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Research Article

Impact of land-use change on soil microbial communities, organic carbon, and total nitrogen contents in Barkachha, Mirzapur District, India

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Abstract

Land-use change is a major driver of ecosystem degradation, particularly in the dry tropics, where forests are increasingly being converted into agricultural lands. This transformation not only reduces biodiversity and alters ecosystem functions but also significantly impacts soil health. This study assessed the effects of different land-use types, namely, natural forest, degraded forest, bamboo plantation, and agricultural land, on soil microbial community composition and biomass, and soil carbon and nitrogen contents in the dry area of Barkachha, Mirzapur District. A total of 24 composite soil samples were collected from all land use types. Soil organic carbon, total soil nitrogen, microbial biomass, and microbial community composition were determined by the oxidation and titration method, the micro-Kjeldahl method, the fumigation and extraction method, and FAME GC-MS, respectively. The results of the study showed a significant decline in the microbial community in agricultural and degraded lands compared to natural forest ($p<0.001$). In agricultural and degraded lands, the microbial community and biomass decreased by 28.8% and 22%, and 54.5% and 50%, respectively. Similarly, soil organic carbon and total nitrogen contents were markedly lower in converted land uses. Among all land use patterns, the highest organic carbon (0.84±0.054%), total nitrogen (0.123±0.013%), microbial biomass carbon (570.65±35.05μg/g), microbial biomass nitrogen (84.21±3.186μg/g), basal respiration (3.64±0.064μg/g), b-glucosidase (809.68±39.7μgμg PNP g^{-1} dry soil h-1) and microbial community composition were found under natural forest, followed by bamboo plantation, degraded forest, and agricultural land, in decreasing order. Among microbial groups, Gram-negative (G) bacteria and fungi showed similar decreasing trends across the land-use gradient, from natural forest to agricultural land. Conversely, Gram-positive (G^+) bacteria showed an increasing trend along the same gradient. The higher microbial and soil chemical properties in the bamboo plantation led to faster ecosystem recovery compared to either agricultural land or degraded lands. Therefore, bamboo plantation could be used for ecosystem recovery and sustaining soil health in response to disturbance, particularly in relation to land-use change in the dry tropics.

KEYWORDS: Soil microbial indicators; Ecosystem restoration; Soil nutrient; Bamboo Plantation; Degraded forest

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1 Introduction

Land-use change and unsustainable resource use have led to an annual global forest cover loss of approximately 0.6% (Hansen et al., 2010). Land-use change, particularly the conversion of natural forest to degraded and agricultural lands, leads to biodiversity loss, the alteration of ecosystem services, and the degradation of soil biological and physico-chemical properties (Ashagrie et al., 2007; Solomon et al., 2002; Tripathi & Singh, 2009). Recent studies have revealed that similar transformations significantly impact soil health and quality (Kotowska et al., 2015; Logah et al., 2010; Málaga et al., 2021). For instance, the expansion of agricultural land such as cacao (Emch, 2003), tea (Solomon et al., 2002), banana (Powers, 2004), oil palm and rubber (Kotowska et al., 2015; Málaga et al., 2021), and khat (Dessie & Kinlund, 2008; Mellisse et al., 2018; Wuletaw, 2018), frequently occurs at the expense of native forest and agroforestry systems, thereby reducing soil carbon and nitrogen stocks in Southeast Asia, Latin America, and East Africa (Bashir et al., 2021; Belete & Yadete, 2023). These changes in soil physico-chemical properties are intrinsically linked to a shift in the soil's biological engine: the microbial community (J. Zhang et al., 2020).

Even though tropical forests can sequester over 200 million tons of carbon each year, and are home to a diverse microbial community, land use change remains a major challenge (Keller et al., 2025; Lan et al., 2021). This challenge is particularly severe in the dry tropics, such as Mirzapur District, where ecosystems are characterized by seasonal water scarcity, higher temperatures, and often inherently lower soil fertility (Ashagrie et al., 2007; Tripathi & Singh, 2009) . These conditions make them highly sensitive to disturbances, and the recovery of such systems is often slow and challenging, creating a risk of permanent desertification. Several strategies have been designed to restore degraded lands. Among the several strategies, multipurpose tree plantation is considered an ideal measure for the restoration of degraded lands (Kumar & Ghoshal, 2017; M. K. Singh & Ghoshal, 2014). Bamboo, a fast-growing perennial, presents a promising candidate, offering both economic benefits and potential ecological restoration services. However, while its economic value is recognized, its capacity to restore soil biological integrity and nutrient cycling in degraded dry tropical landscapes remains critically understudied.

Soil microbes are important factors in terrestrial ecosystems. They drive numerous ecosystem services such as nutrient cycling, conservation of soil function (fertility and structure), and to mitigate global climate change, by acting as carbon sources and sinks, and by generating greenhouse gases (Chandra et al., 2016; Kumar & Ghoshal, 2017; D. M. Singh et al., 2018; Q. Zhang et al., 2016). The composition and activity of microbial communities in the soil are governed by foliage cover, nutrient availability, competition, humidity content, land use practices, and other physico-chemical parameters (Bashir et al., 2021; Belete & Yadete, 2023; N. K. Singh & Rai, 2024). Additionally, microbial properties are highly sensitive to environmental disturbances and frequently respond more rapidly than physical or chemical soil indicators, making them effective early warning signals of land use change, sustainability, and the restoration of ecosystems (M. K. Singh & Ghoshal, 2014; N. K. Singh & Rai, 2024). However, the degree and complexity of land-use-induced variations are highly variable and strongly dependent on the ecosystem. Although the impact of land-use changes on soil microbial community structure and function, and carbon-nitrogen dynamics has been widely studied, limited knowledge exists for the dry tropics, especially with reference to the restoration of degraded lands. Additionally, the specific response of soil microbial communities and carbon-nitrogen dynamics in the distinct geo-climatic context of Barkachha, Mirzapur, remains inadequately quantified. Thus, monitoring changes in microbial community structure and function can offer valuable insights for sustainable land management and ecosystem restoration (J. Zhang et al., 2020).

The present study tested the following hypotheses: (i) land use change alters the concentration of microbial community soil and biomass, and carbon-nitrogen dynamics; (ii) shifting of microbial community structure in terms of PLFA occurs with the land-use change, and (iii) restoration of degraded lands can be achieved through plantation of bamboo. The present study was aimed at estimating the impact of various land-use patterns, i.e., natural forest, degraded forest, agricultural land, and bamboo plantation, in a dry tropical environment in the levels of soil microbial community and biomass, and carbon-nitrogen dynamics. We used a PLFA profiling analysis to quantify the microbial community across four land-use types and related these differences to measured edaphic properties in Mirzapur district in India.

2 Methods and Materials

2.1 Description of the study area

The study area, Barkachha, is in the southwest of Mirzapur District, Uttar Pradesh, along the Robertsganj Highway. Soil samples were collected from the Barkachha area located in Mirzapur district during the dry season. Barkachha is located at 25° 10' N latitude and 82° 37' E longitudes at an average elevation of 80 meters (masl) (Figure 1). It is a city in Uttar Pradesh, India, 650 km from both Delhi and Kolkata, 89 km from Allahabad, and 57 km from Varanasi. It has a population of 233,691 (2011 census). The climate in Bakachha in Mirzapur district is warm. In winter, there is much less rainfall than in summer in the district. The average annual temperature and rainfall are 26°C and 975 mm, respectively. The study area was classified into four sites based on their vegetation cover: Natural Forest (NF), Degraded forest (DF), Bamboo plantation (BP), and agricultural land (AL)(Figure 2). The collected soil samples were immediately brought to the laboratory of the Department of Botany, Institute of Science, Banaras Hindu University (BHU) for further analysis.

Mixed Forest

The forest site was the mixed dry deciduous type dominated by *Acacia nilotica, Tectona grandis, Butea monosperma, Madhuca indica, Dalbergia sissoo, Leucaena leaucocephala, Acacia catechu, Al-*

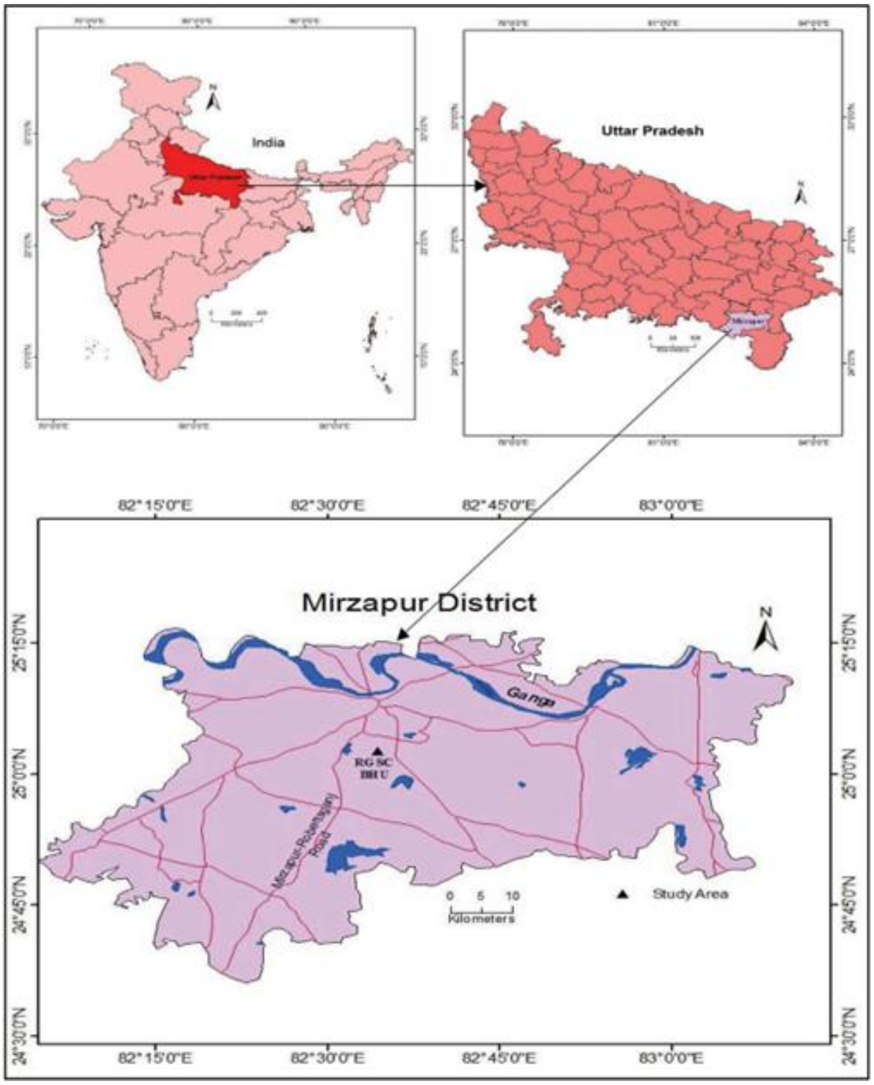

Figure 1: Map showing the location of the Study Area

bizia odoratissima, Boswellia serrata, Nyctanthes arbortristis, with scattered trees of Azadirachta indica Juss and Zizyphus glaberrima Santap. The forest floor was covered with herbaceous vegetation comprising *Ocimum americanum. L., Pisum arvense L., Rhynchosia minima (L.) DC., Cassia sophera(L.) Roxb., Acrocephalus indicus (Burm.f.) Kuntze, Cynodon dactylon (L.) and Oplismenus burmannii Ritz*. The total coverage of the forest area is 500 acres. The forest site is found in Barkachhakalan, Windom Fall Road, 4.8 km, Southwest, Rajiv Gandhi South Campus (RGSC), BHU. The forest site is located at 25° 1' 41.6994" N latitude and 82° 36' 40.842" E longitudes (Figure 2A).

Degraded Forest

The degraded forest site was dominated by Z. glaberrima, Chrysopogon fulvus, Heteropogon contortus, Adina cordifolia Roxb., and scattered trees of Bute amonosperma Lamk. Herbaceous vegetation in the degraded forest was dominated by Cassia tora L., Oldenlandia diffusa Roxb., Sporobolus spp., Panicum psilopodium Trin, and Alysicarpus varginalis (Figure 2B).

Agricultural Land

The farmers of the region depend mostly on rain for irrigation, rain-fed farming being the traditional farming practice of the area. Common crops grown are rice, wheat, lentil, chickpea, etc. Horticultural crops grown include guava, mango, custard apple, bael, karonda, etc. The soil of this region is red laterite and very poor in fertility status (Figure 2C).

Bamboo Plantation

The bamboo plantation consisted mostly of Dendrocalamus strictus, Bambusa nutans, B. tundra, and B. hamiltonii species of bamboo. This site was located in Barkachakhurd. The bamboo plantation site is found in Barkachhakalan, 2.9 km, Northwest, Southwest, RGSC, BHU, geographically located at 25° 4' 28.1244" N latitude and 82° 35' 24.1146" E longitudes (Figure 2D).

