upon arrival at each subarea center, the sampling team established a transect and surveyed fields matching the predefined land use categories. The first field encountered along the transect that met the respective land use criteria was selected for sampling. Fields representing the third rotation exhibit a geographically aggregated distribution because they were found only in the epicenter of the early *A. mearnsii* plantations establishment. The total area of the watershed was 119 km^2.

Soil samples were collected from 49 fields representing three land use categories. The land use included 37 fields under *A. mearnsii*, five fields under continuous cropland cultivation, and seven fields formerly planted with *A. mearnsii* (FAM) but subsequently converted back to cropland. The *A. mearnsii* fields represented three distinct rotation cycles, with 12, 13, and 12 fields from the first, second, and third rotation cycles, respectively. Within each rotation, soil samples were collected

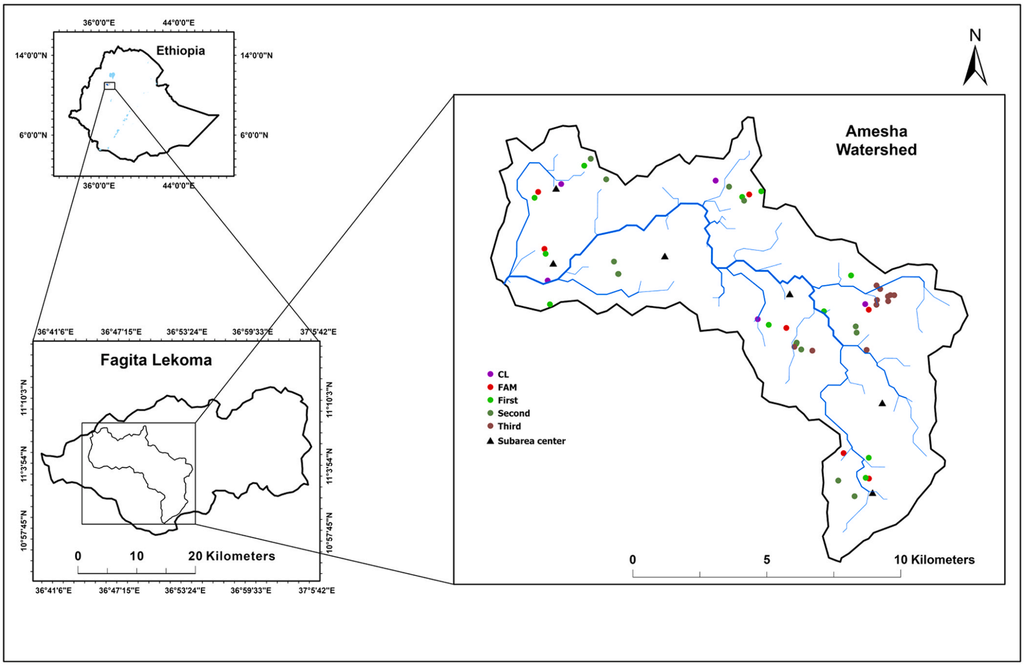

Fig. 1. Map of sampling watershed with drainage networks and soil sampling fields. Abbreviations: CL = cropland; FAM = former *A. mearnsii* field converted back to cropland; first, second, and third = first, second, and third rotation A. mearnsii plantations.

Table 1
Land use classes, number of fields sampled per class and definitions of the land use classes.

Land use class	Number of fields sampled	Definition
CL	5	Cropland - fields used to produce *E. tef*
First rotation	12	Fields under *A. mearnsii* plantation in the first rotation cycle with a stand age of 5 and 6 years.
Second rotation	13	Fields under *A. mearnsii* plantation in the second rotation cycle with a stand age of 5 and 6 years.
Third rotation	12	Fields under *A. mearnsii* plantation in the third rotation cycle with a stand age of 5 and 6 years.
FAM	7	Field that was formerly planted *A. mearnsii* but has now been converted back to cropland (*E. tef*) cultivation

from stands aged five and six years. The FAM fields represented land that has been converted from *A. mearnsii* cultivation to cropland for a minimum of 2–3 years before samples were collected. Of the seven FAM fields, five were planted for a single rotation, whereas the remaining two were planted for two rotations.

Biomass samples were collected from *A. mearnsii* plantations with a stand age of five and six years from the first and second rotation. These stand ages were selected based on previous studies (Bazie et al., 2020) and assessments conducted during the fieldwork, which indicated that most farmers harvest the plantation for charcoal production when the stand age have reached five years or older.

2.4. Soil and biomass sampling

A 10 m x 10 m sampling plot was established in each field and soil samples were collected from the four corners and center of the plot at two depth intervals: 0–15 and 15–30 cm. The five subsamples from the same depth were pooled to form a composite sample for each depth.

Undisturbed soil samples for bulk density determination were collected using a cylinder with known volume. The cylinder was pushed into the soil at 0–15 cm and 15–30 cm depth and the soil retained in the cylinder was used for bulk density determination. The samples were placed in sealable plastic bags and transported to the laboratory for bulk density determination.

Biomass samples were collected from 12 plantation fields with stands aged five and six years. Within each field, a 10 m x 10 m sampling plot was established and the total number of trees within the plot was recorded. Subsequently, the height and diameter at breast height (DBH) of 20 representative trees were measured within each plot. The height of the trees was measured using a graded bamboo stick and DBH was measured at 1.3 m above the ground using a digital caliper. On each plot, one tree with height and DBH close to the average height and DBH of the trees in the plot was selected for destructive sampling. A total of 12 trees were destructively sampled, and their components were separated into stem, branches, leaves, and roots. An additional 12 leaf samples were collected from stands aged three and four. Leaves and twigs were not separated and were weighed together as single unit. The fresh weight of the harvested biomass was measured using a portable hanging scale and the total fresh biomass was recorded on site. Subsamples from each component were collected for laboratory analysis. Stem samples, including wood and bark, were obtained from disks cut at 20 % intervals along the height of the tree. Branch and leaf samples were collected along the height of the crown. Root samples were obtained by excavating around the sample trees to a depth of 40 cm. Collected roots were classified into three diameter classes: fine (< 2 mm), medium

(2–5 mm), and coarse (> 5 mm) (FAO, 1990). Although dry mass of the whole root biomass was measured, the chemical composition analysis was performed only on the coarse roots. This is because coarse roots are the root fractions harvested for firewood and removed from the field prior to land preparation for subsequent planting. Furthermore, a biomass sample of *Croton macrostachyus* was collected from the same watershed. This plant is a non N_2-fixing species and therefore mainly source its N from soil N. As a result, it has a δ^{15}N signature similar to the δ^{15}N of the soil. It is used as a reference in the calculation of the magnitude of N_2 fixation by *A. mearnsii* (Shearer and Kohl, 1986).

2.5. Sample preparation and laboratory analysis

The soil samples were air-dried, homogenized, and sieved through a 2 mm sieve. One gram of the homogenized sample was ground into a fine powder using a ball mill for stable N isotope analysis. Biomass samples were oven dried at 65°C until a constant weight was achieved. The bark was carefully separated from the woody stem and all dried samples were milled to pass through a 2 mm sieve. An additional one gram of the homogenized ground sample was ground into a fine powder using a ball mill for stable N isotope analysis.

The dry biomass weight for each tree component was determined using the oven-dried samples. The dry matter weights for each component were calculated by multiplying the dry matter percentages of each component by its corresponding fresh weights. The total dry matter weight of each tree was obtained by summing the dry matter weights of all components. Subsequently, the dry biomass per hectare was estimated by multiplying the average dry biomass per tree by the average number of trees per hectare.

Nutrient concentration in the soil samples were determined using the Mehlich-3 extraction procedure (Mehlich, 1984). All soil samples were extracted, and the concentration of P, K, magnesium (Mg), calcium (Ca), and sulfur (S) in the extract was measured using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, Avio 200, Perkin Elmer, Waltham, MA, USA). The analysis was performed at the Swedish University of Agricultural Sciences, Department of Soil and Environment laboratory, SLU, Uppsala.

Sixty biomass samples were analyzed for nutrient concentration. The samples consisted 12 from each of woody stem, bark, branches, leaves, and roots. The samples were digested in a mixture of nitric acid and hydrogen peroxide with trace amount of hydrogen fluoride in a microwave oven according to a standard procedure of SS-EN 13805:2014. The obtained solution was analyzed using Inductively Coupled Plasma Sector Field Mass Spectroscopy (ICP-SFMS) according to standard procedures SS-EN ISO 17294–2:2016 and US EPA method 200.8:1994. The analyses were carried out by the ALS Scandinavia Laboratory in Luleå, Sweden.

The total nitrogen (TN) content in the soil and biomass was determined through dry combustion according to ISO 13878 (ISO, 1998). Analysis was performed using an elemental analyzer for macro samples (TruMac ® CN, Leco corp, S:t Joseph, MI, USA). The analysis was performed at the Swedish University of Agricultural Sciences, Department of Soil and Environment laboratory, SLU, Uppsala.

