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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

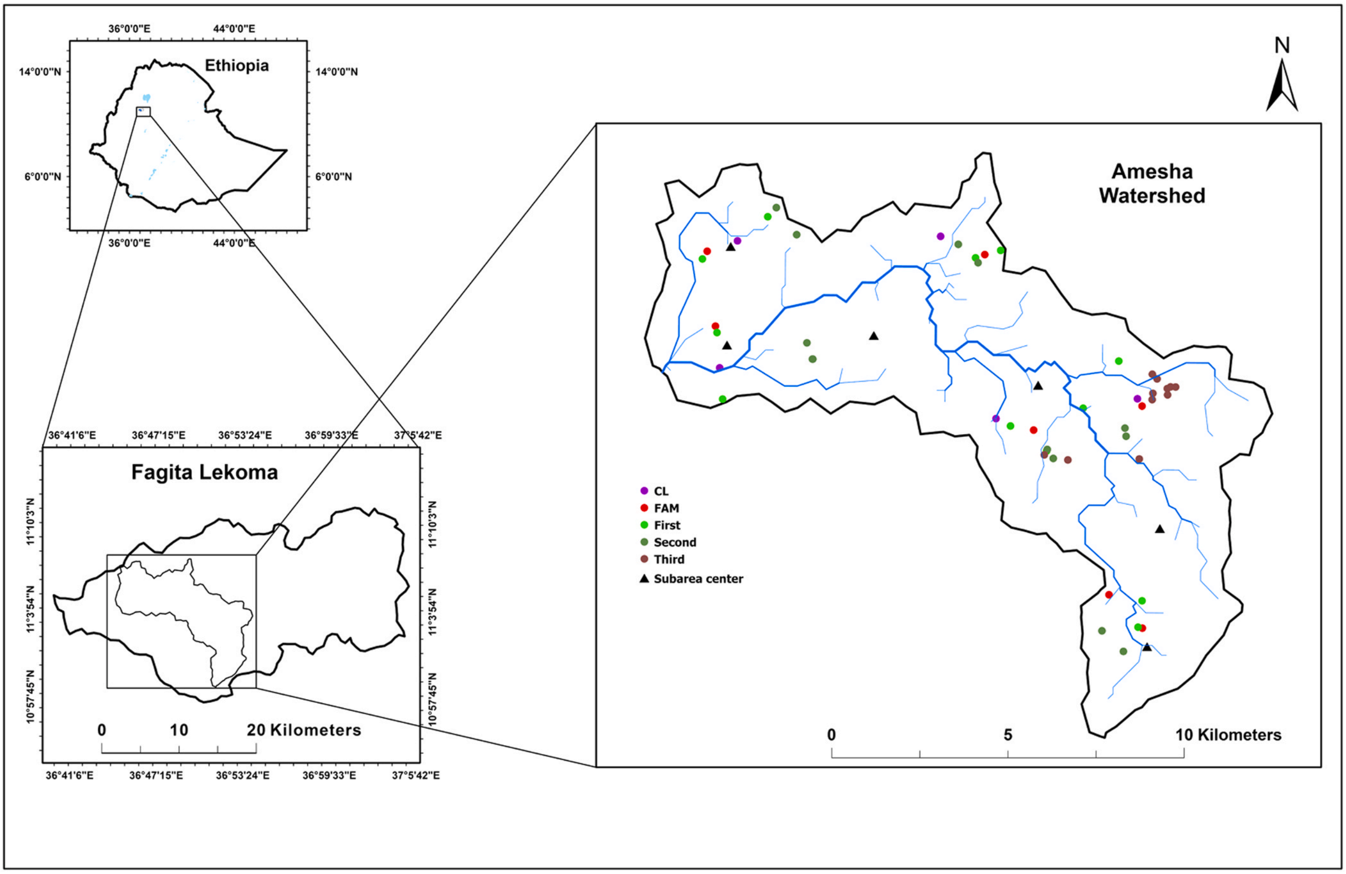

Fig. 1. Map of sampling watershed with drainage networks and soil sampling fields. Abbreviations: CL = cropland; FAM = former *A. mearnsii* field converted back to cropland; first, second, and third = first, second, and third rotation A. mearnsii plantations.

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 $\delta^{15}N$ signature similar to the $\delta^{15}N$ 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 ($\delta^{15}N$) 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 $\delta^{15}N$ 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 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.

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 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).