Figure 2: The study land uses (A) Natural Forest (NF), (B) Degraded forest (DF), (C) Agricultural land (AL), and (D) Bamboo plantation (BP) (Photo: Ghosha 2016)

2.2 Soil sampling and processing techniques

Soil samples were collected from the Barkachha area located in Mirzapur district during the dry season. The soil sample was taken from four land use types, namely NF, DF, BP, and AL. The NF was further divided into six sub-sites of 100m x 100m (Figure 3). From each subsite, four soil samples were collected from the corner (i.e., 24 composite soil samples in total from each study site) and mixed to represent the single composite sample to determine the soil microbial community, and soil organic carbon and nitrogen. The same procedure was followed by DF, BP, and AL. The soil samples were collected from one depth (0-15cm) using a core sampler. Then the collected soil samples were immediately brought to the laboratory (approx. 250g) in clean, dry, and sterile polythene bags for microbial properties, and organic carbon and nitrogen analyses (Allen et al., 1974, and Waksman, 1952). Separate plastic bags were used for soil samples for microbial and chemical analyses. Soil processing for organic carbon and nitrogen determination was initiated immediately after collection, whereas samples for microbial analysis were stored at 4 °C until the experiment commenced. The collected soil samples were air dried at room temperature, mixed well, grinded by using a mortar and pestle, and made to pass through a 0.5 mm sieve for soil organic carbon and total nitrogen analysis.

Soil Organic Carbon (SOC) and Total Nitrogen (TN)

The SOC content was analyzed by dichromate oxidation and back titration of unused dichromate (Kalembasa and Jenkinson, 1973), whereas TN concentration was measured by the micro Kjeldahl method (Jackson, 1973) by using a Gerhardt digester and distillation unit.

Microbial Biomass

The microbial biomass carbon (MBC) was estimated by the chloroform fumigation extraction method using purified CHCl3 treatment used by Brookes et al. (1985) and Vance et al. (1987). Microbial biomass nitrogen (MBN) concentration was measured by the micro-Kjeldahl method according to Jackson (1973) by using a Gerhardt digester and distillation unit. Microbial biomass determination involved a series of steps, including incubation, fumigation, extraction, and titration. Fresh soil samples (20 g) were incubated at room temperature in a closed container for 7 days. After incubation, two subsamples were prepared for each soil sample: Sample A (without chloroform/non-fumigated) and Sample B (with chloroform/fumigated) to estimate the microbial biomass. The fumigated and non-fumigated soil samples were extracted with 100 mL of K2SO4. Finally, 8ml and 4ml extracts were used for MBC and MBN analyses. Microbial biomass carbon (μg dry soil) and MBN (μg dry soil) are calculated by the following formulas:

$$MBC = \frac{NFu - Fu}{B} \times 3168 \tag{1}$$

$$MBN = (Fu - NFu) \times 207.407 \tag{2}$$

Where; NFu-non fumigated; Fu-fumugated; B-blank

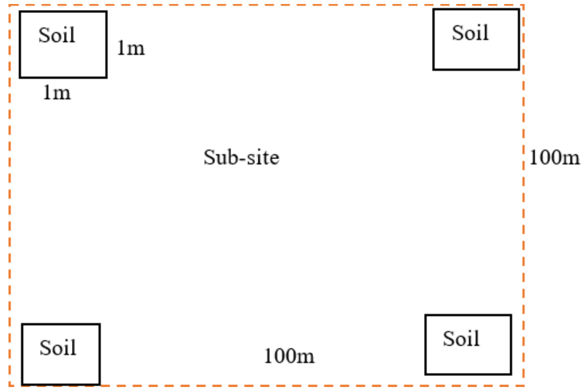

Figure 3: Sample layout for soil chemical and microbial properties

Basal Respiration (BR)

The basal respiration/metabolic activities of the soil microbial community were determined byNamipieri et al. (1990) method.

$$\mu g\ CO_2 \text{ oven dry soil/h at } 22^{\circ}C = \frac{(V_o - V) \times S \times 22 \times 12 \times 1000}{M \times DWt. \times t \times 44} \quad (3)$$

Whereas; Vo- volume of HCl used for titration of blank (mean of three replicates); V-Volume of HCl used for titration of sample (mean of three replicates); S- the strength of the HCl in normality; M- weight of soil g/sample; dwt- the oven dry weight of 1g sample; t- time of incubation in hrs.

Soil Enzyme

The β-Glucosidase activity was assayed by the method of (Eivazi & Tabatabai, 1988), using the substrate analogue para-nitrophenyl-β-d-glucopyranoside (pNPG). The activity of the enzyme is calculated by the following formula:

$$EA = \frac{OD}{CF} \times 100 + \frac{n(n-1)x^2}{2} \quad (4)$$

Soil Microbial Community Analysis

Soil microbial community was analyzed using phospholipid fatty acid assay (PLFAs) (Willers et al., 2015). The PLFAs include extraction, fractionation, methylation, and chromatography. Phospholipid fatty acids were extracted and quantified from 3g (dry weight equivalent) of soils using a procedure described by Bossio et al. (1998). The microbial community composition in terms of PLFA concentration was determined using the modified Bligh and Dyer (1959) and Willers et al. (2015) methods. Identification of peaks was based on the retention time against known standards (Supelco 37 Component FAME Mix 47885-U and Supelco BAME # 47080-U, Sigma-Aldrich, USA), with the peak area representing the abundance (%) of bacterial PLFAs (sum of gram-positive bacterial (G+) and gram-negative bacterial (G-) PLFAs) and fungal PLFAs.

2.3 Statistical Analysis

Soil organic carbon, total nitrogen, microbial biomass, and PLFA data were summarized, and mean values with standard deviations were calculated. Normality was evaluated with the Shapiro-Wilk test and homogeneity of variances with Levene's test. Analysis of variance (ANOVA) was performed to assess the effects of land use change on SOC, TN, SMB, and microbial community. For significant ANOVA results, Tukey's HSD post hoc (α=0.05) test was applied to determine pairwise differences among land use types. The Pearson correlation method was used to analyze the correlation between MBC, MBN, SOC, and TN. All statistical analyses were carried out using SPSS version 23.0. The figures were generated using Origin version 28. $\alpha = 0.05$ was statistically significant. Mean ±standard error mean was used by the software Statistic 10, shown in tables.

3 Results

3.1 Soil organic carbon and total nitrogen

Soil organic carbon (SOC) and TN differ significantly among the four land-use types (Table 1). Soil organic carbon ranged from 0.435% to 0.84%, while TN varied between 0.014% and 0.123%, with mean values of 0.635% and 0.0685%, respectively. The highest SOC and TN contents were observed in the NF, followed by BP, with the lowest values recorded in AL. Specifically, the NF showed the highest SOC (0.84±0.054%) and TN (0.123±0.013%), whereas the AL showed the lowest SOC (0.435±0.042%) and TN (0.014±0.0016b%). Analysis of variance indicated that soil TN in NF was significantly higher (α =0.05) than in the other land-use types, while the difference in SOC between the NF and BP was not statistically significant.

Table 1: Soil organic carbon (SOC), soil total nitrogen (TN), Microbial biomass carbon (MBC), Microbial biomass nitrogen (MBN), and soil basal respiration (BR) under different land use types

	Land use type					
	NF	DF	BP	AL	LSD	P-value
SOC (%)	0.84 ± 0.054^a	0.448 ± 0.113^b	0.72 ± 0.074^a	0.435 ± 0.042^b	0.21	< 0.001
TN (%)	0.123 ± 0.013^a	0.027 ± 0.003^b	0.033 ± 0.0034^b	0.014 ± 0.0016^b	0.021	< 0.001
MBC (μg/g)	570.65 ± 35.05^a	233.94 ± 60.36^b	479.03 ± 21.48^a	225.59 ± 20.84^b	114	< 0.001
MBN (μg/g)	84.21 ± 3.186^a	48.95 ± 2.506^b	63.05 ± 4.281^c	43.14 ± 1.784^b	9.23	< 0.002
BR (μg CO_2)	3.64 ± 0.064^a	2.69 ± 0.11^b	3.37 ± 0.067^a	2.56 ± 0.11^b	0.29	< 0.003
β-glucosidase (μg PNP g^{-1} dry soil h^{-1})	809.68 ± 39.7^a	380.50 ± 17.02^c	577.28 ± 84.39^b	492.88 ± 58.13^c	181.35	< 0.001
MBC/MBN	6.77	4.78	7.59	5.23		

Values are Mean ± SE. Different superscript letters (a, b, c) indicate significant differences among mean values at α = 0.05 level.
(Source: Authors' own findings)

3.2 Microbial biomass

In this study, the values of MBC across the four land-use types ranged from 146.21 to 619.67μg/g soil, with mean values of 377.3μg/g soil. The MBC and MBN were highest in NF, with a mean of 570.65μg/g and 84.21μg/g, respectively (Table 1). While the BP showed a moderate decrease in MBC and MBN (mean 479.03μg/g, 63.05μg/g), DF and AL lands exhibited substantially lower levels, with mean values of 233.94, 48.95μg/g and 225.58, 43.14μg/g, respectively. Analysis of variance revealed that MBC in the NF and BP plantation was significantly higher than in AL and DF (α =0.05). However, there was no significant difference in MBC between NF and BP, nor between AL and DF.

3.3 Basal respiration (BR)

The values of basal respiration are presented in Table 1. Soil basal respiration (BR) across the four land-use types ranged from 2.36 to 3.75 CO_2/g soil with a mean value of 3.07 CO_2/g soil. Basal respiration (BR) was significantly higher in NF (3.64 μg CO_2/g soil), followed by BP (3.37 μg CO_2/g soil). In contrast, DF (2.69 μg CO_2/g soil) and AL (2.56 μg CO_2/g soil) exhibited significantly lower respiration rates (Table 1).

3.4 Enzyme activity

The results of b-glucosidase activity varied significantly among the land uses, and the activity ranged from 350.559 to 872.07µg PNP g^{-1} dry soil h-1, with a mean value of 565.08µg PNP g^{-1} dry soil h-1 (Table 1). The b-glucosidase activity under NF ranged from 735.88 to 872.07µg PNP g^{-1} dry soil h-1, with a mean value of 809.69µg PNP g^{-1} dry soil h-1; for BP, the values ranged from 408.55 to 665.24µg PNP g^{-1} dry soil h-1, with a mean of 577.29µg PNP g^{-1} dry soil h-1; and for AL, the values ranged from 432.93 to 609.13μg/g, with a mean value of 492.88μg/g soil. FFor DF, it ranged from 350.59 to 409.54µg PNP g^{-1} dry soil h-1, with a mean of 380.50µg PNP g^{-1} dry soil h-1. Analysis of variance revealed that b-glucosidase activity in the NF was significantly higher (α =0.05) than in all other land-use types. However, there was no significant difference in b-glucosidase activity between DF and AL.

3.5 Soil Microbial PLFA Profiles

The composition and structure of the soil microbial community, as determined by phospholipid fatty acid (PLFA) analysis, varied significantly across the four land-use types (Table 2). The highest total PLFA was found in NF (73.55 nmol g^{-1}), followed by BP (63.23 nmol g^{-1}), DF (57.38 nmol g^{-1}), and AL (52.75 nmol g^{-1}). The trend of total PLFAs across all land-use types was in the order: NF BP DF AL. In terms of microbial groups, G bacteria and fungi were higher in NF, followed by BP, DF, and AL. However, G+ bacteria followed the reverse trend; NF< BP <DF< AL. Analysis of variance revealed that G bacteria differed significantly across all land-use types, whereas the pattern was not consistent for G bacteria and fungi. The ratio of G+/G- bacteria increased from NF to AL as the proportion of G+ bacteria rose, with a significant difference observed in AL. Conversely, the F/B ratio decreased along the same gradient, showing significant differences between NF and AL, NF and DF, and BP and AL.

Correlation

Pearson's coefficient correlation analysis revealed strong positive relationships among all measured soil variables (Table 3). Soil BR was highly correlated with SOC and MBC (r= 0.997**). MBC also showed near-perfect correlations with SOC (r = 1.00**) and strong associations with MBN (r = 0.955*). β-glucosidase activity was strongly correlated with SOC (r = 0.91), MBC (r = 0.903), STN (r = 0.901), and MBN (r = 0.924). Soil TN showed slightly lower but still strong correlations with carbon-related variables and MBN; r values ranged from 0.811 to 0.901.

Table 2: The amount of total phospholipid fatty acids (PLFAs), Gram-positive bacterial, Gram-negative bacterial, and fungal PLFAs (mg/g DW) under four land uses.

	Land use				P -value
	NF	BP	DF	AL	
G^-	37.43 ± 2.21^{a}	22.51 ± 1.75^{b}	15.78 ± 0.85^{c}	5.29 ± 0.477^{d}	< 0.001
G^+	15.61 ± 1.25^{a}	25.17 ± 2.02^{b}	30.64 ± 0.82^{b}	39.4 ± 3.73^{c}	< 0.001
Fungi	20.49 ± 1.24^{a}	15.55 ± 1.14^{b}	10.96 ± 0.86^{c}	8.06 ± 0.59^{c}	< 0.001
Total PLFA	73.55 ± 2.85^{a}	63.23 ± 1.8^{b}	57.38 ± 1.02^{bc}	52.75 ± 4.04^{c}	< 0.001
G^+/G^-	0.42 ± 0.01^{a}	1.12 ± 0.18^{a}	1.94 ± 0.15^{a}	7.44 ± 1.08^{b}	< 0.001
F/B	0.392 ± 0.046^{a}	0.326 ± 0.02^{ac}	0.236 ± 0.02^{cb}	0.18 ± 0.01^{b}	< 0.001

Values are Mean ± SE (mg/g dry weight). G^-: Gram-negative bacteria, G^+: Gram-positive bacteria, F/B: Fungi to Bacteria ratio. Different superscript letters within a row indicate significant differences at $\alpha = 0.05$ level.

Table 3: Correlation matrix for physical, chemical, and microbiological characteristics of soils from different land uses.