Stable N isotope analysis was performed on all soil samples and 49 biomass samples. The biomass samples included six leaf samples from each stand aged three to six years, for 25 leaf samples. One of the leaf samples was a non-N_2 fixing reference plant, *Croton macrostachyus*. Additionally, samples of stem, bark, root, and branch were analyzed, with each component represented by six samples. The stem, root, bark, and branch samples were collected from the six year old stand. The stable N isotope ^{15}N:^{14}N ratio was analyzed using an isotope ratio mass spectrometer coupled with an elemental analyzer (EA-IRMS) at the stable isotope laboratory of Swedish University of Agricultural Sciences (SLU) in Umeå, Sweden. Wheat and maize flour calibrated against reference standard IAEA-600, IAEA-N-2, USGS40 and USGS41 were used as working standard. The ^{15}N abundance data were expressed using the standard notion (δ^{15}N) in parts per thousand (‰) relative to the atmospheric ^{15}N:^{14}N ratio:

$$\delta^{15}N_{(‰)} = \left(\frac{R_{sample}}{R_{standard}} - 1\right) x \quad 1000 \tag{1}$$

where R denotes the ratio of ^{15}N/^{14}N in sample and standard.

2.6. Determination of the percentage of N derived from atmospheric N_2 fixation

The proportion of N derived from N_2 fixation by *A. mearnsii* was estimated using the equation by Shearer and Kohl (1986):

$$\%Ndfa = \frac{\delta^{15}N_{Rp} - \delta^{15}N_{AM}}{\delta^{15}N_{Rp} - B} \tag{2}$$

where:%Ndfa = the percentage of plant N derived from atmospheric N_2,$\delta^{15}N_{Rp}$ = the ^{15}N value of the non-N_2 fixing reference plant,$\delta^{15}N_{AM}$ = the ^{15}N value of *A. mearnsii*,B = the δ^{15}N value of *A.mearnsii* grown in an N free medium obtaining its entire N from N_2 fixation.

In the absence of a locally determined B value, we used a value of −1.76 based on recommendation provided by Unkovich et al. (2008). We applied the equation given by Forrester et al. (2007) to estimate the percentage of soil N derived from N_2 fixation by *A. mearnsii*. Cropland soils that had never been planted with *A. mearnsii* was used as the reference soil. Nitrogen derived from N_2 fixation in the litter layer was estimated based on our litterfall measurement, the N content of senesced leaves of *A. mearnsii* (Railoun et al., 2021), and the proportion of N derived from N_2 fixation. Litterfall was assumed negligible during the initial two years of stand establishment and was therefore excluded from the estimation.

2.7. Nutrient stock

The biomass nutrient stock was calculated as the sum of nutrient stocks in individual tree components:

$$NS_t = \sum (DM_i{}^*N_i) \tag{3}$$

where,NS_t = total nutrient stock in the tree,DM_i = dry matter of tree component i,N_i = nutrient concentration of tree component i.

The soil nutrient stocks in the 0–15 and 15–30 cm depth intervals were calculated as the product of the bulk density, extractable nutrient concentration, and soil sampling layer thickness. Prior to nutrient stock estimation calculation, the bulk density of the soil was corrected for the coarse fraction and subsequently adjusted according to the method specified by Fowler et al. (2023). The coarse fraction retained on the 2 mm sieve was used to calculate the coarse fraction percentage.

$$NS_s = \sum (\rho_i{}^*t_i{}^*C_i) \tag{4}$$

where:NS_s = soil nutrient stock,ρ_i = soil density at the ith depth,t_i = thickness of the layer at ith depth,C_i = nutrient concentration in the soil at the ith depth.

Soil nutrient concentrations under different land uses are presented in the supplementary material, Table S1.

2.8. Nutrient budget

2.8.1. Nutrient inputs

Nutrient inputs included fertilizer application, N_2 fixation, ash from charcoal production, weathering, organic matter (OM) mineralization and atmospheric deposition. Data on N, P, and S fertilizer application rates for *E. tef* cultivation were obtained from the Ethiopian Statistical Service data portal (ESS, 2022). The data show that over 60 % of the farmers applied mixed NPS fertilizer (19 %N, 38 % P_2O_5, and 7 % S)

(Tegbaru, 2015) while the remaining used urea and di-ammonium phosphate (DAP). The NPS application rate was calculated based on the quantity of fertilizer applied and the total area of application. Quantity and area of application for urea and DAP was not presented and as a result rates were estimated using the national average fertilizer application rates in Ethiopia: 43 kg urea ha^{-1} and 65 kg DAP ha^{-1} (Elias, 2017). The quantity of N fixed by *A. mearnsii* was estimated by multiplying the percent of N fixed (Eq. 2) by the total N content in *A. mearnsii*.

The quantity of nutrients returned to the field in ash from charcoal production was calculated using the difference between the nutrient content of the original wood and bark biomass and the nutrient content of the resulting charcoal. The ash fraction of the original biomass and charcoal were measured since the nutrients are found within the ash fraction (Pitman, 2006). The average ash content of the tree components was determined using ignition of weighed biomass samples at 550 °C over a 24 hour period and subsequently weighing the remaining ash. The quantity of nutrients exported with the charcoal was estimated using 3.41 % ash content in *A. mearnsii* charcoal (Cromarty et al., 2023) and 25 % charcoal production efficiency of traditional kilns (Tazebew et al., 2023). The difference between the total ash content of the biomass and the ash exported in charcoal accounted for 4.6 % of the total biomass ash content. As a result, it was assumed that 4.6 % of the total nutrient stock in the components used for charcoal production remained in the field.

Two key assumptions considered in the calculation include:

(1) Charcoal is produced in the same field where the trees are harvested, leaving behind ash (Chanie and Abewa, 2021; Nigussie et al., 2021a)
(2) The stem is used for charcoal production, while larger roots and branches are used as firewood and therefore removed from the field (Chanie and Abewa, 2021; Nigussie et al., 2021a). Roots with a diameter exceeding five mm were categorized as larger roots.

Two harvest intensity scenarios were evaluated: whole biomass harvest (WBH) and leaves retained on site (LRS). WBH represents a management where leaves and twigs are removed from the field in preparation for subsequent agricultural operations. Conversely, LRS is a potential alternative scenario where nutrients in the leaves are returned to the soil. Both scenarios were mentioned in the literature, where Abebe et al. (2020) mentioned that leaves and twigs are removed as firewood, while Nigussie et al. (2021b) indicated that they are left on site. During fieldwork, farmers reported that they either remove the residual biomass as firewood or burn it on the field to ease subsequent farming operations. Therefore, we considered these scenarios to be the end members in the varying leaf management practices.

The atmospheric deposition data for N and P was obtained from Mulualem et al. (2024), who measured deposition in a watershed near our study area. Atmospheric deposition estimate for K, S, Ca, and Mg were obtained from Ashagrie and Zech (2010). For the *E. tef* field, the deposition through rainfall presented in the study were directly applied. However, for the *A. mearnsii* field, the average enrichment factor for *Eucalyptus* and *Cupressus* presented by Ashagrie and Zech (2010), was multiplied by the rainfall deposition to account for nutrient interception by the trees from dry and wet deposition.

Due to the unavailability of locally measured weathering and OM mineralization rates, their contribution to the nutrient budget were calculated as unexplained remaining input needed to balance outputs. Nutrient export exceeding known inputs, which could potentially be offset by weathering and OM mineralization, is referred to as excess export in the text.

2.8.2. Nutrient outputs

Nutrient export via grain and residue harvest from *E. tef*, charcoal and firewood harvest from *A. mearnsii*, litterfall, leaching, erosion, and gaseous losses were the outputs considered in the budget calculation. The quantity of nutrient exported with charcoal was estimated using a 25 % conversion efficiency from traditional kilns (Tazebew et al., 2023) and 3.41 % ash content in *A. mearnsii* charcoal (Cromarty et al., 2023). Biomass export for firewood was evaluated under the WBH and LRS scenarios. Branches, large roots, and twigs with leaves are primary biomass components harvested for firewood. The annual nutrient uptake by the plantation stand was estimated by dividing the average of the total nutrient stock in the biomass for stand age five and six by the average stand age. The calculated nutrient uptake rates were compared to the annual nutrient uptake of *E. tef* to determine which production system results in greater nutrient removal from the field. Nutrient removal from cropland through *E. tef* grain and residue harvest was quantified using secondary data (see supplementary materials: Table S2, S3, and S4). Nutrient stocks in *E. tef* were estimated based on a grain yield of 980 kg ha^{-1} (Nigussie et al., 2020) and average harvest index of 0.26, compiled from different studies. The *E. tef* residues are normally used for mud house construction and animal feed (Dula, 2017; Tessema et al., 2023). This practice leads to nutrient removal from cropland and, as a result, the crop residue was treated as an output in budget calculations.

Nutrient loss through litterfall was estimated using the measured litter layer mass from this study and the nutrient concentration ratios of senesced leaves relative to fresh leaves. Ratio of N and P were obtained from Railoun et al. (2021), while ratio of the other nutrients were obtained from Vergutz et al. (2012).