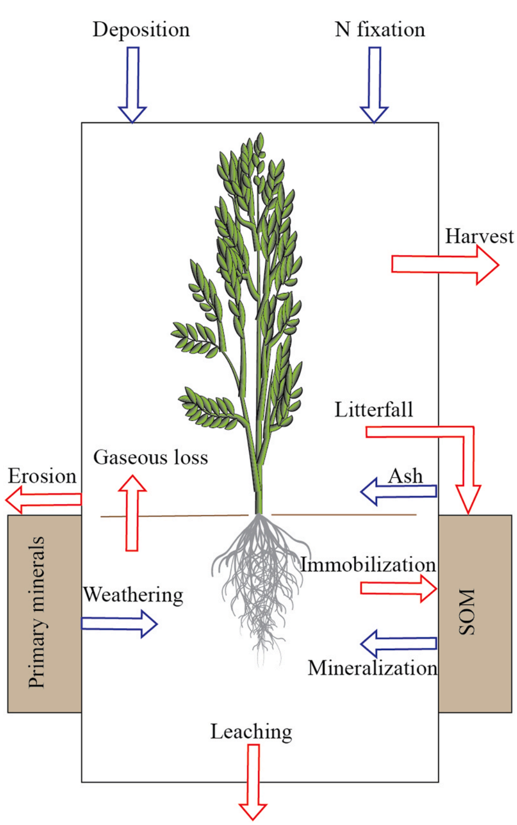

Fig. 2. Schematic diagram of the system boundary with the main inputs (blue arrows) and outputs (red arrows).

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	Annual TN fixed	Note
					Kg ha^{-1}	kg^{-1} ha^{-1} y^{-1}	
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.

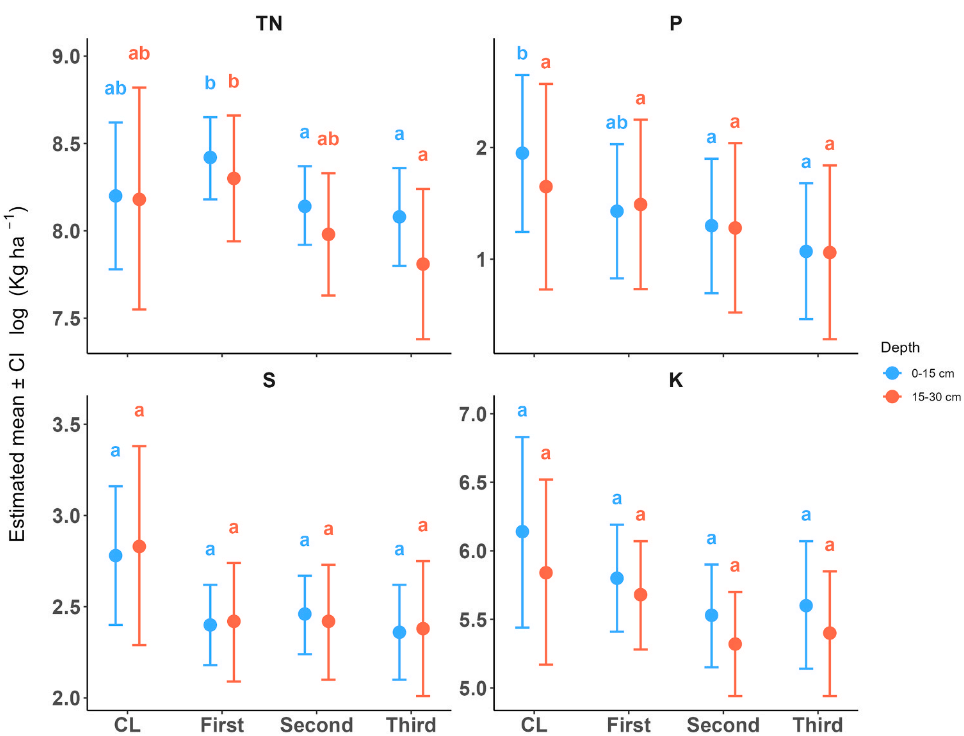

Fig. 3. Total N and Mehlich-3 extractable stock of P, S and K (mean ± CI, α=0.05) in soil under cropland (CL) and *A. mearnsii* plantations across the three rotation cycles. Note: Mean values sharing the same letter indicate no significant difference. The analyses were performed separately for each depth 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 $\delta^{15}N$ 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 $\delta^{15}N$ 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 $\delta^{15}N$ 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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