Soil variable	BR	SOC	MBC	B-glucosidase	STN	MBN
SOC	0.997^{**}	1				
MBC	0.997^{**}	1.000^{**}	1			
B-glucosidase	0.877	0.91	0.903	1		
STN	0.815	0.828	0.811	0.901	1	
MBN	0.960^{*}	0.963^{*}	0.955^{*}	0.924	0.944	1
BR	1	0.997^{**}	0.997^{**}	0.877	0.815	0.960^{*}

SOC: Soil organic carbon; STN: Soil total nitrogen; MBC: Microbial biomass carbon; MBN: Microbial biomass nitrogen; BR: Soil basal respiration.
*Significant at $\alpha = 0.05$, **Significant at $\alpha = 0.01$.
(Source: Authors' own findings)

4 Discussion

This study demonstrated that land-use change significantly affects soil microbial communities, microbial biomass, basal respiration, and the levels of soil SOC and TN in the dry tropics of India (Fig. 2, Tables 1,2, and 3). The conversion of native ecosystems, such as natural forests, to other land uses, particularly agricultural land, had a negative impact on both soil chemical and microbial properties in the study area. This agrees with the results of the studies conducted by Chen et al. (2010), Q. Zhang et al. (2016), and Zhou et al. (2002) who stated that land-use change alters soil chemical and biological properties by influencing key ecological processes.

Soil organic carbon (SOC) and TN are considered to be among the major attributes of soil fertility and agricultural sustainability (Paltineanu et al., 2024). The present results suggest that the conversion of NF to AL leads to significant declines in SOC and TN levels. The trend of SOC and TN across all land-use types was in the order: NF BP DF AL (Table 1). These findings are consistent with previous studies conducted in similar agroecological settings (Gol, 2009; Iqbal et al., 2014; Pereira et al., 2013). Another study also reported that native forest had higher SOC than pasture and agricultural lands, but the difference was not significant (Mazzetto et al., 2016). The superiority of SOC and TN in the NF relative to BP, DF and AL was associated with the regular addition of plant litter/greater total litter (above and below ground tree parts), root exudates and minimal anthropogenic disturbance, including the absence of tillage, low grazing pressure and high plant biodiversity (Iqbal et al., 2014; Srivastava & Singh, 1991). Additionally, the higher SOC and TN in BP, as compared to DF and AL were associated with the roughly twice as high leaf litter pool and fine roots in BP due to the bamboo ecosystem. The degradation of natural forests significantly decreased SOC and TN. The disturbances associated with deforestation might have led to a loss of vegetation, which in turn has resulted in land degradation, erosion, and subsequently, considerable losses of SOC and nutrients (Tripathi & Singh, 2009; Xiangmin et al., 2014). The least SOC and TN in AL, as compared to DF, could be due to continoues tillage, removal of crop residue and intensive grazing, all of which accelerate native soil organic matter oxidation by destroying soil aggregates and exposing newer sites to microbial attack, which in turn results in the loss of soil organic carbon (Chaudhary et al., 2008; Saha et al., 2010; S. Singh & Ghoshal, 2006; Tripathi & Singh, 2009).

Changes in land-use patterns from NF to BP, DF, and AL resulted in 1.19, 2.53, and 2.44-fold decrease in the level of MBC, respectively. Similarly, the MBN in NF was found to be higher and significant with other land use types except BP (Table 2). These findings are consistent with previous studies (Kara & Bolat, 2008; Q. Zhang et al., 2016). S. Singh et al. (2025) reported that a closed mixed Sal Forest had significantly higher MBC than the open mixed Sal Forest across the soil profile, with a strong seasonal effect. Lepcha and Devi (2020) also found that the annual mean MBC was highest in the forest (455.03μg/g), followed by cardamom agroforestry (392.86μg/g) and paddy cropland (317.47μg/g). The elevated MBC and MBN in NF soils are likely a result of increased input of soil organic matter, more diverse organic inputs, and enhanced biological processes. For instance, mixed forest systems have been shown to produce higher-quality litter, support faster litter decomposition, and enhance soil nutrient mineralization compared to other land use types. In addition, high levels of root biomass and root exudates in natural forests contribute to greater microbial activity and biomass (Bhuyan et al., 2013; Kara & Bolat, 2008). Similarly, increased availability of resources such as soil organic matter, more diversified organic matter input, and related processes are believed to be the cause of the higher MBC and MBN in diversified ecosystems. Bamboo plantation increased the MBC and MBN by 50% and 14%, respectively, over the DF and AL. Such arise in MBC and MBN indicate the trend of restoration of degraded land towards the NF occurring with bamboo plantation. Similarly, (Cheng et al., 2013) reported that the increase in the microbial biomass may be ascribed to the accumulation of soil organic carbon. The lower microbial biomass in DF and AL might be attributed to reductions in the vegetation cover, leading to lower levels of litter input, root necromass, and root exudates to the soil (M. K. Singh & Ghoshal, 2014).

Soil basal respiration (BR), quantified by the amount of CO2 produced /O2 consumed, varied significantly across the different land-use types. Similar findings were reported by. Soil BR in BP was 2% lower than NF, but 5% and 6% higher than DF and AL, respectively. The analysis of variance confirmed that BR in NF and BP were not significantly different from each other but were both significantly higher than in AL and DF. The similarity of the BR values between NF and BP, and AL and DF, suggested similar microbial activity (Pereira et al., 2013). The higher soil BR in NF and BP indicates the higher soil microbial activity due to the permanent and continuous addition of a source of labile organic matter to the soil and the consequent stimulation of heterotrophic microorganisms. Additionally, higher soil respiration is indicative of high biological activity, suggesting rapid decomposition of organic residues that make nutrients available for plant growth (Pereira et al., 2013) (Araújo et al., 2009). In contrast, the lower BR in AL and DF may reflect reduced microbial biomass or substrate availability, possibly due to soil degradation, lower organic inputs, or frequent soil disturbances such as tillage. This pattern aligns with the understanding that soil respiration is a sensitive indicator of soil biological activity and health, and its decline signals deteriorating soil quality under intensified or unsustainable land use.

This study demonstrated that changes in land-use impact the microbial community composition and enzyme activity under tropical conditions. The b-glucosidase activity in the NF was significantly higher than and significantly from other land use types at $p<0.05$. The trend of b-glucosidase activity across all land-use types was in the order: NF BP DF AL. This result is consistent with previous studies Bandick and Dick (1999) and Roldan et al. (2005). Sarto et al. (2020) reported that the higher β-glucosidase activity from ICLS (integrated crop-livestock system) as compared to native savanna, pasture, and maize. The higher β-glucosidase activity in the natural ecosystem was associated with the composition and quality of plant residues, because β-glucosidase is more active with less-complex residues (Lopes et al., 2013, 2015). The higher β-glucosidase activities in NF may be the consequence of both microbial growth and stimulation of microbial activity by enhanced resource availability (increase in the input of organic matter in the soil and improvement of soil physical properties), as well as of changes in microbial community composition (Bhattacharyya et al., 2005; Kong et al., 2007). On the other hand, the increment of enzyme activity in BP as compared to DF and AL may be due to the addition of leaf litter and root exudates from bamboo, which leads to stimulating microbial metabolism and decomposition rate (Masciandaro et al., 2003). Unlikely, the β-glucosidase activity was decreased as compared to NF may be due to the thinner canopy and greater soil exposure may have resulted in greater temperature and soil moisture fluctuation, as well as other factors that influence the decrease in microbial activity (Pereira et al., 2013).

The results of the present study showed that NF exhibited the highest microbial abundance in terms of total PLFAs, compared to BP, DF, and AL (Table 2). This finding is consistent with previous research (Mishra et al., 2024; Steenwerth et al., n.d.; Torsvik & Øvreås, 2002; Wang et al., 2025). For instance, García-Orenes et al. (2013) reported that native forest had the highest microbial PLFA concentration compared to various agricultural management systems in the Mediterranean Agro-Ecosystem. Similarly, Q. Zhang et al. (2016) found that higher microbial PLFA biomass from an afforested area as compared with cropland and uncultivated soils. In line with these findings, Steenwerth et al. (n.d.) also observed greater PLFA content in grasslands than in cultivated soils. These consistent patterns across studies suggest that natural and less-disturbed ecosystems support richer and more active microbial communities than intensively managed or degraded systems. The variation of total PLFA among the land use patterns could be due to soil pH, plant species diversity (Guo et al., 2016), and soil carbon and nitrogen availabilities (Q. Zhang et al., 2016). The higher total microbial PLFA in NF and BP is possibly attributed to increased litter input and soil organic carbon and nitrogen content. In contrast, the lower total microbial PLFA in DF and AL could be due to physical disturbance, mainly tillage, and limited levels of carbon and nitrogen input (M. K. Singh & Ghoshal, 2014).

Land-use change not only influenced the overall microbial community but also affected the composition of specific microbial taxonomic groups (Guo et al., 2016; Mishra et al., 2024; Nagendran et al., 2014). In this study, three major soil microbial groups were considered: Gram-negative bacteria (G-), Gram-positive bacteria (G+), and fungal communities. The abundance of G- G-bacteria and fungal communities declined sharply along the land-use gradient from NF to AL, indicating a reduction in microbial diversity with increasing disturbance. In contrast, G+ bacteria exhibited a reverse trend, increasing in relative abundance from NF to AL. The same result has been reported by Kumar and Ghoshal (2017), Mishra et al. (2024), Steenwerth et al. (n.d.), and Torsvik and Øvreås (2002). Similar findings were reported by Bossio et al. (2005) and Moore-Kucera and Dick (2008), who observed an increase in G+ bacterial dominance following deforestation and the conversion of forest to cropland.

The relatively higher abundance of G– bacteria in NF may be attributed to the presence of diverse vegetation and continuous organic matter inputs that provide labile carbon substrates, which favor fastidious microorganisms (Moore-Kucera & Dick, 2008). In contrast, AL and DF, characterized by reduced litter input, physical disturbance (tillage), and greater environmental stress (e.g., fluctuating moisture and temperature), tend to favor G+ bacteria, which are more resistant to nutrient limitation and desiccation (Boylen & Ensign, 1970). Additionally, G– bacteria were associated with simple carbon compounds (alkyls), whereas G+ bacteria were more strongly associated with more complex carbon forms (carbonyls) (Fanin et al., 2019). The drop in the fungal community in DF could be because filamentous fungi are more sensitive to physical disturbance than single-celled bacteria (Kabir et al., 1999; Mishra et al., 2024). In AL, physical disturbance, substantially tillage, destroyed fungal mycelium networks, and the combination of mechanical destruction, soil contraction, and reduced severance volume inclusively led to the smallest fungal PLFA values (Bardgett et al., 2001; García-Orenes et al., 2013). This might be due to changes in litter quantity and quality, which conceivably accounts for the changes in fungal PLFAs (Denef et al., 2009).

The fungal: bacterial PLFAs (F:B) ratio is used to evaluate the responses of the soil microbial community to soil carbon and nitrogen dynamics and environmental changes (Fanin et al., 2019; Q. Zhang et al., 2016). The G/G ratio increased with land-use disturbance, from 0.42 in natural forest to 7.44 in agricultural land, indicating a shift toward microbial communities more tolerant of environmental stress. Likewise, the fungi-to-bacteria (F/B) ratio declined from 0.386 in NF to 0.18 in AL, suggesting a transition from fungal-dominated communities associated with stable carbon-rich systems to bacterial-dominated communities with faster nutrient cycling and reduced carbon retention. This result is consistence with a former study (García-Orenes et al., 2013), the ratio of bacteria: fungi was higher in wild forest coverage and land abandoned systems, as well as in the soil treated with oat straw. These patterns collectively highlight the adverse effects of land-use change on microbial community composition, soil biological functioning, and ecosystem resilience.

According to Oyedele et al. (2015), MBC and MBN were significantly correlated with the SOC and TN. In this study, on average, 95% of the microbial biomass and activities were governed by the SOC and TN (Table 3). The significant positive relations between the soil MBC and SOC agree with earlier reports by Bhuyan et al. (2013), Cheng et al. (2013), Makova et al. (2011), and Yang et al. (2010). This might be due to microbial biomass concentration depending on the organic matter availability to microbial activity (Anderson & Domsch, 1989); however, Insam et al. (1989) found no correlation between the biomass carbon and organic carbon. Similarly, SOC was significantly correlated to TN Bhuyan et al. (2013), Cheng et al. (2013), Kara and Bolat (2008), and Yang et al. (2010), while TN was strongly related to MBN agrees with the results by (Yang et al., 2010). These results indicate that MBN levels in the soils were determined by SOC and TN (Adeboye et al., 2011). The results of many studies showed a close correlation between MBC and SOC or TN because most microorganisms are heterotrophic and their distribution and biological activity often depend on organic matter (Kara & Bolat, 2008; M. K. Singh & Ghoshal, 2014; Xiangmin et al., 2014). Several studies have found strong correlations between MBN and TN (Anderson & Domsch, 1989; Insam et al., 1989).

5 Conclusions

This study demonstrated that land-use change significantly affects soil microbial biomass, SOC, and TN contents in the study area. The most severe impacts of natural forest conversion were observed in the DF and AL, where soil PLFA, microbial biomass, enzyme activity, SOC, and TN levels were the lowest. Following the NF, the BP exhibited higher levels of SOC, TN, BR, β-glucosidase activity, microbial biomass, and PLFA content, indicating a healthier and more functionally diverse soil ecosystem, which favoured the restoration of degraded forests toward natural forests. Significant variations in microbial PLFA composition and biomass among land-use types suggest that these parameters can serve as reliable indicators of ecosystem recovery. Based on the higher soil PLFA content, microbial biomass, and faster recovery rates, it is suggested that bamboo plantation could be adopted as a major strategy for restoring degraded lands in the dry tropics.