Nitrogen and P loss through erosion was determined using soil loss estimate from different land uses in the area (Ter Borg, R.N., 2020) and the N and P content of eroded sediments. Nitrogen loss due to erosion was estimated by multiplying the total N content in the 0–15 cm layer by the amount of soil lost from each land use. Phosphorus loss through erosion from cropland was estimated using a weighted average P loss reported by Erkossa et al. (2015). Although this study was not from the same area, it was assumed to provide more accurate estimates than using a pedotransfer function. Phosphorus loss from *A. mearnsii* stands was estimated by applying the N:P ratio derived from eroded cropland sediments to the weighted average P content of eroded sediments reported by Erkossa et al. (2015). Due to lack of relevant data, erosion based losses of K, S, Ca, and Mg were estimated using the pedotransfer function recommended by Smaling et al. (1993) with an enrichment factor of 1.5. Nutrient leaching and gaseous loss of N were also estimated using a transfer function provided by Smaling et al. (1993). In cases where there are higher inputs than outputs, the difference is assigned as net immobilization.

Due to the practice of intercropping *E. tef* with *A. mearnsii* during seedling establishment, as well as harvesting grass for animal feed from the understory in the second year (Nigussie et al., 2020), the nutrient export from these two harvests was included in the budget under the *A. mearnsii* cultivation system. Although some studies have suggested that intercropping *E. tef* with *A. mearnsii* can double *E. tef* yield, this study applied a more conservative 25 % increase in yield and corresponding nutrient export, based on data presented by Chanie and Abewa (2021). Data on the amount of grass harvested per hectare for natural pasture in the communal pastureland of the area were obtained from Desta et al. (2023). The corresponding nutrient concentration values for natural pasture grasses were obtained from data presented by Kabaija and Little (2013). The N concentration was estimated from the presented crude protein data using a conversion ratio of 16 %. The data is provided in supplementary materials Table S5 and S6.

2.8.3. Nutrient budget estimation

A nutrient budget was calculated as the difference between the inputs and outputs, representing a mass balance of nutrients per unit area (Zhang et al., 2020) as follows:

$$0 = (n_{fix} + n_{fert} + n_{ad} + n_{ash} + n_{wOM}) - (n_{harv} + n_{lf} + n_{leach} + n_{ero} + n_{gas} + n_{im}) \quad (5)$$

where: n_{fix} = N_2 fixation by *A. mearnsii*, n_{fert} = fertilization in *E.tef* crop cultivation, n_{ad} = atmospheric deposition, n_{ash} = ash input from onsite charcoal production, n_{wOM} = nutrients from weathering and/or organic matter net mineralization, n_{harv} = export via grain and residue of *E. tef* and charcoal and firewood harvest, n_{lf} = nutrients in litterfall, n_{leach} = loss through leaching, n_{ero} = loss through erosion, n_{gas} = gaseous loss and, n_{im} = nutrient net immobilization in soil.

A schematic diagram of the system boundary with the inputs and outputs considered in this study is presented in Fig. 2.

2.9. Statistical analysis

Statistical analyses were performed using R version 4.2.3. A mixed effects model was used to assess the effect of land use, with land use as fixed effect and subareas as a random effect. The model was fitted separately for the two depth layers using the *lme* function from the *nlme* package. Post-hoc comparisons were performed with the *emmeans* package, using a Tukey adjustment. Response variables were log and square root transformed when model assumptions were not met. Data are presented as means ± confidence intervals. The confidence interval for aggregated means represent the cumulative uncertainty propagated from individual components. Statistical significance was determined at $p < 0.05$.

3. Results

3.1. Dry matter yields

The average total dry matter biomass yield of *A. mearnsii* for stand age five and six was 151 Mg ha^{-1} with woody stems accounting for an

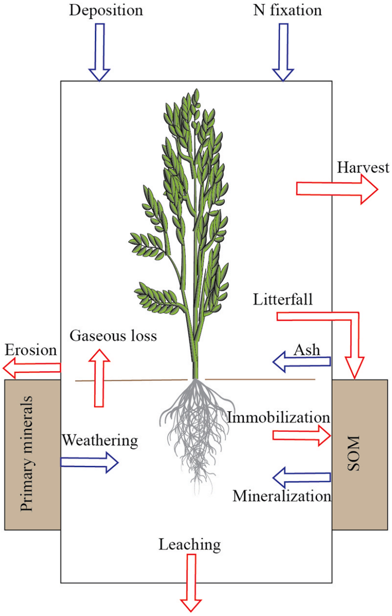

Fig. 2. Schematic diagram of the system boundary with the main inputs (blue arrows) and outputs (red arrows).

average of 62 % of the total dry matter mass (Table 2). Branches, barks, root and leaves with twigs accounted for 15 %, 8 %, 8 %, and 7 % of the total dry weight biomass respectively. Of the total root dry matter weight (11.6 Mg ha^{-1}), 55 % consisted of larger roots (>5 mm).

3.2. Nutrient stock in the biomass

Table 3 presents the nutrient stocks in the *A. mearnsii* biomass and *E. tef* grain and straw. Leaves and twigs represent only 7 % of the total biomass but account for approximately 35 %, 28 %, 21 %, and 35 % of the N, P, K, and S stock in the biomass, respectively. The woody stem and bark accounted for 40 %, 42 %, 49 %, and 36 % of the N, P, K, and S, respectively. The combined stock of base cations (K, Ca, and Mg) within woody stem and bark are 50 % of the total biomass base cation stock. The accumulation rates of the major nutrients N, P, K, and S in biomass, excluding fine roots, are 162, 8.6, 72, and 8.5 kg ha^{-1} y^{-1}, respectively.

The straw fraction *E. tef* contains similar amounts of N and P compared to the grain. However, the stocks of base cations and S in straw are 6 and 2 times higher, respectively, than in the grain.

The average annual N uptake of *A. mearnsii* is five times higher, and the base cation uptake is three times higher than that of *E. tef*.

3.3. Nitrogen fixation

A. mearnsii stands fixed a total of 175 kg N ha^{-1} y^{-1}. The proportion of N originating from N_2 fixation varied among the different biomass tissues and stand ages. The stem contains the highest proportion of N derived from atmospheric N_2 fixation, whereas the bark and root has the lowest proportions (Table 4). $\delta^{15}N$ values in leaves of *A. mearnsii* increased with increasing stand age. The percentage of N fixed by the *A. mearnsii* decreased from 94 % to 78 % as the stand age increased from three to six years (Table 5). Approximately 87 % of the total biomass N is derived from atmospheric N_2 fixation, corresponding to a total of 960 kg N ha^{-1} per rotation.

The concentration of molybdenum (Mo) in different biomass compartments of *A. mearnsii* showed that the highest accumulation was found in root biomass, while concentration were below the detection limit in all other biomass components (supplementary materials: Table S7).

Soil $\delta^{15}N$ values in the 0–15 cm depth were significantly lower in the second and third rotation *A. mearnsii* plantations compared to the first rotation, cropland, and FAM soils (Table 6). No significant difference in $\delta^{15}N$ values were observed between cropland, first rotation *A. mearnsii*, and FAM soils. *A. mearnsii* cultivation added an average of 84 kg N ha^{-1} y^{-1} and 54 kg N ha^{-1} y^{-1} to the soil in the second and third rotations, respectively, corresponding to an average of 69 kg N ha^{-1} y^{-1} over the three rotations.

Despite a higher proportion of N originating from N_2 fixation in the soil under the second and third rotations of *A. mearnsii* cultivation, no corresponding accumulation of TN in soil was observed (Fig. 3.).

Table 2
Dry matter weight of *A. mearnsii* biomass components in Mg ha^{-1} (mean ± CI) at the expected harvest age.

Stand age	n	Stem	Bark	Root	Branch	Leaf & twig	Total
	–	Mg ha^{-1}					
5	6	71.8 ± 27.4	11.3 ± 3.74	9.86 ± 3.66	21.0 ± 9.39	9.97 ± 3.54	124 ± 43.3
6	6	115 ± 30.1	14.7 ± 3.12	13.4 ± 6.24	23.1 ± 8.43	11.5 ± 4.13	178 ± 45.6
Average		93.4 ± 22.0	13.0 ± 2.30	11.6 ± 3.17	22.1 ± 5.20	10.7 ± 2.28	151 ± 31.3

Table 3
Nutrient stocks (kg ha^{-1}) in biomass components *E. tef* and *A. mearnsii* (mean ± CI).

Nutrients	*E. tef*			*A. mearnsii*					
	Grain	straw	Total	Stem	Bark	Root	Branch	Leaf & twig	Total
N	15.3 ± 1.05	15.7 ± 3.38	31.0 ± 3.54	201 ± 23.6	158 ± 13.7	32.0 ± 7.63	193 ± 20.8	308 ± 11.2	892 ± 36.9
P	4.10 ± 0.48	3.24 ± 0.52	7.35 ± 0.71	14.7 ± 3.42	5.33 ± 0.75	2.11 ± 1.25	12.0 ± 4.25	13.5 ± 0.90	47.6 ± 5.72
K	3.97 ± 0.43	29.3 ± 2.30	33.2 ± 2.34	145 ± 26.9	47.7 ± 11.8	10.7 ± 1.60	107 ± 30.9	83.0 ± 11.9	394 ± 44.3
S	1.60 ± 0.26	4.10 ± 1.51	5.69 ± 1.53	11.3 ± 1.53	5.34 ± 0.59	3.38 ± 1.18	10.5 ± 1.58	16.3 ± 0.98	46.8 ± 2.75
Ca	1.52 ± 0.21	9.20 ± 3.96	10.7 ± 3.97	98.1 ± 13.8	105 ± 14.0	14.8 ± 2.95	87.6 ± 13.2	95.2 ± 7.77	400 ± 25.1
Mg	1.87 ± 0.14	5.30 ± 1.15	7.15 ± 1.16	24.7 ± 1.94	16.6 ± 3.05	2.40 ± 0.37	20.6 ± 3.58	22.0 ± 2.14	86.2 ± 5.53

Note: The data sources used to determine *E. tef* nutrient concentrations in grain and straw, as well as the yields of grain and straw per hectare, are presented in supplementary materials Tables S1–S3. For *A. mearnsii*, nutrient stock values in biomass components are based on the average of 12 measurements per component and represent nutrient accumulation in stands at the typical harvest age of 5 and 6 years.