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Availability of data and materials

All data generated or analysed during this study are included in this manuscript

Competing interests

The authors declare that they have no conflicts of interest.

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Research Article

Analysis of farm households' price efficiency in the production of Maize: The case of Abobo District, Gambella Regional State, Ethiopia: An application of stochastic frontier analysis and dual cost approach

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Abstract

Even though agriculture is the backbone of the Ethiopian economy, its performance is unsatisfactory, and food production is very low compared with population growth. As the possibility of improving production by bringing extra resources into use became increasingly restricted, the efficiency with which the farmers use existing resources has received the utmost attention to block the gap between the supply and demand of food. However, price efficiency in maize production has not been extensively studied because previous studies mainly focused on economic efficiencies. This study was carried out to analyse the productivity and price efficiency of smallholder farmers in maize production in the Abobo district, Gambella Regional State, Ethiopia. To meet the objectives of the study, secondary data were used in addition to the primary data. The primary data were gathered via structured questionnaires from 152 randomly selected sample households during the 2023/24 production year, and secondary data were collected from different sources. Cobb-Douglas production function was applied to analyse the productivity, whereas the Tobit model was used to estimate farm households' price efficiency. The results of the survey showed that mean price efficiency was estimated to 70.9%, implying that there exist considerable levels of price inefficiencies in the production of maize in the study area. The Tobit model results revealed that livestock holding, frequency of extension contact, land fragmentation and off/non-farm activity had a considerable effect on price efficiency. The result of the study shows that there exists an opportunity to boost the efficiency of maize producers in the study area. In addition, policy measures derived from the results of the study include increasing the livestock production, strengthening the extension services, promoting off/non-farm activity and raising the resettlement programs in the study area.

KEYWORDS: Cobb-Douglas; Dual Cost; Price Efficiency; Stochastic frontier; Tobit

1 Introduction

Currently, the world population is increasing at an alarming rate. About 80% of the world's population depends on farming, live in rural areas and are almost poor. In the world, agricultural development is expected to can support in sinking down poverty. Maize (Zea mays L.) was domesticated from teosinte in Mexico, and it spread to the rest of the world in the 16th through 18th centuries. It is the most widely distributed and the first most important cereal crop followed by rice and wheat in the world ("FAOSTAT 2013," 2013; Njeru, 2010; Shiferaw et al., 2011). Africa is an agrarian continent whereby two-thirds of the people directly or indirectly engaged their livelihood depending on the agriculture sector. The Sub-Saharan Africa region accounts for more than 950 million people, approximately 13% of the global population (OECD/FAO, 2016).

Maize accounts for the calories and protein consumed in ESA and in West Africa. Aside from its staple food use, it makes a significant contribution to animal feed (especially poultry), biofuel and industrial uses (Ntabakirabose, 2017). In developed countries, 70% of maize is destined for feed, 3% is consumed directly by humans, and the remaining 27% is used for biofuels, industrial products, and seed. In Sub-Saharan Africa, 77% of maize is used as food and only 12% serve as feed. In Ethiopia, cereals are the major food crops both in terms of area coverage and volume of production (Haile et al., 2018).

The major cereal crops grown in Ethiopia are teff, maize, wheat, barley, sorghum and millet (Central Statistical Agency, 2007; Mustefa, 2014). Maize is one of the five major staple cereal crops in Ethiopia. Among the crops grown in Ethiopia, maize is the most significant cereal crop in terms of total production, area coverage, and better availability and use of new production technologies (Cochrane & Bekele, 2017). Maize is a major source of food and cash for smallholder farmers (Abdulai et al., 2018). It is the highly demanded food crop in the southwestern part of Ethiopia. High productivity and efficiency in maize production is critical to improve food security, reduce the level of poverty and achieve or maintain agricultural growth.

According to the Central Statistical Agency (2017) report, maize is cultivated on over 2.13 million hectares of land, with an annual production of 7.8 million tons with a yield of 36.75 qt/ha, contributing about 27.02% of the total cereal production in Ethiopia. In terms of area of production, maize stands second by covering 16.98% of the total cereal crop areas, followed by only teff (24.00%), followed by sorghum (14.97%) and wheat (13.49%). From the total cereal production, maize ranks first in the country. In the Gambella region, the total area covered by maize in the production year of 2023/24 was 4831 hectares and 125,828 quintals of maize was produced by 5.36 million smallholder farmers and the average productivity was 38.18 qt/ha (Tilahun et al., 2023). At the same time, there were 329,242 smallholders producing 4.6 million quintals of maize with a yield of 42.30 qt/ha from 108,914 ha of land in the Illubabor zone.

In the Abobo woreda, where this study was conducted, maize (Zea mays L.) production is the means of livelihood of the people to meet the household consumption and to generate income. However, to the knowledge of the researcher, there was no study conducted in the district before to identify whether the farmers are using the inputs in an optimal proportion, given input prices for maize production. Therefore, this study aimed to estimate the levels of price efficiency and to identify the major factors affecting it by collecting cross-sectional data from maize-producing smallholder farmers in the Abobo district.

2 Materials and methods

2.1 Description of the Study Area

The Abobo district is in the Gambella regional state of the Agnwa zone, Ethiopia. The Abobo district is one among the five woredas of the Agnwa zone. It is located 813 Km southwest of Addis Ababa and 47 Km south of Gambella, which is the capital of the region. Geographically, it lies between $07^{\circ}45'00''$ N to $08^{\circ}00'00''$ N latitudes and $34^{\circ}30'00''$ E to $34^{\circ}45'00''$ E longitudes. The woreda bordered with Gambella zuriya woreda to the north, Etang special woreda to the northwest, Goge woreda to the south, Jikawo and Jore woredas to the west, Mengeshi woreda and Oromiya Regional State to the east. It covers a total area of 361324.58. Km2 and has 16 rural kebele administration and one urban administration (Abobo Woreda Office of Finance and Economic Development (AWOFED), 2023; Central Statistical Agency, 2007).

The terrain of the woreda can be mostly characterized by a vast flat landscape and a slight plateau to the east. The altitude ranges from 460 to 1650 m.a.s.l. The major water bodies in the woreda include the river Alwero and Lake Alwero, which is an artificial one. The woreda has two agro-climatic zones. These are woinadega (10%) and Kolla (90%). Accordingly, the mean annual minimum and maximum temperature of the woreda ranges between $18^{o}C$ and $39oC$, respectively. The average annual rainfall ranges between 900 and 920 mm, and the main rainy season in the woreda is from mid-April to October (Abobo Woreda Office of Finance and Economic Development (AWOFED), 2023).

According to Central Statistical Agency (2007), the total population of the district is 15,741. In Abobo, there is crop production with gradual encroachment to rangelands showing the future expansion of crop cultivation. Farmers rear cattle, goats and chickens together with their crop cultivation practices. They produce cereal crops mainly maize, sorghum, sesame, millet, and rice. In Abobo woreda, there are two major types of farming systems: mixed farming and shifting cultivation practiced by settlers and native local people of the area, respectively (Gelayenew et al., 2016).

Out of the total farm area of 535 km^2, about 355 km^2 is under the control of small-scale farmland holders and the remaining 180 km2 land is in the hands of large-scale farmholders. The populations of interest for this research were maize-growing household farmers, especially the HHs that grew maize in the 2023/2024 cropping season.

2.2 Sampling technique and sample size determination

In this study, a two-stage random sampling technique was used to select sample households. In the first stage, out of the 16 maize producers, kebeles existed in the district; four kebeles (mender 7, 8, 11/12 and 13, Table 1) were randomly selected. In the second stage, 152 sample farmers were selected using a simple random sampling

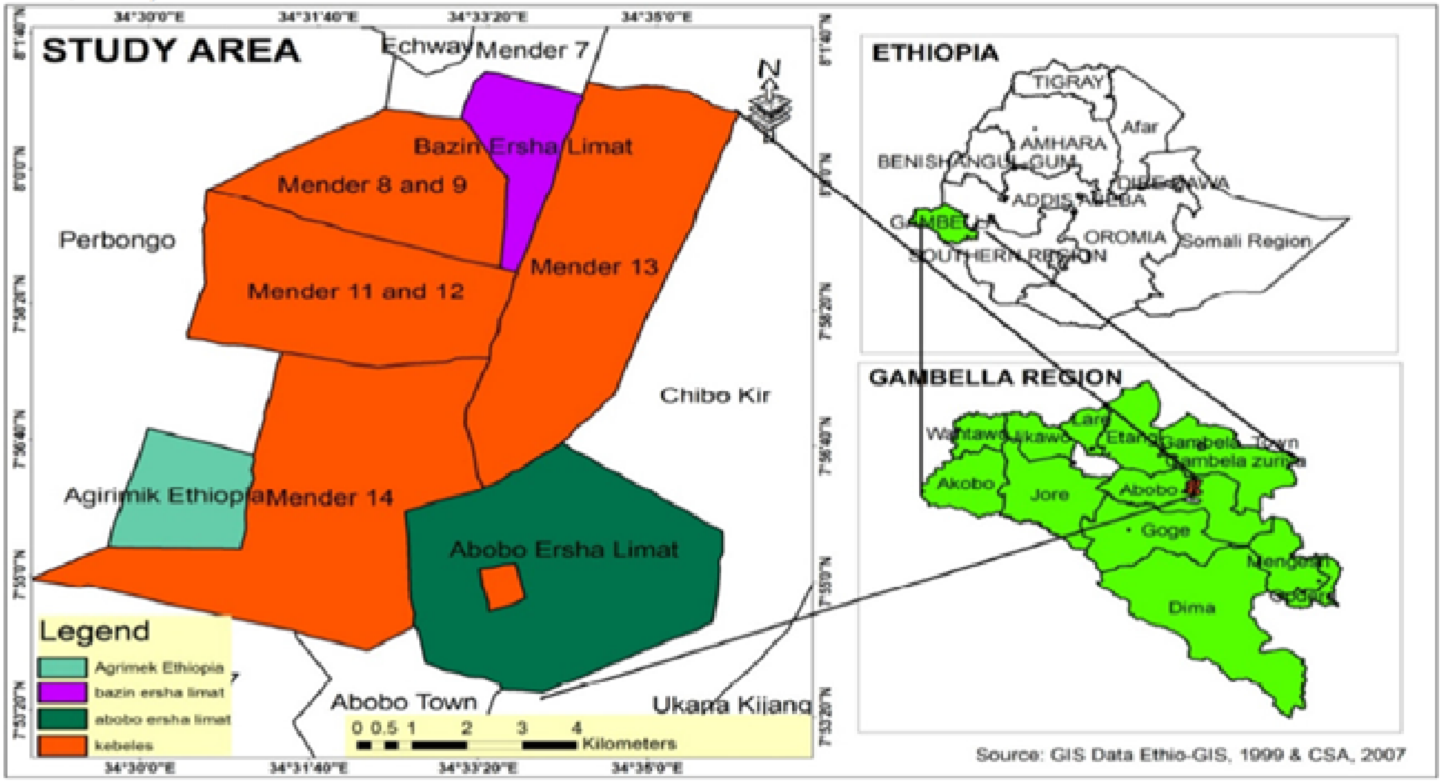

Figure 1: Map of the study area

technique based on the probability proportional to the size of the maize producers in each of the four selected kebeles. The sample size was determined based on the following formula given by (Yamane, 1967):

The formula used for the sample size determination is

$$n = \frac{N}{1 + N(e)^2} \quad (1)$$

$$n = \frac{1100}{1 + 1100(0.08)^2} = 152$$

2.3 Data types and methods of data collection

This study used both qualitative and quantitative types of data. Both primary and secondary data sources were used. The primary data was collected from sample households using a structured questionnaire that was administered by the trained enumerators based on the actual farming practices existed in the study area. Moreover, the local measurement scales customarily used by the farmers were converted into their respective standard units to minimize the measurement errors that could arise from the variability of the local units. Secondary data were collected from local administration offices, governmental and NGOs, published and unpublished documents and CSA, which were used as additional information to strengthen the primary information provided by the sample households in the study area. FGD and key informant interviews were conducted with farmers, development agents, concerned agricultural professionals and administration offices at all levels by the researcher.

2.4 Methods of data analysis

An econometric model such as the Cobb-Douglas stochastic production frontier model was used to predict the price efficiency scores of the sample farmers and the Tobit model was used to analyze the determinants of price efficiency.

2.4.1 Dual cost approach of efficiency measurement

According to Sharma et al. (1999), the dual cost frontier of the Cobb-Douglas production functional form is defined as follows:

$$\ln(C_i) = \beta_o + \sum_{j=1} \beta_j ln P_{ji} + \beta_j Y^* \quad (2)$$

Given the input-oriented function, the efficient cost function can be specified as follows:

$$\min_x \sum c = \sum_{j=1} W_j X_j \quad (3)$$

Table 1: Sample distribution of maize producer households in the selected kebeles

Selected Kebeles	Total number of households	Number of sampled households	Proportion of sampled households (%)
Mender 7	214	28	19.68
Mender 8	423	65	39.25
Mender 11/12	260	35	21.50
Mender 13	203	24	19.57
Total	1100	152	100

Source: Abobo District Agricultural Office and its own computation

Subjects to

$$Y * _A XjjWhere \quad Exp(_0) \quad A \tag{4}$$

The solution to the problem in the above equation is the basis for driving the dual cost frontier. Substituting the input demand equations derived using shepherd‘s lemma (4) and the yield adjusted for stochastic noise (predicted value of yield) in the minimization problem above, the dual cost function can be written as follows:

$$C(Y\, i*, W\,)HY\, ijWjj \tag{5}$$

According to **sharma1999**, the explained cost measures that enable us to estimate PE are:

$$CiC(Wi,\ Y\, i*,\ ) \tag{6}$$

where i refers to the i_{th} sample household, Ci is the minimum cost of production, Wi denotes input prices; Y refers to farm output, which is adjusted for noise and ’ s is parameters to be estimated.