Table 4
δ15 N and proportion of N derived from atmospheric N_2 fixation by *A. mearnsii* in different biomass components over a rotation period (mean ± CI).

	n	$\delta^{15}N$ ‰	%N from N_2 fixation	N_2 fixed kg ha^{-1}	Note
Acacia mearnsii					
Stem	6	−2.34 ± 0.95	100 %	201 ± 23.6	
Bark	6	−0.52 ± 0.97	79 %	125 ± 10.8	
Branch	6	−1.15 ± 0.81	90 %	173 ± 18.7	
Root	6	−0.65 ± 1.15	81 %	47.1 ± 6.18	
Leaves	24	−1.05 ± 0.25	83 %	256 ± 9.30	
Litter fall				158 ± 12.4	
Total			87 %	960 ± 36.1	
Croton macrostachyus	1	4.79			Reference plant

Note: The N fixed in the litter fall was estimated as the product of fresh leaves N concentration, the proportion of N not resorbed prior to senescence as presented by Railoun et al. (2021), measured litter dry matter, and proportion of N derived from atmospheric N_2 fixation (%Ndfa) as determined in this study.

Table 5
$\delta^{15}N$ / ‰ values of *A. mearnsii* leaves and percent of N derived from N_2 fixation (%Ndfa) for stand age between 3 and 6 years (mean ± CI).

Stand age	n	$\delta^{15}N$ / ‰	%Ndfa
3	6	−1.39 ± 0.29	94 %
4	6	−1.24 ± 0.28	91 %
5	6	−1.08 ± 0.68	88 %
6	6	−0.49 ± 0.79	78 %

3.4. Total N and Mehlich 3 extractable nutrient stocks in soil

The estimated mean available nutrient stocks in soil under cropland and the three successive *A. mearnsii* rotations are presented in Fig. 3. The results from the ANOVA showed significant differences in TN and P stocks between cropland and successive *A. mearnsii* rotations. The P stock in the 0–15 cm layer for the second and third rotations was significantly lower compared to cropland, but not in the 15–30 cm layer. For TN, the second and third *A. mearnsii* rotation had significantly lower TN stock than the first rotation at the 0–15 cm depth but did not differ significantly from cropland. Although the overall ANOVA indicated only a marginally significant difference for S ($p = 0.06$) in the 0–15 cm, the successive rotations of *A. mearnsii* had significantly lower S stock compared to cropland. A similar decreasing trend was observed for S at 15–30 cm, but the ANOVA did not detect significant differences between cropland and the rotations. Similarly, K stock decreased with successive rotations, but this difference was not statistically significant. Moreover, no statistically significant difference was observed for Ca and Mg between cropland and successive rotations of *A. mearnsii* cultivation. The average nutrient stocks on the original scale are provided in supplementary material Table S8.

3.5. Nutrient budgets

Table 7 summarizes the mean nutrient budgets of *E. tef* and *A. mearnsii* cultivation under two different harvest scenarios. A comparative analysis showed that both production systems resulted in a net loss of soil N. *E. tef* resulted in a net mineralization of 19.7 kg N ha^{-1} y^{-1}, equivalent to a 0.25 % annual depletion of the average TN stock in cropland soil. Despite N_2 fixation by *A. mearnsii*, the budget indicated a net N mineralization of 13 kg ha^{-1} yr^{-1} and 69 kg ha^{-1} yr^{-1} under the LRS and WBH scenarios, respectively. These corresponded to average annual depletion of 0.16 % and 0.86 % of the TN stock in soil over the three rotations for the two scenarios, respectively. While the P and S budget for *E. tef* cultivation was balanced, *A. mearnsii* cultivation depleted the soil of 13.0 kg P ha^{-1} y^{-1} and 10.4 kg P ha^{-1} y^{-1} under WBH and LRS scenarios, respectively. Similarly, S depletion rates were 10.1 kg S ha^{-1} y^{-1} and 7.10 kg S ha^{-1} y^{-1}under WBH and LRS scenarios.

Potassium budgets also showed excess export in harvest in relation to known inputs under both cultivation systems and harvest scenarios. Compared to *E. tef*, *A. mearnsii* resulted in 100 % (38.8 kg ha^{-1}) and 65 % (25.3 kg ha^{-1}) higher K excess export under WBH and LRS, respectively. Ash from charcoal production accounted for 2 % (1.63 kg ha^{-1}) of the annual excess K exported.

Calcium export under *A. mearnsii* cultivation is significantly exceeded that of *E. tef* by more than three times in both WBH and LRS scenarios, resulting in excess export of 87.5 kg $ha^{-1}$and 71.1 kg ha^{-1}, respectively. Excess Mg export was 22.3 kg ha^{-1} and 18.5 kg ha^{-1}, under WBH and LRS, respectively. Ash from charcoal production accounted for 2 % of the annual excess export of Ca and Mg. Overall, *A. mearnsii* cultivation resulted in a larger base cation export compared to *E. tef*, with 110 % and 155 % higher export under LRS and WBH harvest scenarios, respectively.

4. Discussion

4.1. Biomass

4.1.1. Dry matter stock and nutrient accumulation

The average dry matter accumulation of *A. mearnsii* observed in this study (151 Mg ha^{-1}) is lower than the 282 Mg ha^{-1} reported by Mekonnen et al. (2006) for *A. mearnsii* grown on Vertisols of the Ethiopian highlands over 64 months. There are three factors that probably contributed to the difference in dry matter accumulation between the studies. The first one is that the study by Mekonnen et al. (2006) was carried out in a researcher controlled experiment with more careful management as compared to the farmer managed fields in this study.

Table 6
$\delta^{15}N$ and proportion of TN in soil attributable to the *A. mearnsii* plantation over a rotation period(mean ± CI).

Land use	n	Depth	$\delta^{15}N$ / ‰	%N from N_2 fixation	TN derived from AM plant Kg ha^{-1}	Annual TN fixed kg^{-1} ha^{-1} y^{-1}	Note
Cropland	5	0–15	6.83 ± 1.54^a				$\delta^{15}N$ of cropland used as a reference
		15–30	6.93 ± 1.46^a				
FAM	7	0–15	6.42 ± 1.02^a	-	-		NS
		15–30	6.80 ± 0.82^a	-	-		NS
First rotation	12	0–15	5.67 ± 0.61^a	-	-		NS
		15–30	6.09 ± 0.70^a	-	-		NS
Second rotation	13	0–15	4.63 ± 1.62^b	26 %	927 ± 182	84	
		15–30	5.72 ± 1.02^a	-	-		NS
Third rotation	12	0–15	4.78 ± 1.44^b	24 %	897 ± 160	54	
		15–30	5.61 ± 1.26^a	-	-		NS

Note: Means with the same letter are not significantly different from each other. NS indicates that no statistically significant difference was observed between cropland and the respective land uses in those soil depths. Therefore, there is no evidence of N from *A. mearnsii* N fixation at the depths indicated by NS. The annual TN derived from N_2 fixation by *A. mearnsii* stands was calculated by dividing the TN fixed during the second and third rotations by their respective length under the plantation, 11 and 16.5 years, respectively. The average rotation length was 5.5 years.

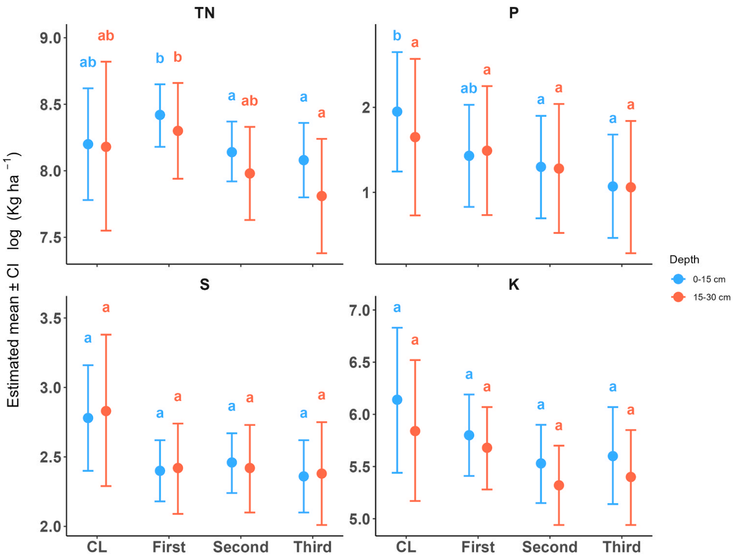

Fig. 3. Total N and Mehlich-3 extractable stock of P, S and K (mean ± CI, α=0.05) in soil under cropland (CL) and *A. mearnsii* plantations across the three rotation cycles. Note: Mean values sharing the same letter indicate no significant difference. The analyses were performed separately for each depth but are plotted together for comparative visualization. The values presented are on a log scale. Mean stocks on the original scale are provided in supplementary material Table S8.