2.4.2 *Efficiency measurement*

Most empirical studies on efficiency in Ethiopia were analyzed using the Cobb-Douglas stochastic production frontier model (Asfaw et al., 2019; Nigusu, 2018; Tolesa et al., 2019). The main reason is that the stochastic production frontier model allows for statistical noise such as measurement error and climate change, which are beyond the control of the farmers. Following Aigner et al., 1977 , the specified stochastic production frontier (SPF) model was defined as follows:

$$\ln(Y_i) = F\,(X_i, \beta_i) + v_i - \mu_i \quad i = 1, 2, 3 \ldots n \tag{7}$$

Where: i- Indicates the number of sample households ln $(Y\, i)$- Indicates the natural log of the (scalar) output of the ith household. $F\,(X_i, \beta_i)$ ¬¬ is a convenient frontier production function (e.g., Cobb-Douglas); X_i- Represent a vector of input quantities used by the ith household β_i– Indicates a vector of unknown parameters to be estimated v_i- is a symmetric component and permits a random variation in output due to factors beyond the control of the decision-making unit, such as weather, measurement error, omitted variables, and other exogenous shocks. It is assumed to be independently and identically distributed $N\ (0,\ \sigma^2_v)$ and μ_i - intended to capture the inefficiency effects in the production of maize measured as the ratio of the observed output to the maximum feasible output of the i^{th} afarmer. It was assumed to be independently and identically distributed as a half-normal $u\ N\ (u,\ \sigma^2_u)$.

The dual cost function, which was derived analytically from the SPF, is given on the basis of the following for computing price efficiency:

$$\ln CM_i = 2.51 + 0.03 \ln w_{1i} + 0.32 \ln w_{2i} + 0.01 \ln w_{3i} + 0.17 \ln w_{4i} + 0.08 \ln w_{5i} + 0.02 \ln w_{6i} + 0.48 \ln Y * \tag{8}$$

where ln is the natural logarithm; CMi is the minimum cost of maize production of the ith farmer; w1i refers to the price of seed per kg; w2i is the cost of land per ha; w3i is the cost of NPS per kg; w4i is the cost of urea per kg; w5i is the cost of oxen per day; w6i is the cost of labor per day; Y is an index of output adjusted for any statistical noise and scale effects; ith refers to the ith sample household.

2.4.3 *Determinants of price efficiency*

In this study, to analyze the effect of demographic, socio-economic, farm attributes and institutional variables on price efficiencies, a second stage procedure was used where the efficiency scores estimated from the stochastic production frontier were regressed on the hypothesized explanatory variables using the Tobit model. This model is best suited for such analysis because of the nature of the dependent variable (efficiency scores), which takes values between 0 and 1 and yields the consistent estimates for the unknown parameter vector (Maddala, 1999). Estimation with the OLS regression of the efficiency score would lead to a biased parameter estimate since the OLS regression assumes a normal and homoscedastic distribution of the disturbance and the dependent variable (Greene, 2003). Following Maddala (1999), the model can be specified as

$$y^*_{i\,PE} = \delta_0 + \sum_{n=1}^{n} \delta_n Z_{in} + \mu_i \tag{9}$$

Where: i refers to the i^{th} farm in the sample households, n is the number of factors affecting price efficiency; y_i is efficiency scores representing the price efficiency of the i^{th} farm. y_i the latent variable, δ_n are unknown parameters to be estimated and μ_i is a random error term that is independently and normally distributed with a mean of zero and a common variance of σ^2 μ_i IN $0, \sigma^2$. Z_{in} are demographic, institutional, socio-economic, and farm-related variables that were expected to affect price efficiency. Denoting yi as the observed variables,

$$y_i = \begin{cases} 1 & if y^*_i \geq 1 \\ y^*_i & if 0 < y^*_i < 1 \\ 0 & if y^*_i \leq 1 \end{cases} \tag{10}$$

The distribution of the dependent variable in equation (10) is not a normal distribution because its value varies between 0 and 1. The ordinary least square (OLS) estimation will give biased estimates (Maddala, 1999). Therefore, the alternative approach is to use the maximum likelihood estimation (MLE), which can yield consistent estimates for unknown parameters. Following Maddala, 1999, the likelihood function of this model is given by

$$L(\beta, \delta \mid y_j, X_j, L_{1j}, L_{2j}) = \prod_{y_j = L_{1j}} \phi\left(\frac{L_{1j} - \beta' X_j}{\delta}\right) \times \prod_{y_j = y_j^*} \frac{1}{\delta} \varphi\left(\frac{y_j - \beta' X_j}{\delta}\right) \times \prod_{y_j = L_{2j}} \left(1 - \phi\left(\frac{L_{2j} - \beta' X_j}{\delta}\right)\right) \tag{11}$$

Where $L_{1j} = 0$ (lower limit) and $L_{2j} = 1$ (upper limit) where ϕ (.) and (.) are normal and standard density functions, respectively. In practice, since the log function is a monotonically increasing function, it is simpler to work with the log of the likelihood function rather than the likelihood function, and the maximum values of these two functions are the same (Greene, 2003).

The regression coefficients of the Tobit regression model cannot be interpreted like traditional regression coefficients that give the magnitude of the marginal effects of change in the explanatory variables on the expected value of the dependent variable. In a Tobit model, each marginal effect includes both the influence of the explanatory variables on the probability of the dependent variable to fall in the uncensored part of the distribution and on the expected value of the dependent variable conditional on it being larger than the lower bound. Thus, the total marginal effect considers that a change in the explanatory variable will have a simultaneous effect on the probability of being allocatively efficient and the value of the allocative efficiency score. A useful decomposition of marginal effects that was extended by Gould et al., 1989 was proposed by McDonald and Moffitt, 1980. From the likelihood function of this model stated in equation (6), Gould et al. (1989) showed the equations of the three marginal effects as follows:

The unconditional expected value of the dependent variable:

$$\frac{\partial E(y)}{\partial x_j} = \left[\phi(Z_U) - \phi(Z_L)\right] \cdot \frac{\partial E(y^*)}{\partial x_j} + \frac{\partial[\phi(Z_U) - \phi(Z_L)]}{\partial x_j} + \frac{\partial[1 - \phi(Z_U)]}{\partial x_j} \tag{12}$$

The expected value of the dependent variable conditional upon being between the limits

$$\frac{\partial E(y^*)}{\partial x_j} = \beta_n \cdot \left[1 + \frac{\{\Phi(Z_L) - \Phi(Z_U)\}}{\{\phi(Z_U) - \phi(Z_L)\}} - \frac{\{\Phi(Z_L) - \Phi(Z_U)\}^2}{\{\phi(Z_U) - \phi(Z_L)\}^2}\right] \tag{13}$$

The probability of being between the limits

$$\frac{\partial[\phi(Z_U) - \phi(Z_L)]}{\partial x_j} = \frac{\beta_n}{\sigma} \cdot \left[Z_L - Z_U\right] \tag{14}$$

Where $\phi(\cdot)$ is the cumulative normal distribution, $\varphi(\cdot)$ is the normal density function, $Z_L = -\beta' X/\sigma$ and $Z_U = (1 - \beta' X)/\sigma$ are standardized variables that come from the likelihood function given the limits of y^*, and σ is the standard deviation of the model. The marginal effects represented by the equations above were calculated by the STATA command mfx, which was complemented by specific options that allowed the estimation of the marginal effects of change in the explanatory variables.

The ratio of the standard error of $u(u)$ to the standard error v (v) known as lambda (), was 2.3802. Based on the value of the lambda, the gamma value is derived using the formula

$$\gamma = \lambda^2/(1 + \lambda^2) \tag{15}$$

3 Results and discussion

3.1 Demographic and socio-economic features

Age is one of the most important factors that determine the management experience of the farmers. The average age of the sample households during the survey period was about 42.24 years. This means that most household heads were within their productive age (Table 1).

Table 2: Descriptive statistics for the continuous variables

Variable description	Mean	Std. Dev.	Min	Max
Age (Year)	42.24	9.35	24	72
Education level (Year)	4.20	3.08	0	12
Family size (No.)	6.19	2.40	1	14
Total Cultivated land (ha)	1.48	0.87	0.25	4.75

Family labour plays an important role in the success of smallholder farming practices. In the study area, the average family size of the sampled households was found to be 6.22 with a minimum of 1 and a maximum of 14 (Table 1). Education is a tool to enhance the quality of labour and hence increase the efficiency of producers. According to the survey results, the average number of years of formal schooling of the sampled farmers was grade 4.20 (Table 1).

3.2 Farm and institutional characteristics

Land use and availability in the study area Land is a scarce resource and the most important factor of production for the rural people of the country in general and the study area in particular. The survey result shows that the mean land owned by the sampled farmers in the study area during the survey period was 1.78 ha. The mean cultivated land was 1.48 ha (Table 1).

Major crops grown in the study area

In the study area, the most important annual crops produced by the sampled households were maize; they produce root crops such as sweet potatoes and Taro/Godere' and fruit crops such as bananas, mangos and papayas (Tilahun et al., 2023). On average, sample households allocated 0.81 ha (57.86%) of the total cultivated land for maize production. Next, sweet potatoes and bananas were from roots and fruit crops that took the largest proportion of the household's total cultivated land covering 0.32 ha and 0.13 ha, respectively. The sample households allocated 0.11 ha and 0.06 ha of the total cultivated land for mangoes and papayas, respectively. Moreover, taro/Godere was a root crop that took a certain share of the household's total cultivated land covering 0.02 ha in the study area (Table 2).

Table 3: Average production of the major crops

Crop types	N	Production (Qt)		Area allocated (ha)	
		Mean	Percentage	Mean	Percentage
Maize	152	23.25	54.24	0.81	57.86
Sweet potatoes	112	7.21	16.81	0.32	20.12
Bananas	88	4.26	9.93	0.13	8.18
Mangos	64	3.57	8.31	0.11	6.92
Papayas	36	2.41	5.61	0.06	3.77
Taro/Godere'	22	0.95	2.21	0.02	1.26

The average production of major crops in quintals in the study area. Given the difference in productivity among crops, sample households on average got 23.25 quintals of maize, which is 54.21% of the total production (Table 2).

Major problems of maize production in the study area

their farming activities. From the problems, weed infection, shortage of fertilizer, shortage of improved seed, labor shortage, soil factors, maize disease, poor land preparation, and seed productivity problems were the major ones. Because of the study shows, soil factors were the main serious problem that farmers were facing followed by maize disease and fertilizer shortage. From the total sample, about 19.74% of respondents reported that they were facing soil factors, while 17.76% were facing maize disease and 13.81% of the farmers were facing fertilizer shortage. In addition, according to information obtained from the sampled respondents, there is a recently occurring disease that affects the yield of their maize crop. As they reported, it needs immediate control. Additionally, 13.16% and 12.50% of the respondents faced seed productivity problems and weed infection, respectively (Table 3). Farmers also reported an improved seed shortage during the peak agricultural production seasons.

Table 4: Major problems of maize production

Variables	Frequency	Percentage
Weed infection	19	12.50
Shortage of fertilizer	21	13.81
Shortage of the improved seed	15	9.87
Labor shortage	11	7.24
Soil factors	30	19.74
Maize disease	27	17.76
Poor land preparation	9	5.92
Seed productivity problem	20	13.16
Total	**152**	**100.00**

3.3 Econometric Model Outputs

3.3.1 Production costs

Like the production function, the mean and standard deviation of each variable used in the cost function along with their contribution to the total cost of production are presented in Table 4. On average, a total cost of 9197.11 birr was required to produce 23.25 quintal of maize. Among the various factors of production, the cost of labor and land accounted for the highest share of 2808.55 birr and 2421.88 birr, respectively. Following the cost of labor and land, the cost of urea, oxen, and NPS takes 1380.62 birr, 1320.32 birr, and 866.19 birr, respectively, out of the total cost of production. Among the total input used to produce maize output, the cost of seed took the smallest share, 380.15 birr (Table 4).

Table 5: Average maize production and its associated costs

Variable	Unit	Mean	Std. Dev.	Min	Max
Output	Quintal	23.25	14.67	5	72
Total cost of production	The birr	9197.11	6201.91	610	35410
Cost seed	The birr	380.15	226.32	99.92	1471.2
Cost land	The birr	2421.88	1438.79	700	7510
Cost NPS	The birr	866.19	553.55	190.3	3015
Cost urea	The birr	1380.62	898.13	262.75	4432
Cost oxen	The birr	1320.32	726.45	360	3440
Cost of human labour	The birr	2808.55	1517.92	634	7830

3.3.2 *Maximum Likelihood Estimation and Stochastic Production Frontier*

Using Maximum Likelihood Estimation (MLE) of the parameters (equation 11) and the Stochastic Production Frontier (SPF) (equation 7) were obtained using the Stata 13 computer program. The results of the ML estimates of the average production function are presented in Table 5. The result of the model showed that, from the total of six variables considered in the production function, four inputs (land, seed, oxen, and labor) had a significant effect in explaining the variation in maize yield among the sampled farmers. The coefficients of the production function are interpreted as the elasticity of the output produced with respect to the input used. If there is a 1% increase in land, amount of seed, number of oxen and amount of labor allotted for maize production, maize output would increase by 0.3190%, 0.2827%, 0.1244% and 0.1574%, respectively, suggesting that maize production was responsive to land, seed, oxen and labor in the study area. This result agrees with the findings of Meftu, 2016; Mustefa et al., 2017; Sisay et al., 2015 . Hence, the increase in these inputs would increase the production of maize significantly as expected. Moreover, the coefficient for land used was 0.3190, which implies that, at meters paribus, a 1% increase in land would result in a 0.3190% increase in maize production. Alternatively, this indicates that maize production was more responsive to land.

Table 6: Estimation of the Cobb-Douglas frontier production function

Variables	MLE Parameters	Coefficient	Std. Err.
Constant	β_0	1.1751**	0.5064
LNSEED	β_1	0.2827***	0.0945
LNLAND	β_2	0.3190***	0.1031
LNPS	β_3	0.0615	0.0704
LNUREA	β_4	0.0900	0.0690
LNOXN	β_5	0.1244*	0.0609
LNLBR	β_6	0.1574*	0.0800
Variance Parameters			
$\sigma^2 = \sigma_v^2 + \sigma_u^2$		0.2306***	0.0512
$\lambda = \sigma_u/\sigma_v$		2.3802***	0.1130
Gamma (γ)		0.850	
Log likelihood		-40.97	
Return to the scale		1.035	

Note: *, ** and *** refer to the 10%, 5% and 1% significance level, respectively.

Return to the scale of all input used in the production process is the measure of the total factor in productivity. The scale coefficient was calculated to be 1.035, indicating increasing returns to scale (Table 5). This implies that there is potential for maize producers to continue to expand their production because they are in stage I of the production surface, where resource use and production are believed to be inefficient. Therefore, a percent increase in all inputs proportionally would increase the total production by 1.035%. This is consistent with the findings of Mustefa, 2014; Solomon, 2012; Tolesa et al., 2019 , who estimated the returns to scale to be 1.0404%, 1.039% and 1.0341% respectively in their studies, which falls in stage I of production surface. The diagnostic statistics of the inefficiency component revealed that sigma squared (2) 0.2306 was statistically significant at 1%. This indicates the goodness of fit, and the correctness of the distributional form assumed for the composite error term.

Based on gamma value estimate, it was shown that about 85% of the variations in the output of maize was caused by technical inefficiency. The remaining 15% variation was due to random noise that was beyond the control of the smallholder farmers.

3.3.3 *Efficiency score of maize producers in the study area*

The mean level of price efficiency of farmers in the study area was 70.9% and ranged from 35.03% to 91.80%, indicating that on average, maize producer households can save 29.1% of their current cost of inputs if resources are efficiently utilized (Table 6). This shows that there is an enormous opportunity to increase the efficiency of maize-producing households by reallocating resources in a cost-minimizing way. For instance, a farmer with an average level of price efficiency would enjoy a cost saving of about 22.77% derived from (1 – 0.709/1.000)*100 to attain the level of the most efficient farmer. The most price-inefficient farmer would have an efficiency gain of 61.84% derived from $\frac{10.3503}{1.000} \times 100$ to attain the level of the most price-efficient household. This result is close to the results of Tukela et al. (2013), Alelign (2017) and Tolesa et al. (2019).

Table 7: Summary statistics of the efficiency score of the sample households

Variable	Observation	Mean	Std. Deviation	Minimum	Maximum
PE	152	0.709	0.110	0.350	91.80

3.3.4 *Distribution of the price efficiency scores*

The price efficiency distribution score shows that 38.82% of the sample households had a price efficiency score between 70 and 79.99%. Households in this group can save at least 20% of their current cost of inputs by behaving in a cost-minimizing manner. About 25.66% of the maize farmers in the study area were operating between the efficiency score of 60 to 69.99% (Fig. 2). Only 1.32% of the total sample households had a price efficiency score above 90%.

This shows that almost all maize-producing households (98.68%) can at least save 10% of their current input cost by reallocating resources in a cost-minimizing way.

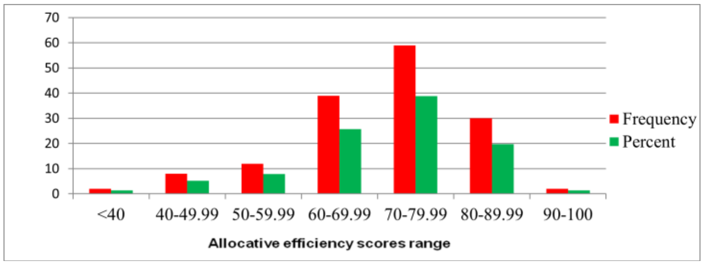

Figure 2: Distribution of price efficiency scores (%)

3.3.5 *Determinants of the price efficiency of maize-producing farmers*

The results of the Tobit regression model showed that among the hypothesized variables, three variables (livestock holding, frequency of extension contact and land fragmentation) significantly influence the price efficiency of smallholder farmers in maize production in the study area.

Livestock holding: The coefficient for livestock holding (TLU) was positive and had a significant influence on PE at the 10% significance level. The result reveals that having the largest number of livestock holdings helps to shift the cash constraint, provide manure and satisfy all the needs of farmers in the study area. Each unit increase in the value of TLU would increase the probability of a farmer being price efficient by 0.238% and the expected value of PE by about 0.398% with an overall increase in the probability and the level of PE by 0.442%. This finding was consistent with the results obtained by Getachew et al., 2017; Kifle et al., 2017; Mustefa, 2014; Saulos, 2015; Solomon, 2012.

Frequency of extension contact: Unfortunately, the frequency of extension contact affects price efficiencies significantly and negatively at a 10% significance level. This might be due to the fact that as a farmer contacted the extension worker frequently, he/she would not have enough time to potentially and appropriately allocate the resources. They are trained to maximize the output of the farmers to solve the problem of food security, and they have limited knowledge for appropriate resource allocation. In addition, during data collection, farmers in the area said that most of the time extension workers did not raise issues specific to agricultural production mechanisms (agronomic practices, post-harvest handling, crop disease control methods, etc.) rather they spent more time in involving on the activities which are not related to their professions or non-farm activities. For instance, health-related issues (construction of toilets, initiating farmers to vaccinate their children, etc.), awareness creation on political issues and collection of loans and taxes. So, there is no new knowledge they got from extension workers regarding agricultural production in order to improve their skills. Generally, these factors would make the efficiency of the farmers to decline. Furthermore, the computed marginal effect indicated that a unit increase in the number of extension contacts would decrease the probability of a farmer being price efficient by 0.094% and the mean value of price efficiency by about 0.156% with an overall decrease in the probability and the level of price efficiency by 0.174%. This result is in line with the previous findings of Ermiyas, 2013; Fetagn et al., 2017; Jema, 2008; Musa H., 2013; Mustefa et al., 2017; Mustefa, 2014 .

The coefficient of land fragmentation for price efficiency is negative and statistically significant at the 10% significance level, as expected. The result confirms the expectation because fragmented land leads to reduced efficiency by creating a lack of family labor, wastage of time and other resources that would have been available at the same time. Moreover, as the number of plots operated by the farmer increases, it may be difficult to manage those plots. Moreover, the computed marginal effect indicated that a unit increase in the number of the plot would decrease the probability of the farmer being price efficient by 0.084% and the mean value of price efficiency by about 0.141% with an overall decrease in the probability and the level of price efficiency by 0.157%. This result agrees with the empirical results of Assefa et al., 2016; Mustefa et al., 2017.

4 Conclusions and recommendations

4.1 Conclusions

By and large, the agricultural sector in Ethiopia is characterized by its poor performance and subsistence orientation. While maize farmers are producing more than ever before, the demand for grain has consistently outpaced the supply. This requires looking for a means to increase the agricultural productivity of smallholder farmers. In this context, the measurement of the existing efficiency in agricultural production and identifying the determinant to seek alternative solutions for these problems becomes paramount. The result of the study shows that, on average, 23.25 quintal of maize was produced at a total cost of 9197.11 birr. Among the factors of production, the cost of labor and land accounted for the highest share, valued 2808.55 birr and 2421.88 birr, respectively. Among the total input used to produce maize output, the cost of seed took the smallest share, which accounted for 380.15 birr. The estimated mean values of the price efficiency levels were 70.9%. Accordingly, as expected, livestock holding had a positive and significant effect on price efficiencies, implying that household heads that had more livestock were more price efficient than the others. Furthermore, the frequency of extension contacts and land fragmentation have negative and significant impact on price efficiency. In all, the present study revealed that maize producers in the study area are not operating at full levels of agricultural efficiency (AE), and there exists considerable room to improve the levels of AE of maize producers in the study area.

Table 8: Tobit model estimates for the determinant of PE and its marginal effects

Variable	PE		Marginal effects (PE)		
	Coefficient	Std. Err	$\frac{\partial E(y)}{\partial x_j}$	$\frac{\partial E(y^*)}{\partial x_j}$	$\frac{\partial[\Phi(Z_U) - \Phi(Z_L)]}{\partial x_j}$
Constant	0.8385***	0.06723	0.00896	0.00759	0.00752
LIVESTSIZ	0.0045*	0.00269	0.00442	0.00398	0.00238
EXTENCNT	-0.0017*	0.00095	-0.00174	-0.00156	-0.00094
LNDFRGMNT	-0.0016*	0.00082	-0.00157	-0.00141	-0.00084

Note: *, ** and *** significant at the 10%, 5% and 1% level of significance, respectively.
$\frac{\partial E(y)}{\partial x_j}$ (Total change), $\frac{\partial E(y^*)}{\partial x_j}$ (Expected change) and $\frac{\partial[\Phi(Z_U) - \Phi(Z_L)]}{\partial x_j}$ (change in probability).

4.2 Recommendations

The results of this study provide information to policy makers on how to minimize the cost of production and improve the efficiencies of farmers in the study area. The following policy recommendations were drawn based on the results of the study.

- Use efficient farmers as benchmarks to set targets, identify weaknesses, and share knowledge through field days, visits, forums, and training.
- Improve livestock production by addressing feed shortages and health services to boost efficiency
- Strengthen extension agents' focus on input allocation, cost minimization, and skill upgrading with better policy support.
- Consolidate fragmented farms and expand household farm sizes through resettlement or off-farm opportunities.
- Go beyond technical efficiency by examining allocative and economic efficiencies to enhance crop performance over time.

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Data Availability

' Data can be made available on the behavior of the request

Declaration of interests' statement

The author declares no competing interests.

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Research Article

Roles of watershed management interventions in enhancing woody plant species diversity and vegetation restoration: Evidence from Ethiopia's Central Highland

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Abstract

Watershed management (WSM) has emerged as a key strategy for rehabilitating degraded lands, conserving biodiversity, and enhancing agricultural productivity in developing countries. However, the contribution of WSM to biodiversity conservation and vegetation restoration has little been assessed in Ethiopia. Therefore, this study aimed to assess the role of WSM in biodiversity conservation and vegetation restoration, using the highly degraded Central Ethiopian Highland region as a case study site. In this study, it was hypothesized that good watershed management enhances woody plant species diversity and restores vegetation. The research involved a comparative analysis of two micro-watersheds: Laga-Gur (well-treated) and Laga-Jaldu (less-treated), which share similar agroecological and biophysical characteristics but differing in degree of management intervention. The study used field vegetation inventory and key informant interview as primary data sources. A total of twenty-four sample plots, each covering an area of 20m * 20m (400m2), were systematically set up along transect lines to evaluate vegetation status. Additionally, subplots measuring 5m * 5m (25m2) and 1m * 1m (1m2) were established within the main plots to inventory shrubs and herbaceous plants, respectively. Data was analyzed using descriptive statistics like frequencies and percentages and inferential statistics like t-test. The comparative analysis of vegetation status revealed that the Laga-Gur watershed (well-treated) had significantly higher overall mean diversity (3.482) and richness (42) and higher evenness (0.774) of woody plant species than the Laga-Jaldu watershed (less-treated) with 2.701, 25, and 0.727 respectively, highlighting the positive impact of watershed interventions on biodiversity conservation. On the other hand, the vegetation community distribution showed the order of seedling < sapling < trees/shrubs in both watersheds indicating the poor vegetation regeneration status in the study area. The study result underscored the significance of watershed management interventions in boosting woody plant species diversity and overall ecological functioning. Therefore, strengthening watershed management initiatives is essential for conserving biodiversity in the central highlands of Ethiopia and other regions of the country.