The second is the difference in soil type as Vertisols are known for having a much higher inherent soil fertility as compared to the Acrisols of the study area (FAO, 2014). A third potential contributing factor is the rust disease caused by *Uromycladium acacia*, which has been prevalent in the area since the beginning of 2020 (Agena et al., 2023). A study by Pham et al. (2024) indicated that the disease resulted in stunted growth, leading to overall low biomass production. Although the disease primarily affected young saplings, and the trees sampled for this study were from stands aged five and six years, we cannot rule out that the trees were under stress. The study by Mekonnen et al. (2006) also showed that the most common SRF species planted in Ethiopia, including eucalypts, produced significantly lower dry matter yields than *A. mearnsii* over the 64 months of the experiment. A study by Zewdie et al. (2009) also showed that *Eucalyptus globulus* with second coppice and shoots aged five (69.7 Mg ha^{-1}) and seven (92.8 Mg ha^{-1}) years produced an average of 81.3 Mg ha^{-1} dry matter in above ground biomass. This result is 40 % lower than the above ground biomass dry matter yields for *A. mearnsii* in this study.

The nutrient concentrations of different *A. mearnsii* tree compartments are consistent with previous studies conducted by Juba (2020) and Mekonnen et al. (2006) in South Africa and Ethiopia respectively (supplementary materials: Table S7). Leaves represent a smaller fraction of the dry matter, yet have the highest concentrations of nutrients. This has implications for sustainability, as leaf litter plays a crucial role in nutrient recycling (Sayer, 2006). However, when trees are felled for charcoal production, the leaves and twigs are often used as a cover in traditional charcoal making kilns or removed along with branches for firewood (Chanie and Abewa, 2021; Nigussie et al., 2021a; Amare et al., 2022). Retaining leaves on-site could reduce nutrient export by 28 %, while retaining both bark and leaves could reduce nutrient export by 45 %. A study in eucalypt plantations in Uruguay showed comparable result, indicating that retaining bark and leaves on site resulted in 36 % -

Table 7
Ecosystem nutrient budgets for N, P, K, S, Ca and Mg for *E. tef* and *A. mearnsii* cultivated field under two harvest scenarios in kg ha^{-1} y^{-1}.

Nutrient budget	N			P			K			S			Ca			Mg		
	Teff	*A. mearnsii*		Teff	*A. mearnsii*		Teff	*A. mearnsii*		Teff	*A. mearnsii*		Teff	*A. mearnsii*		Teff	*A. mearnsii*	
		WBH	LRS		WBH	LRS		WBH	LRS		WBH	LRS		WBH	LRS		WBH	LRS
Input																		
Atmospheric deposition	5.87	4.55	4.55	0.20	0.04	0.04	0.80	6.53	6.53	1.81	1.29	1.29	1.77	3.24	3.24	0.08	0.87	0.87
N_2-fixation		146	146															
Fertilizer	43.0			13.8						5.64								
Ash					0.17	0.17		1.63	1.63					1.69	1.69		0.35	0.35
Weathering/OM mineralization	19.7	69.0	13.0		13.0	10.4	38.7	77.5	63.9		10.1	7.10	22.0	87.5	71.1	12.2	22.3	18.5
Total in	68.6	220	164	14.0	13.2	10.6	39.5	85.6	72.1	7.45	11.3	8.38	23.8	92.4	76.0	12.3	23.5	19.7
Output																		
Export in *E. tef* harvest of grain and straw	31.0	7.08	7.08	7.35	1.67	1.67	33.20	7.54	7.54	5.69	1.29	1.29	10.70	2.43	2.43	7.15	1.62	1.62
Understory grass harvest		1.80	1.80		0.23	0.23		2.20	2.20		0.24	0.24		0.52	0.52		0.30	0.30
Biomass for charcoal		65.3	65.3		3.64	3.45		35.0	35.0		3.03	3.03		36.9	36.9		7.51	7.51
Biomass for firewood		96.9	40.9		5.02	2.57		36.5	21.40		5.49	2.53		35.9	18.6		8.18	4.18
Litterfall		33	33		1.10	1.10		3.93	3.93		1.29	1.29		13.4	13.4		2.46	2.46
Leaching	18.0	7.51	7.51				3.83	0.00	1.51				3.04		0.80	3.22	2.79	2.99
Gaseous losses	7.72	4.70	4.70															
Loss due to erosion	11.9	3.30	3.30	5.4	1.5	1.5	2.44	0.44	0.44	0.10	0.02	0.02	10.0	3.33	3.33	1.88	0.67	0.67
Immobilization				1.25						1.66								
Total out	68.6	220	164	14.0	13.2	10.6	39.5	85.6	72.1	7.45	11.3	8.38	23.8	92.4	76.0	12.3	23.5	19.7

Note: We did not measure mineral weathering, OM mineralization and immobilization rates, nor did we obtain from literature. We calculated these values based on known inputs and outputs, as discussed in methods section. These values indicate the degree to which the system is depleting (mineralization) or building up (immobilization) nutrient pools.

58 % reductions in nutrient loss (Resquin et al., 2020).

Despite the low nutrient concentration in the woody stem, its large proportion makes it a substantial nutrient stock. The woody stem accounts for 30 % of the P and the base cations (K, Ca, and Mg). Including bark further increases this portion to 42 % for P and 50 % for the base cations. This suggests that exclusion of bark from the woody stem during charcoal production could potentially decrease the base cation export by 40 %. Comparing *A. mearnsii* with *E. globolus*, the dominant exotic tree species planted in Ethiopia, using data presented by Zewdie (2008) for 5 and 7 years old coppices showed that *A. mearnsii* resulted in 8 % higher base cations export per hectare (supplementary materials: Table S9). However, Zewdie's (2008) study was based on above-ground biomass only. Considering that eucalypt roots are retained for coppicing while *A. mearnsii* roots are removed as firewood, *A. mearnsii* systems will result in higher overall nutrient export.

Our result showed that *A. mearnsii* cultivation has a higher annual base cation accumulation in biomass than *E. tef*. Soil acidity already presents a significant challenge for crop production in this region (Wondie and Mekuria, 2018). The extensive removal of base cations by *A. mearnsii* cultivation will further acidify the soil increasing the risk of lower availability of essential nutrients such as P through chemical fixation (Olsson et al., 1996).

4.2. Soil

4.2.1. Nitrogen

The significantly lower δ^{15}N values in *A. mearnsii* biomass and plantation soils, compared to the reference plant and cropland soils respectively, show that *A. mearnsii* fixes atmospheric N_2 in substantial amounts instead of relying on N mineralization (Boddey et al., 2000). The elevated Mo concentration in root biomass further strengthens the evidence for the N_2 fixation activity of *A. mearnsii*. Molybdenum plays a crucial role in the symbiotic N_2 fixation process as a component of the nitrogenase enzyme, which converts atmospheric N_2 into a form usable by plants (Barron et al., 2009; Reed et al., 2013).

Young stands are more reliant on atmospheric N_2 fixation, as reflected by their lower δ^{15}N values. This is due to the high N demand of young growing trees with small root systems to support their rapid growth (Stuiver et al., 2015), which cannot be met by the available soil N. As *A. mearnsii* matures and develops a more extensive root system, it begins to supplement its N acquisition from soil sources. This shift in N uptake can explain the increasing δ^{15}N values observed in leaves as the stand age increased. The result corroborates the observations made by Isaac et al. (2011) in a study of *A. senegal* (L.) Willd. (now referred to as *Senegalia senegal* (L.) Britton) in the Rift Valley region of Kenya. They showed a similar shift in N uptake from predominantly atmospheric fixation in young samplings (9 months old) to increased reliance on soil sources in mature trees (7 years old). Jacobs et al. (2007) also demonstrated a similar age-related shift in N acquisition in *Philenoptera violacea* (Klotzsch) Schrire in South Africa.

Among the components of *A. mearnsii*, the stem had the highest percentage of N derived from atmospheric fixation. This is consistent with the observed trend for woody plant parts in legumes exhibiting lower δ^{15}N values than corresponding leaf material. However, the underlying mechanisms responsible for this variation remain poorly understood (Shearer and Kohl, 1986; Unkovich et al., 2000).