KEYWORDS: Watershed management; Woody plant species diversity; Vegetation restoration; Vegetation structure

1 Introduction

Watershed management (WSM) is crucial for tackling both economic and environmental challenges in developing nations, as noted in recent studies (Naji et al., 2024a, 2024b; Perez & Tschinkel, 2003). Economically, effective WSM boosts agricultural output, secures sustainable water resources, and supports livelihoods reliant on natural ecosystems (Argaw et al., 2023; Naji et al., 2024b). From an ecological perspective, it helps control soil erosion, enhances biodiversity, and mitigates the effects of climate change by promoting sustainable land-use practices (Arshed et al., 2023; Moges & Bhat, 2020). Due to this, over the past few decades, integrated watershed management has gained prominence in many developing countries as an essential approach for restoring degraded lands, preserving biodiversity, and improving agricultural productivity (Habtu, 2024; C. Zhang & Li, 2016). In sub-Saharan Africa, a region which has been heavily affected by climate change and environmental degradation over the years, watershed management is quite essential (Dinko & Bahati, 2023; Nzeyimana et al., 2023). Effective watershed management promotes sustainable water resource utilization, prevents soil erosion, and boosts agricultural productivity—key factors for ensuring food security in this predominantly agricultural region. Additionally, it supports ecosystem health by maintaining vegetation and biodiversity, thereby reducing communities' susceptibility to environmental risks like droughts and floods. Through integrated strategies that balance environmental preservation with socioeconomic priorities, watershed management plays a critical role in fostering resilience, advancing sustainable development, and tackling persistent environmental issues, like climate change and land degradation, in sub-Saharan Africa (George-Williams et al., 2024; Nzeyimana et al., 2023).

Ethiopia has faced severe land degradation, attributed to factors such as extensive farming, the traditional practice of overgrazing beyond the land's carrying capacity, deforestation, and poor land management (Asnake, 2024; Getahun et al., 2024; Solomon et al., 2024). Research indicates that approximately 23% of the country's total land area is degraded, resulting in a significant loss of revenue from agricultural GDP (Gebreselassie et al., 2016; Kirui & Mirzabaev, 2014; Solomon et al., 2024; S. B. Wassie, 2020). This issue is further aggravated by the population's heavy dependence on rainfed agriculture, underdeveloped water resources, rapid population growth, low levels of economic development, insufficient road infrastructure in drought-prone regions of the country, weak institutions, and a limited capacity to adapt to natural shocks like droughts (Gashu & Muchie, 2018; Muir et al., 2023; Tesfa & Mekuriaw, 2014). This challenge in turn has profoundly impacted the country's socioeconomic foundation, ecological systems, and political resources.

In Ethiopia's highland regions, the rate and intensity of human-induced land degradation are increasing, with vegetation degradation, soil degradation, and water resource degradation being the most common forms (Tadesse & Hailu, 2024). Vegetation degradation involves the loss of species and alterations in vegetation structure (Vásquez-Grandón et al., 2018), while soil degradation pertains to adverse changes in the soil's essential physical, chemical, and biological properties (Ekka et al., 2023). Water resource degradation, on the other hand, describes the decline in water quality and availability due to both natural and human-induced activities. Both natural and human-induced factors have hindered the consistent availability of these critical resources, particularly in many developing nations including Ethiopia (Cao et al., 2022; S. B. Wassie, 2020). Research indicates that poor management of natural resources within watersheds is a significant contributor to land degradation, water contamination, and rural poverty in less developed regions like East Africa (Akhtar et al., 2021; Moges & Bhat, 2020; Mondal & Palit, 2022).

The growing trend of land degradation and its adverse effects on the environment and livelihoods prompted the Ethiopian government to initiate watershed management programs as early as the 1970s (Birhanu et al., 2024; Tefera et al., 2024; Tilahun, 2019). Watershed management serves as a critical strategy to mitigate land degradation, preserve biodiversity, and support sustainable human livelihoods (Habtu, 2024; Mishra & Agarwal, 2024). The ecological goods and services provided by watersheds play a vital role in fostering economic growth and ensuring societal well-being (Retallack, 2021; H. Zhang et al., 2024). In developing countries like Ethiopia, adequate water resources and fertile agricultural lands are essential for boosting agricultural productivity and fulfilling the food requirements of an increasingly expanding population. These necessities can be achieved through maintaining healthy and productive watersheds.

Although WSM theoretically holds significant ecological, economic, and social benefits, its practical implementation and sustainability in Ethiopia, including the current study area, faced numerous challenges related to technical, financial, and institutional factors that require research attention (Mersha et al., 2021; Negasa, 2020; Tesfahunegn & Ayuk, 2021). From a technical perspective, the primary obstacles include inadequate integration of physical and biological soil and water conservation (SWC) measures, insufficient maintenance of SWC structures, limited stakeholder involvement at all levels, absence of clear management plans, lack of technical expertise, and poor collaboration across various sectors (Berlie & Belay Ferede, 2021; Bishaw, 2022; Gebregergs et al., 2021). Additionally, the absence of a clear land use policy or a lack of commitment from local governments to enforce such policies has resulted in continued challenges like steep slope cultivation, free grazing, and overgrazing of land across the country (Solomon et al., 2024; Wayesa et al., 2025). Furthermore, the lack of strong, sustainable institutions to support WSM programs in terms of financial, administrative, and policy matters remains a critical issue (Gebregergs et al., 2021; Naji et al., 2024b). Consequently, comprehensive studies on ecological, socioeconomic, and institutional aspects are essential to raise policymakers' awareness of the socioeconomic and ecological significance of watersheds.

The current study case, Girar Jarso Woreda, is located in the North Shewa Zone of the Central Ethiopian Highlands. Over the past three decades, non-governmental and governmental organizations have implemented watershed management initiatives to rehabilitate degraded lands and improve agricultural productivity in this area. However, the ecological and socioeconomic impacts of these efforts remain insufficiently explored in the current study site. Therefore, the specific objectives of this research are to assess the influence of watershed management on the diversity, regeneration, and structure of woody plant species in the study area. In this study, it was hypothesized that good watershed management enhances the diversity, regeneration, and the structure of woody plant species.

2 Materials and methods

2.1 Study area

The study area, Girar Jarso woreda, is located in the North Shewa zone of Oromia National Regional State which is part of the central Ethiopian highlands. This woreda is situated approximately 112 kilometers from the capital city, Addis Ababa, and consists of 17 administrative kebeles (the smallest administrative unit in Ethiopia). The elevation of Girar Jarso woreda varies from 1300 to 3450 meters above sea level and is geographically located between 09°38'52.8' and 10°00'10.8"N latitude and 38°34'22.8" and 38°50'20.4"E longitude (Figure 1). The total area of the District is about 495 km^2 (Abi et al., 2020).

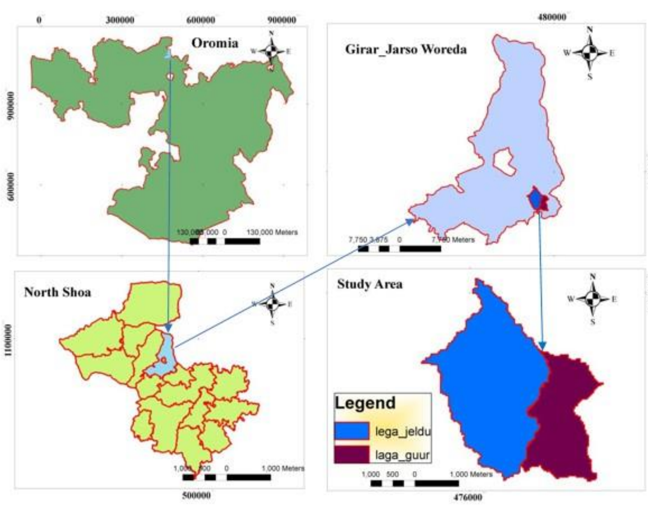

Figure 1: Location map of the study area

The woreda features three primary soil types: Vertisol, Nitosol, and Cambisol, with Vertisol being the most prevalent (Abi et al., 2020). Its agroecology is categorized into three zones— temperate, subtropical, and tropical—based on variations in altitude. The mean yearly temperature varies between 15oC and 26oC. According to data from the Fiche Meteorological Station in the zonal town, the average annual rainfall ranges from 801 mm to 1200 mm. The area undergoes four well-defined seasons: summer from June to August, autumn from September to November, winter from December to February, and spring from March to May. Rainfall exhibits a bimodal pattern, with the primary rainy season taking place between June and August, while a shorter rainy period occurs from March to April. Figure 2 shows the climograph generated for the nearby Fiche Weather Station using MarkSimR DSSAT Weather File Generator Tool which is found at https://gisweb.ciat.cgiar.org/marksimgcm/.

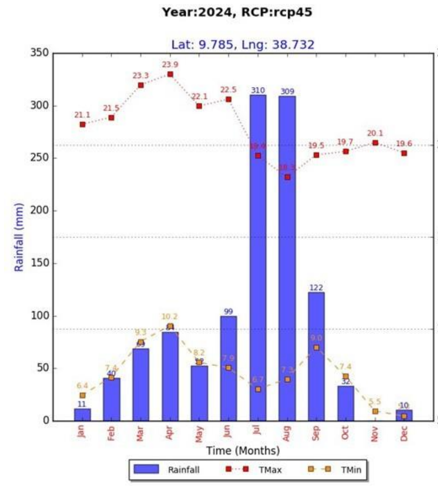

Figure 2: Climograph of the study area

The primary land-use types in the woreda include cultivated land, settlements, and grazing areas. Based on data provided by the Girar Jarso woreda Agriculture Office (GJWAO) in 2020, cultivated land accounts for 79%, settlements for 11%, grazing areas for 3%, and unsuitable land for 8%. Unsuitable areas consist of regions that are inaccessible due to challenging topography, mountainous terrain, and land degradation. The 2022 projections indicated that the overall population of the woreda was estimated to be 94,096, with an approximated density of 190.3 km-2 (Citypopulation, n.d.). Agriculture has been a longstanding and main livelihood practice in the woreda. Rain-fed mixed farming serves as the primary livelihood for over 90% of the population, but agricultural productivity remains low due to significant soil erosion and reduced soil fertility (Abi et al., 2020). Data from GJWAO indicate that most farmers in the studied watersheds engage in subsistence farming systems. The main crops cultivated in these watersheds include wheat, teff ', peas, maize, and beans, while primary vegetable crops consist of onions, tomatoes, and peppers.

From an ecological perspective, the vegetation of the study area belongs to the Afromontane Dry-Evergreen Forest Ecosystems and grassland complex of Ethiopia's vegetation classification (Koricho et al., 2021). However, population pressure has led to extensive deforestation, severely damaging the land's remnant vegetation cover (Gambella Journal of Water, Agriculture and Organization (GJWAO), 2010). The woreda is home to a variety of plant species, including *Acacia tortilis (Forssk.), Acokanthera schimperi (A.DC.) Schweinf, Croton macrostachyus Del., Dichrostachys cinerea (L.) Wight & Arn., Maytenus sensgalensis (Lam) Exell, Ximenia americana L., Cordia africana Lam, Olea europea (subspecies cuspidata), Juniperus procera L., and Hagenia abyssinica (Bruce) J.F. Gmel.*

In the study Woreda, both traditional and modern watershed management methods have been applied since the inception of agriculture. The most commonly applied mechanical SWC structures in the Woreda are stone-faced soil bunds and pure soil bunds. According to the information from key informants, such structures are favored due to their cost-effectiveness, availability of local materials, and their efficiency in minimizing soil erosion. Regarding biological and agronomic SWC practices, crop rotation, vegetative fencing, mulching, area closure, and tree planting has been widely adopted in the Laga-Gur micro-watershed, whereas crop rotation was the predominant agronomic practice in the Laga-Jaldu micro-watershed.

2.2 Data source and types

This research utilized both qualitative and quantitative data, incorporating information from both primary and secondary sources. Primary data was gathered through methods such as forest field inventory, observation checklists, and interview with key informants (KII) selected from farmers and experts. About 15 KIs were selected from the two micro-watersheds. These included five elder farmers (four men and one woman), two community leaders, one development agent, four experts at the kebele level, and three experts from the woreda level. Secondary data sources consisted of both unpublished and published materials, including reports, plans, official records, census information, project documents, and academic research articles.

A set of open-ended guiding questions was prepared to facilitate interviews with key informants (KIs). The questions primarily focused on understanding the perceived role of watershed management in providing ecological and socioeconomic benefits from the perspective of local farmers. To ensure effective communication, the questionnaire was translated into the local language before the interviews.

An observation checklist was developed based on the study objectives to improve the accuracy and consistency of the collected data and frequent field visits were conducted. Simultaneously with the vegetation inventory, careful observations were made regarding actual community involvement, changes resulting from management interventions, challenges encountered, and issues requiring future attention. These observations were thoroughly recorded during fieldwork.

2.3 Vegetation sampling techniques and sample Size

As described by previous studies (Mekonnen et al., 2022; K. B. Wassie et al., 2024; Yigeremu & Woldearegay, 2022) the line transect method was applied, utilizing a systematic sampling approach to gather data on the composition, structure, and rehabilitation status of woody plant species. Six parallel transect lines were established systematically (three in each micro-watershed), approximately 100 meters apart from each other, with four quadrats spaced along each transect. A two-stage sampling technique was applied in each watershed for statistical analysis (with a 95% confidence interval) to accommodate the sample size (Koricho et al., 2021). In total, 24 quadrats (2 micro-watersheds × 3 transects × 4 quadrats) were used for the woody vegetation survey, with 12 quadrats sampled per micro-watershed. Each quadrat measured 20 m × 20 m (400 m²) for tree sampling, with a 50-meter gap between adjacent quadrats (Wassie et al., 2024). Additionally, five 5 m × 5 m (25 m²) subplots for shrub sampling and five 1m * 1m (1 m²) subplots for seedling sampling were established within each quadrat. These subplots were positioned at the center as well as at the four corners of the main quadrat (Yigeremu & Woldearegay, 2022). To avoid the ”edge effect” of the watersheds, the first sampling plot was placed 30 meters away from the boundary (Li et al., 2018; Razafindratsima et al., 2018).