The amount of N_2 fixed observed in this study (175 kg N ha^{-1} y^{-1}) is of the same magnitude as an early nutrient balance study by Orchard and Darb (1956), reported by Dreyfus et al. (1987), which showed that *A. mearnsii* cultivation in tropical regions can fix up to 200 kg N ha^{-1} y^{-1}. However, despite the substantial N_2 fixation in the biomass, isotopic analysis showed that the fixed N did not affect the ^{15}N abundance in the soil organic matter until the second rotation of the plantation. This delay is likely attributable to the time required for litterfall accumulation and decomposition. In the first rotation, insufficient time may have elapsed for the decomposition of litterfall to significantly alter the proportion of fixed N in the TN soil pool. In the second and third rotations, a significant depletion of δ^{15}N was observed in the 0–15 cm soil layer compared to cropland suggesting the presence of N derived from N_2 fixation by *A. mearnsii* in this layer. Similar to the first rotation, the result from FAM fields showed no statistically significant difference in δ^{15}N values compared to cropland. This is likely since most of the FAM fields had only undergone one rotation of *A. mearnsii* before being returned to crop cultivation. This indicates that the ^{14}N-enriched OM previously fixed by *A. meanrsii* had mineralized, and the resulting N is either taken up by subsequent crops or leached from the soil. Alternatively, a single rotation might not produce sufficient litter to significantly alter the ^{15}N signature of the soil, thus supporting the result from the first rotation. However, despite isotopic signature showing significant depletion in the second and third rotations, TN decreased with successive rotations, and the absolute quantity of N derived from N_2 fixation in the third rotation was lower than in the second rotation. The lower proportion of atmospherically fixed N in older stands is evidence that the tree is utilizing mineralized soil N as a complement to N fixed from the atmosphere. This shift may be driven by the need for mineralization of other essential nutrients such as P and S from the SOM (Jiang et al., 2021; Wang et al., 2023). Consequently, TN in the soil did not show any accumulation with the increased rotation despite the N fixation by *A. mearnsii*. A contributing factor to this is the harvest intensity, where most of the biomass is removed for charcoal production and firewood (Nigussie et al., 2020). The N budget estimation supports this, revealing higher net N mineralization under WBH harvest scenarios. Another explanation is that the rate of soil OM mineralization under *A. mearnsii* cultivation exceeds the rate of accumulation. The input of N and C to the soil has been shown to increase OM mineralization through a process known as the priming effect (Kuzyakov et al., 2000). A study by Fontaine et al. (2007) demonstrated that the addition of fresh organic C can stimulate the loss of older OM, with the fresh C providing the energy required for microbial decomposition of the recalcitrant OM. Plant roots also contribute to OM mineralization by releasing exudates to mobilize growth limiting nutrients (Jones et al., 2009; Wu et al., 2018). The absence of TN accumulation in soil, despite considerable N fixation in biomass suggests that a priming effect maybe stimulating the decomposition of soil OM, potentially offsetting the expected N accumulation.

Despite the uncertainties inherent in these estimates, the budget indicates a net N mineralization for both *E. teff* and *A. mearnsii* cultivation. Although internal recycling from litterfall provides input from previously fixed N, it is insufficient to sustain production over a full rotation. The estimated 54–84 kg N ha^{-1} y^{-1} attributable to *A. mearnsii* in the soil is likely due to litter decomposition and mineralization. The estimated N in litterfall, excluding root litter, 33 kg N ha^{-1} y^{-1}, closely corresponds with the lower end of this range. In a similar study using δ^{15}N as a tracer, Forrester et al. (2007) reported a comparable quantity of annual N addition to the soil (50 kg N ha^{-1} y^{-1}).

Previous studies from the area have reported improved soil fertility following *A. mearnsii* cultivation, with reported sustained *E. tef* productivity for one to two cultivation cycles post *A. mearnsii* harvest (Nigussie et al., 2017; Chanie and Abewa, 2021). In addition, informal interviews with farmers and local experts indicated that farmers typically applied half the standard dose of the combined NP fertilizer (di-ammonium phosphate, DAP) but no dedicated N fertilizer like urea when planting crops after *A. mearnsii* harvest. This improvement in crop yield following harvest is likely due to an increased N availability resulting from the preceding *A. mearnsii* plantation. However, the observed absence of fixed N accumulation in this study suggests that this N source is short lived.

4.2.2. Phosphorus

A. mearnsii cultivation depleted soil P under both harvest scenarios while *E. tef* budget remained balanced due to fertilization. The depletion was higher under WBH compared to LRS. The soil in the area is poor in P, with an average available P concentration of 3.75 mg kg^{-1} in the 0–30 cm soil depth (supplementary materials: Table S1). This is lower than the average available soil P in the highlands of northwest Ethiopia (6.9 mg kg^{-1}) (Melese et al., 2015).

Weathering and OM mineralization are the primary input expected to offset P depletion due to biomass export in *A. mearnsii* plantations. A weathering and organic P mineralization rate of 13.0 kg ha^{-1} y^{-1} is required to replenish the P removed through biomass export (Table 7). However, the soil in the area is highly weathered and unlikely to supply the amount. The average P release from chemical weathering in tropical region is 0.5 kg P ha^{-1} y^{-1} (Hartmann et al., 2014) to 0.8 kg P ha^{-1} y^{-1}(Wilcke et al., 2019), suggesting that weathering alone is unlikely to replenish the P exported in biomass. Additionally, an annual depletion of 0.3 kg P ha^{-1} in available P stock observed between cropland to the third rotation (supplementary material: Table S8) but this amount cannot offset the estimated excess export. Therefore, the change in the available P stock cannot explain the observed deficit in the budget but it indicates an imbalance in the P supply.

Organic P represents a large proportion of total soil P in the tropics, ranging from 26 % (Turner and Engelbrecht, 2011) to 44 % (Reed et al., 2011). As a result, organic P cycling through OM mineralization is important for P supply in these regions (Reed et al., 2011). The mole to mole OC:OP ratio of mineral top soils of cropland in the tropics is reported to be 624 (Spohn, 2020), which is equivalent to a C:P mass ratio of 242:1. The average C stock change of land under *A. mearnsii* cultivation in the 0–30 cm from end of first rotation to end of third rotation is −37.7 Mg ha^{-1} (supplementary materials: Table S10), equating to an average annual change of −3.43 Mg C ha^{-1} y^{-1}, assuming an average of 11 years for two rotations. This annual OM mineralization rate is consistent with the annual soil organic carbon (SOC) depletion due to agricultural intensification previously reported by Van Beek et al. (2018) in highlands of Ethiopia. Based on the OC: OP mass ratio, this annual C stock change would potentially correspond to the mineralization of 14 kg P ha^{-1} y^{-1} from organic P. This potential organic P mineralization rate roughly corresponds with the P depletion rate calculated in the budget estimation. Without organically sourced P, the available stock is estimated to be sufficient for only one year of the total growing period of a rotation. Under nutrient-limited conditions, plants invest energy in microbial symbiosis, such as mycorrhizal associations, as a strategy to acquire essential nutrients (Zhang et al., 2018). The estimated rate of organic P mineralization could potentially offset the loss through biomass export. However, this process leads to a gradual loss of SOC, which is unsustainable in the long-term.

4.2.3. Potassium

The cultivation of both *E. tef* and *A. mearnsii* results in depletion of K from the soil due to the excess K export compared to known inputs. This will potentially lead to long-term depletion of soil K stock, potentially affecting future productivity. *E. tef* cultivation exports less K compared to the *A. mearnsii* harvest scenarios. While charcoal production from *A. mearnsii* generates ash containing K, this only accounts for 2 % of the annual K uptake during tree growth. To offset the excess K exported by the removal of *A. mearnsii* biomass and *E. tef* crop, an annual replenishment of 40–75 kg K ha^{-1} y^{-1} would be required under both cultivation systems.

The primary source of K in soil is K bearing minerals, with organic K mineralization providing only a small portion of the required amount (Covert, 1999; Sparks, 2001). The estimated K recycled through litterfall corresponds to 3 kg K ha^{-1} y^{-1}. This amount cannot offset the K exported through biomass harvest. Therefore, the weathering of K bearing minerals is the primary mechanism for replenishing the excess exported K under both cultivation systems.

Studies show that the theoretical K weathering rate in soil ranges between 3 and 82 kg ha^{-1} y^{-1} (Holmqvist et al., 2003; Rangel, 2008). The soils in the region are weathered and characterized by the prevalence of secondary minerals (Regassa et al., 2014; Le Blond et al., 2015). This may suggest that K weathering is lower than the suggested maximum, and therefore, unable to replenish the excess K exported in both production systems. However, paradoxically the available K stock in the studied soils is high (supplementary materials: Table S8), and it is therefore unlikely that K will be a production-limiting factor in the short term.

4.2.4. Sulfur

The cultivation of *A. mearnsii* results in S depletion in soil, while *E. tef* cultivation maintains a balanced or net immobilization of S due to optimal fertilization. The depletion is higher under WBH while LRS can reduce the depletion by 30 % (3 Kg S ha^{-1} y^{-1}). The annual depletion in the available S stock for the change from cropland to the third rotation corresponds to 0.7 kg S ha^{-1} y^{-1} (supplementary material: Table S8). This amount is not large enough to compensate for the excess output in the budget. In addition, the available stock is estimated to be sufficient for only 2–3 years of the total growing period of a rotation. Therefore, in the *A. mearnsii* stands, this S deficit must have been compensated through OM mineralization. However, the decrease in the amount of available S is an indicator on that the system for S supply is not in balance.

Over 95 % of soil S exists in organic forms, primarily as ester sulfates and C bonded S (Edwards, 1998). Ester sulfates are generally less resistant to degradation with their mineralization rate controlled by S supply (Blum et al., 2013). In contrast, the C bound S is more resistant and found within the recalcitrant pool of OM (Kertesz and Mirleau, 2004; Wilhelm Scherer, 2009). During periods of S deficiency, the less resistant ester S mineralize to sulfate, making it available for plant uptake (Wilhelm Scherer, 2009). Solomon et al. (2001) found that C-bonded S was the dominant organic S fraction in Ethiopian highland soils, comprising 77–84 % of the total organic S pool. This suggests that only c. 20 % of the organic S is readily decomposable. The average C:S ratios in these soils were 74 in cropland and 79 in plantation. While a C mineralization rate of 3.43 Mg C ha^{-1} y^{-1} could potentially release 43.2 kg S ha^{-1} y^{-1}, only c. 20 % (8.64 kg S ha^{-1} y^{-1}) is readily available S due to the predominance of recalcitrant C bonded S (Solomon et al., 2001). This estimated mineralization rate roughly corresponds with the annual S depletion rate in *A. mearnsii* cultivation. However, as with P, the uncertainties around the estimate preclude a definitive conclusion on how long the organic S can sustain the plantation before S becomes a limiting nutrient for growth.

4.2.5. Calcium and magnesium

The cultivation of both *E. tef* and *A. mearnsii* leads to an excess export of Ca and Mg compared to known inputs, with *A. mearnsii* cultivation leading to more than a double export compared to *E. tef*. The primary source of Ca and Mg in soil is the weathering of soil minerals. In the highly weathered Acrisols of the study area, weathering rates are likely low (Hurni, 1988; Regassa *et al.*, 2023). This is corroborated by studies by Le Blond et al. (2015) in Gojam province of Ethiopia, close to our study area, and Regassa et al. (2014) in the Gilgel Gibe catchment. These studies showed that soils in these regions are highly weathered and are predominantly characterized by prevalence of iron oxides and kaolinite minerals, suggesting a limited potential for additional weathering and subsequent nutrient release. When weathering is insufficient, nutrient replenishment relies on OM and litter mineralization. However, given the large quantity of Ca and Mg lost through harvest, the internal nutrient recycling in *A. mearnsii* cultivation is unlikely to offset the excess export of Ca and Mg.

Calcium and Mg stocks in *A. mearnsii* soils were lower than in cropland soils, with FAM soils exhibiting even lower stock than both *A. mearnsii* and cropland soil. This indicates a lingering effect of past *A. mearnsii* harvest in FAM and suggests potential long-term nutrient depletion of base cations with repeated harvest cycle of the plantations. However, the current plant available Ca and Mg stock in soil remains large and can support production for 13 rotation cycles at the current harvest intensity. Therefore, it is unlikely that these nutrients will become production limiting nutrients in the short term. However, the export of Ca and Mg in harvested biomass not only affects tree growth but also has implications for soil acidification (Court et al., 2018). The depletion of base cations, combined with N-fixation by *A. mearnsii*, can potentially contribute to increased soil acidification (Olsson et al., 1996).

4.2.6. Trend in soil nutrient stock

Consistent with the nutrient budget estimates, the nutrient stock analysis showed a trend of progressive nutrient depletion with successive *A. mearnsii* rotations. Although TN indicated an increase during the first rotation—likely due to the absence of harvest—subsequent rotations showed a decline, suggesting that *A. mearnsii* depends on both N_2-fixation and soil N mineralization for its growth. Phosphorus and S decreased with successive rotations likely due to the absence of fertilization in *A. mearnsii* fields, unlike annual crops, and reduced organic input due to WBH. As P and S are mainly organically recycled nutrients (Condron et al., 2005; Wilhelm Scherer, 2009), successive biomass harvest results in P and S depletion of the soil. Despite the lack of a clear statistically significant difference with successive rotations for K, the observed decreasing trend indicates a limited potential for K replenishment through weathering to offset losses from successive biomass removal. Calcium and Mg stock did not show a clear directional trend across the rotations. However, their removal through biomass harvest was large. This, coupled with the observed decline in K and the limited potential of the soil for base cation replenishment through weathering, suggests a potential increase in soil acidity over successive rotations.

5. Methodological uncertainties

The nutrient budget calculation contains inherent uncertainties due to the variability of input and output data, as well as a number of assumptions made due to low data availability. We compiled input and output data for *E. tef* from various studies with differing methods of analysis. Additionally, we used general empirical formulas to estimate inputs and outputs where measured data were unavailable. In some cases, the available measured data were from studies conducted in locations distant from our study area. Moreover, we used space for time substitution in this study and we acknowledge that spatial gradients may not fully represent long-term temporal complexities. A potential limitation is the effect of historical land use decisions, whereby farmers may have progressively expanded *A. mearnsii* cultivation to more productive areas. As a result, the results observed for the successive rotation may also be influenced by historical land use decisions and not only by the direct effects of *A. mearnsii*. Furthermore, while WBH is the dominant harvest practice, our biomass removal estimates may be overstated because harvest residues and charcoal production byproducts could return to the soil during the different operations. These unaccounted for residues may contribute to the soil nutrient pool, which is not included in this analysis. Beside this, our N_2 fixation estimate may be underestimated due to the conservative $\delta^{15}N$ B value we used in the %Ndfa calculation. Previous studies have used $\delta^{15}N$ B values of −1.3 (Forrester et al., 2007) and −1.56 (Tye and Drake, 2012) for *A. mearnsii* in Australia and South Africa, respectively. In the absence of a local B value, we used a value of −1.76 based on the recommendation provided by Unkovich et al. (2008).

6. Conclusions

Comparative nutrient budget analysis indicated that both *A. mearnsii* and *E. tef* production leads to N depletion in the soil. Both the budget calculations and the $\delta^{15}N$ values in the soil indicated a net mineralization of N from soil organic matter over successive *A. mearnsii* rotations for both the WBH and LRS scenarios.

The *A. mearnsii* production leads to a depletion of P and S in the soil. The result indicates that the *A. mearnsii* plantations relies on SOM mineralization to mobilize P and S, suggesting the need for external nutrient input to sustain productivity over multiple rotations. Phosphorus and S remains balanced in *E. tef* production due to addition of fertilizer.

Both harvest intensity scenarios for *A. mearnsii* cultivation results in higher export of base cations compared to the *E. tef* production. However, this is unlikely to present a problem in the short term due to the considerable stock of base cations in the soil.

Result from this study underscore the need for improving management practices to promote on-site nutrient recycling. In the absence of improved nutrient management practices, both *E. tef* and *A. mearnsii* production systems are likely to lose productivity with time. Potential mitigation measures include adopting less intensive harvesting practices, such as retaining leaves and litter on the field as far as possible. In addition, the bark contains large amount of base cations. Therefore, further research should investigate methods for separating the bark from the wood prior to charcoal production, thus allowing the bark to remain in the field as a soil amendment. Additionally, retaining and uniformly distributing ash from charcoal production prior to subsequent agricultural activities could potentially mitigate nutrient loss. Furthermore, P and S fertilization can help mitigate future production limitations, while also increasing plant growth and biomass production, potentially enhancing C storage in soil OM over time.

CRediT authorship contribution statement

Karltun Erik: Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yimer Fantaw:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Tiruneh Getachew Gemtesa:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Barron Jennie:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Alemu Asmamaw:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.122762.

Data availability

Data will be made available on request.

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Table S1

Concentration of major nutrients in the land uses studied (Mean ± CI).

		TN	p	K	S	Ca	Mg
Land use	**Depth**				**mg kg^{-1}**		
CL	0-15	2160 ± 1060	4.07 ± 2.76	288 ± 195	9.42 ± 4.58	1660 ± 1140	386 ± 322
	15-30	2020 ± 1110	2.78 ± 2.19	214 ± 198	9.47 ± 5.54	1590 ± 1000	343 ± 257
FAM	0-15	3110 ± 960	5.78 ± 3.84	331 ± 234	10.1 ± 5.09	1400 ± 740	255 ± 142
	15-30	2690 ± 1150	4.28 ± 3.11	270 ± 192	8.00 ± 4.86	1240 ± 680	253 ± 141
First rotation	0-15	2930 ± 1110	3.22 ± 1.61	239 ± 91.0	7.22 ± 2.39	1690 ± 460	344 ± 103
	15-30	2530 ± 1030	3.47 ± 2.30	184 ± 80.5	6.59 ± 1.86	1650 ± 530	358 ± 133
Second rotation	0-15	2150 ± 500	2.94 ± 1.72	182 ± 57.5	7.39 ± 1.70	1400 ± 220	296 ± 52.5
	15-30	1670 ± 530	2.99 ± 2.27	118 ± 41.1	5.92 ± 1.57	1310 ± 290	287 ± 64.8
Third rotation	0-15	2150 ± 340	2.22 ± 0.52	163 ± 52.8	6.96 ± 1.79	1350 ± 240	255 ± 51.3
	15-30	1410 ± 350	2.09 ± 0.68	123 ± 46.3	6.02 ± 1.19	1350 ± 230	267 ± 42.1

Abbreviations: First, second and third rotation = Fields under *Acacia mearnsii* plantation in the first, second, and third rotation cycles with stand age 5 & 6 years, CL= cropland and FAM= former *A. mearnsii* field later converted back to cropland

Table S2

Concentration of major nutrients in *E. tef* grain compiled from different studies.

	HI	N	P	K	S	Ca	Mg	Na	Reference
Grain						g kg^{-1}			
	0.24	16.2							(Balcha *et al.*, 2006)
		13.9	3.3	4.3					(Tulema *et al.*, 2007)
		15.4	3.9	4					(Tulema *et al.*, 2007)
			4.38	3.95	1.51	1.36	1.98	0.021	(Haileselassie *et al.*, 2019)
			4.4	4.89	1.68	1.45	2.07	0.044	(Haileselassie *et al.*, 2019)
			4.34	4.29	1.71	1.55	2.02	0.036	(Haileselassie *et al.*, 2019)
				3.67		1.21	1.4	0.033	(Nyachoti *et al.*, 2021)
			4.4	3.6		1.8			(Ketema, 1997)
			4.6	2		1.7	1.9		(Ketema, 1997)
		14.8	3.35	4.2			1.95		(Misskire *et al.*, 2019)
		15.7	3.56	4.23			1.93		(Misskire *et al.*, 2019)
		17.4	3.66	4.8			2.16		(Misskire *et al.*, 2019)
		17.1	3.55	4.46			1.88		(Misskire *et al.*, 2019)
	0.27								(Abeje, 2019)
			4.29	4.27		1.8	1.84	0.12	(USDA, 2019)
			4.21						(da Silva Goersch *et al.*, 2019)
		14.2	6.7						(Tsegaye *et al.*, 2021)
Mean ± CI	**0.26**	**15.6 ± 1.1**	**4.19 ± 0.5**	**4.05 ± 0.4**	**1.63 ± 0.3**	**1.55 ± 0.2**	**1.91 ± 0.2**	**0.05 ± 0.1**	

Note: The data presented above are compiled from studies cited in the reference column. The observations are from researches conducted under controlled environments in research fields and, therefore, may not reflect conditions in typical farmer field. Abbreviation: HI: Harvest index.

Table S3

Concentration major nutrients in *E. tef* straw compiled from different studies.

	N	P	K	S	Ca	Mg	Na	Reference
				g kg^{-1}				
		0.96	8.91	0.96	2.23	0.76	0.049	(Haileselassie *et al.*, 2019)
		1.22	9.73	1.6	2.96	1.68	0.211	(Haileselassie *et al.*, 2019)
		1.29	10.1	1.7	3.66	2.2	0.092	(Haileselassie *et al.*, 2019)
		1.6	11.7	1.6	4.3	1.9		
	4.74	0.88	10.1			2.15		(Misskire *et al.*, 2019)
	5.25	1.1	10.6			2.23		(Misskire *et al.*, 2019)
	6.15	1.2	11.8			2.18		(Misskire *et al.*, 2019)
	6.36	1.05	11			2.03		(Misskire *et al.*, 2019)
Mean ± CI	**5.63 ± 1.2**	**1.16 ± 0.2**	**10.49 ± 0.8**	**1.47 ± 0.5**	**3.29 ± 1.4**	**1.89 ± 0.4**	**0.12 ± 0.2**	

Note: The values presented above are compiled from studies cited in the reference column.

Table S4

Grain and straw yield of *E. tef* in the study area.

		Reference
Average yield of *E. tef* (kg ha^{-1})	980	Nigussie *et al.* (2020)
Average HI (grain: total biomass weight)	0.26	Balcha *et al.* (2006), Abeje (2019), and Bayable *et al.* (2021)

Note: Nutrient stocks in *E. tef* grain (Table 2) were calculated by multiplying average *E.tef* grain yield per hectare by the corresponding nutrient concentrations (Table S2). Straw biomass was calculated from the harvest index and grain yield per hectare presented above. Nutrient stock in *E. tef* straw were then calculated by multiplying the estimated straw biomass by the corresponding straw nutrient concentrations (Table S3).

Table S5

The nutrient concentrations of natural pasture grasses in the Ethiopian highlands as presented by Kabaija and Little (2013).

	CP	**N**	**P**	**K**	**S**	**Ca**	**Mg**
Grass name				**g kg^{-1}**			
Cenchrus ciliaris	75.0	12.0	1.50	23.5	2.10	2.00	1.60
Themeda triandra	50.0	8.00	1.20	12.0	1.00	4.10	1.50
Chrysopogon aucheri	60.0	9.60	1.00	1.00	1.10	2.20	1.60
Pennisetum Mezianum	63.0	10.1	1.40	12.0	1.10	3.20	2.00
Mean	62.0	9.92	1.28	12.1	1.33	2.88	1.68

Table S6

Average annual nutrient removal by natural pasture grasses harvest in the second year of *A. mearnsii* plantation.

Dry matter yield kg ha^{-1}	N	P	K	S	Ca	Mg
	kg ha^{-1} y^{-1}					
1000	1.80	0.23	2.20	0.24	0.52	0.30

Note: With one harvest per rotation, the average annual nutrient export is calculated by dividing the total nutrient stock removed in grass harvest by the average stand age of *A. mearnsii*.

Table S7

Concentration of nutrients in the different biomass tissues of *A. mearnsii* (Mean ± CI, n=12)

Nutrients	Stem	Bark	Root	Branch	Foilage
	g kg^{-1}				
N	2.15 ± 0.25	12.2 ± 1.06	5.02 ± 1.19	8.74 ± 0.94	28.7 ± 1.04
P	0.16 ± 0.04	0.41 ± 0.06	0.33 ± 0.2	0.55 ± 0.19	1.26 ± 0.08
K	1.56 ± 0.29	3.68 ± 0.91	1.68 ± 0.25	4.85 ± 1.4	7.75 ± 1.11
S	0.12 ± 0.02	0.41 ± 0.05	0.53 ± 0.19	0.48 ± 0.07	1.52 ± 0.09
Ca	1.05 ± 0.15	8.06 ± 1.08	2.31 ± 0.46	3.97 ± 0.6	8.88 ± 0.73
Mg	0.26 ± 0.02	1.28 ± 0.23	0.38 ± 0.06	0.94 ± 0.16	2.05 ± 0.2
Mo (mg kg^{-1})	-	-	0.13 ± 0.12	-	0.05 ± 0.03

Note: the root biomass analyzed in this study are size > 5 cm in diameter.

Table S8

Total N and Mehlich 3 extractable soils nutrient stock in cropland and land under *A. mearnsii* cultivation (mean ± CI).

Land use	Number of samples	Depth of sampling	TN	P	K	S	Ca	Mg
						kg ha^{-1}		
First rotation	12	0-15	4850 ± 1320	5.55 ± 2.78	434 ± 164	12.3 ± 2.79	3020 ± 756	620 ± 178
	12	15-30	5540 ± 3010	7.16 ± 4.76	361 ± 165	13.7 ± 5.42	3290 ± 1253	700 ± 278
Second rotation	13	0-15	3620 ± 710	4.89 ± 2.86	317 ± 98.0	12.7 ± 2.84	2470 ± 513	520 ± 119
	13	15-30	3490 ± 1360	6.31 ± 4.89	234 ± 89.0	11.8 ± 3.39	2530 ± 467	560 ± 107
Third rotation	12	0-15	3750 ± 670	3.93 ± 1.06	288 ± 95.0	12.0 ± 2.91	2420 ± 567	455 ± 115
	12	15-30	2820 ± 730	4.07 ± 1.21	237 ± 81.0	11.7 ± 2.03	2620 ± 440	515 ± 64.0
CL	5	0-15	3740 ± 1380	6.84 ± 3.40	491 ± 241	16.3 ± 5.98	3060 ± 2397	715 ± 669
	5	15-30	4100 ± 2920	5.77 ± 5.70	437 ± 498	18.7 ± 12.9	2970 ± 1594	640 ± 424
FAM	7	0-15	5410 ± 1090	11.3 ± 9.46	610 ± 430	17.4 ± 6.90	2580 ± 1323	470 ± 258
	7	15-30	5650 ± 2980	7.67 ± 4.48	519 ± 383	16.9 ± 12.7	2400 ± 1440	490 ± 297

Abbreviations: AM = *A. mearnsii* and the number in front of AM indicates rotation cycle, CL= cropland, FAM= former *A. mearnsii* cultivated land, but now under crop cultivation.

Table S9

Base cation stock in *Eucalyptus globolus* coppice age of five and seven years as presented by Zewdie (2008).

Coppice age	K	Ca kg ha^{-1}	Mg
5	181	325	27.3
5	235	434	72.4
7	322	751	98.8
7	280	507	38.8
Mean	255	504	59.3

Table S10

Carbon stock in the 0-30 cm of *A. mearnsii* plantations at stand ages 5 and 6 years, presented by rotation cycle, and the rate of carbon stock change from the first to third plantation rotation.

***A. mearnsii* rotation**	**Carbon stock Mg ha^{-1}**	**Change in stock**	**Annual stock change Mg ha^{-1} y^{-1}**
First	123 ± 48.1		
Second	94.2 ± 30.9		
Third	85.3 ± 20.6		
First - third		**- 37.7**	**- 3.43**

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A competitive agroforestry system offers a sustainable energy solution for developing countries dependent on biomass. High market demand for charcoal has led to land use change from crop to short rotation forestry (SRF) in the northwestern highlands of Ethiopia. This thesis investigated the environmental sustainability of the SRF as compared to the crop it replaced. The SRF increased carbon sequestration in the landscape and reduced pressure on natural forests. However, long-term sustainability over multiple rotations requires management intervention.

Getachew Gemtesa Tiruneh received his PhD education at the Department of Soil and Environment, Swedish University of Agricultural Sciences, Uppsala. He holds a Master of Science in Environmental Pollution and Risk Assessment with a major in Soil Sciences from the same university.

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