The height (H) and the diameter at breast height (DBH) at 1.3 meters above the ground were recorded for each woody plant using a Sunto clinometer and tape measure, respectively. These measurements were utilized to characterize vegetation structure, including parameters like basal area, dominance, frequency, and importance value index. In each quadrat, trees and shrubs with a diameter at breast height (DBH) of at least 2.5 cm and a minimum height of 3 m were measured and documented (K. B. Wassie et al., 2024). For trees and shrubs with branches, the DBH was measured for each branch and averaged. Individual seedlings, saplings, and trees/shrubs of each species were counted within each plot to evaluate the status of vegetation regeneration. A seedling was described as a woody plant that grows to a height of less than 1 meter, while a sapling referred to a woody plant with a height between 1 m and 3 m (K. B. Wassie et al., 2024). Plant identification was done both at the field and herbarium. The vernacular (local) names of woody species were identified with the assistance of local experts familiar with the forest. Specimens of all plants that were difficult to identify in the field were labeled, prepared, and deposited in the Salale University Botanical Herbarium for further identification with the help of experts. Scientific names were subsequently determined using previously published books like Bekele-Tesemma (2007), Hedberg (1996), and Hedberg and Edwards (1989) . Data collection for this study was conducted during September to February 2023.

2.4 Data Analysis

Prior to analysis, data rarefaction was performed to standardize varying sample sizes. This involved randomly subsampling larger datasets to a uniform sequencing depth, resulting in consistent datasets that enable equitable and reliable diversity estimates. Rarefaction curves were also generated during this process to illustrate diversity trends and evaluate sampling adequacy.

2.4.1 Analysis of vegetation diversity and similarity Indices

The assessment of species diversity in the two micro-watersheds was conducted using the Shannon-Wiener Index (H’), also known as the Shannon Diversity Index, as proposed by Shannon and

Weaver (1949). This index is represented by the following equation (Eq. 1):

$$H' = -\sum_{i=1}^{S} pi\,[\ln(pi)] \tag{1}$$

Where, H⊠ signifies species diversity, while Σ represents summation. S denotes the total number of species, and ln stands for the natural logarithm. Pi refers to the proportion of individuals belonging to the i-th species (ranging from 0 to 1) and is determined using the formula Nn/N. Here, n indicates the number of individuals in a specific species, and N represents the total number of observed individuals.

The Equitability or Evenness Index (J), introduced by Shannon, is calculated as the ratio of the observed diversity to the maximum possible diversity, following the formula given by Shannon and Weaver (1949) (Eq. 2):

$$J = \frac{H'}{H'_{max}} = \frac{H'}{\ln(s)'} \tag{2}$$

In this equation, H' max is represented by ln(S), where J indicates evenness, H⊠ refers to the Shannon-Wiener diversity index, ln(S) is the natural logarithm of the total species count in a community, and S represents the number of species present in each community. Species richness is a particular metric commonly known as Menhinick's index (D) (Menhinick, 1964). Such diversity of woody species was calculated using the formula provided in Eq. 3:

$$D_{Mn} = \sqrt{\frac{S}{N}} \tag{3}$$

In this context, D refers to species richness (calculated using the Menhinick index), S represents the total number of species in the sample, and N signifies the total number of individuals in the sample. The Sorensen Similarity Index (SSI) is calculated to analyze patterns of species turnover between consecutive communities. This index measures the similarity between two habitats and is expressed using the formula provided by Sørensen (1948) (Eq. 4).

$$SSI = \frac{2C}{A + B} \tag{4}$$

Where: A represents the total number of species observed in the first community, B represents the total number of species observed in the second community, and C denotes the total number of species shared by both communities.

2.4.2 *Analysis of vegetation structure*

This research employed species density, relative density (RD), frequency, relative frequency (RF), height class distribution, Importance Value Index (IVI), diameter at breast height (DBH), and basal area (BA) to analyze the structural features of woody plants. The data on the vegetation structure for woody species were computed and summarized in Microsoft Excel sing the formula outlined below as described by (Abunie & Dalle, 2018) (Eq. 5-12).

$$\text{Density} = \frac{\text{Total number of individuals of the species in all quadrats}}{\text{Total number of quadrats studied}} \tag{5}$$

$$\text{RD} = \frac{\text{Number of individuals of the species}}{\text{Number of individuals of all the species}} \times 100 \tag{6}$$

$$\text{Frequency (\%)} = \frac{\text{Number of individuals of the species occurred}}{\text{Total number of quadrats studied}} \times 100 \tag{7}$$

$$\text{RF} = \frac{\text{Number of Occurrence of the species}}{\text{Number of Occurrence of all the species}} \times 100 \tag{8}$$

$$\text{Abundance} = \frac{\text{Total number of individual of species in all quadrats}}{\text{Total number of quadrats in which the species occurred}} \tag{9}$$

The Relative Basal Area (BA) of the woody species was determined using:

$$\text{BA} = \frac{\pi d^2}{4} \tag{10}$$

Where: BA represents Basal Area in square meters per hectare, d is the diameter at breast height in meters, and $\pi \approx 3.14$.

$$\text{Relative Dominance} = \frac{\text{Total basal area of the species}}{\text{Total basal area of all the species}} \times 100 \tag{11}$$

The Important Value Index (IVI) was calculated by summing the Relative Dominance (RDO), Relative Density (RD), and Relative Frequency (RF) following (Kent & Coker, 1992).

$$\text{IVI} = \text{RDO} + \text{RD} + \text{RF} \tag{12}$$

2.4.3 *Analysis of vegetation regeneration Status*

The population structure and regeneration status were evaluated by comparing the ratio of seedlings to saplings, saplings to mature trees or shrubs, and the height class relative to the density of each height category (Mekonnen et al., 2022). Based on this analysis, the regeneration status was classified as follows: "good" when the number of seedlings exceeds saplings, which in turn exceeds mature individuals; "fair" when seedlings outnumber saplings, but saplings are fewer than mature individuals; "poor" when mature individuals outnumber saplings, which in turn outnumber seedlings; "none" if it is not found in both the sapling and seedling stages but is present in the mature stage. It is referred to as "new" when no mature individuals are present, but the species is found in the sapling and/or seedling stages.

3 Results

3.1 Woody species diversity

3.1.1 Floristic Composition

The woody plant species composition, along with their respective genera and family categories in the study area is summarized in Table 1, while a detailed list of species with their scientific and local names is provided in Supplementary Material Table S1. The vegetation inventory revealed a total of 42 species spanning 36 genera and 29 families identified across both micro-watersheds. Specifically, Laga-Gur contained 42 species from 29 families, while Laga-Jaldu comprised 25 species from 20 families. Of these, 25 species (60%) from 20 families were found in both micro-watersheds, whereas 17 species (40%) from 9 families were exclusive to Laga-Gur. This indicates that Laga-Gur has 40% more species than Laga-Jaldu. As detailed in Supplementary Material Tables S2 and S3, Laga-Gur recorded 759 trees, 475 saplings, and 287 seedlings, compared to Laga-Jaldu's 295 trees, 101 saplings, and 43 seedlings. These findings suggest that Laga-Gur's vegetation community has a higher density and greater diversity of trees, saplings, and seedlings compared to Laga-Jaldu. In terms of species count, the Fabaceae family (with 6 species, 14.3%) and the Myrtaceae family (with 3 species, 7.1%) were the most abundant in Laga-Gur. In Laga-Jaldu, in contrast, the Fabaceae family was the most dominant, comprising four species (16%), while Asteraceae and Myrtaceae followed, each represented by two species (8%) (Table 1). The Fabaceae family, known for its high diversity, was represented by six species and three genera in both watersheds (Table 1). Furthermore, approximately 72.4% of the families contained only a single genus and species, meaning that the remaining 41 species were distributed among just 27.6% of the families. Among the dominant tree and shrub species identified, the top five in Laga-Gur were Croton macrostachyus Del., Eucalyptus camaldulnesis Dehnh, Albizia gummifera (J.F. Gmel.)CA.Smith, Carissa spinarum L., and Eucalyptus globulus Labill. In Laga-Jaldu, the leading five tree species were Croton macrostachyus Del., Vernonia amygdalina Del., Acacia abyssinica Hochst. Ex Benth. , Albizia gummifera (J.F. Gmel.)CA.Smith, and Lippia adoensis Hochst.ex Walp.

Table 1: Number of species in different plant families in the study area

Family	Number of species		Total	
	Laga-Gur	Laga-Jaldu	Genera	Species
Acanthaceae	1	1	1	1
Anacardiaceae	1	1	1	1
Apocyanceae	1	1	1	1
Aquifoliaceae	1	1	1	1
Asteraceae	2	2	2	2
Boraginaceae	1	NP	1	1
Celastraceae	2	1	1	2
Cupressaceae	1	NP	1	1
Euphorbiaceae	1	1	1	1
Fabaceae	6	4	3	6
Icacinaceae	1	1	1	1
Loganiaceae	1	1	1	1
Malvaceae	1	NP	1	1
Meliaceae	2	1	2	2
Melianthaceae	1	1	1	1
Moraceae	2	1	1	2
Myrsinaceae	2	NP	2	2
Myrtaceae	3	2	2	3
Oleaceae	1	1	1	1
Phytolaccaceae	1	NP	1	1
Podocarpaceae	1	1	1	1
Proteaceae	1	NP	1	1
Rosaceae	2	NP	2	2
Rutaceae	1	NP	1	1
Salicaceae	1	NP	1	1
Santalaceae	1	1	1	1
Sapindaceae	1	1	1	1
Verbenanaceae	1	1	1	1
Vitaceae	1	1	1	1
Total	**42**	**25**	**36**	**42**

NP = Not present

3.1.2 Diversity and similarity of woody species

The results suggest that the diversity of woody plant species varies between the two watersheds. The values for the Shannon diversity index (H') and Shannon evenness index (E) are presented in Table 2. As shown in the table, the Laga-Gur watershed has a higher Shannon diversity index (H') of 3.482, compared to 2.901 for Laga-Jaldu, suggesting a 20% greater than H' value in the former. Likewise, the Evenness index (E) in the Laga-Gur watershed (0.774) is approximately 7% higher than that in the Laga-Jaldu watershed (0.727).

Sorensen's Similarity Index (SSI) varies from 0 to 1, where a value of 1 indicates complete overlap between plant communities, and a value of 0 signifies no similarity. In this study, the SSI for the two watersheds was 0.507 (Table 2). This suggests that the woody plant species communities of Laga-Gur and Laga-Jaldu are approximately 51% similar and 49% different, meaning about half of the plant species are shared between the two communities.

Table 2: Values of various important vegetation indices in the studied watersheds

Name of Index	Values	
	Laga-Gur	Laga-Jaldu
Total number of seedlings	287	43
Total number of saplings	475	101
Total number of trees/shrubs	759	295
Number of species (Richness)	42	25
Shannon Diversity Index (H')	3.482	2.901
Evenness Index (E)	0.774	0.727
Relative Dominance (RDO)	100	100
Relative Frequency (RF)	100	100
Relative Density (RD)	100	100
Importance Value Index (IVI)	300	300
Sørensen Similarity Index (SSI)	0.507	–

Note: SSI is calculated between the two watersheds, hence only one value is reported.

3.2 Structure and Regeneration of Woody Plant Species

3.2.1 Vegetation structure

I. Density of Woody Plant Species

The density status of woody plant species across plant communities in the two separate watersheds under investigation is as illustrated in Table 3. An independent sample t-test revealed that the average density of trees and shrubs is significantly higher ($p = 0.000$) in Laga-Gur (38.7) than in Laga-Jaldu. Similarly, the mean density of saplings in Laga-Gur is significantly greater (31.2) ($p = 0.037$) than that in Laga-Jaldu. However, while the density of seedlings in Laga-Gur still exceeds by 20.3 than that of Laga-Jaldu, the difference is not statistically significant ($p= 0.138$).

II. Frequency

A summary of the distribution of the most commonly occurring tree species in the study area is provided in Table 4. Carissa spinarum was identified as the most dominant species, present in 92% of the 12 quadrats (11 out of 12) surveyed in the Laga-Gur watershed. Croton macrostachyus followed with an occurrence of 83%, found in 10 of the 12 quadrats. Other frequently observed species included Eucalyptus globulus (75%), Albizia gummifera (67%), and Acacia abyssinica (58%). In contrast, within the Laga-Jaldu watershed, Croton macrostachyus emerged as the most prevalent species, appearing in 83% of the quadrats (10 out of 12). Rhocissus tridentata ranked second with a frequency of 75%, recorded in 9 of the 12 quadrats. Additional common species in this area includes Lippia adoensis (67%), Albizia gummifera (58%), and Vernonia amygdalina (50%).

III. Diameter at Breast Height (DBH) and Height Class Distribution

The DBH of woody plant species was categorized into seven classes, with the number of individuals per hectare for each class illustrated in Figure 3. The field inventory revealed that the first DBH class (DBH ≤ 10 cm) exhibited the highest density of plant communities in both micro-watersheds. The number of individuals per class gradually decreased, as the DBH class size increased, and vice versa. A higher proportion of plants in the smaller diameter class indicate strong regeneration potential in the two micro-watersheds. The DBH class distribution in Laga-Gur displayed a typical inverted J-shape pattern (Figure 3a), reflecting a high regeneration rate due to effective protection from human and livestock disturbances, as well as ongoing conservation efforts. However, while the overall trend was similar, the DBH class distribution in Laga-Jaldu exhibited an irregular inverted J-shape pattern (Figure 3b). This irregularity is attributed to insufficient management interventions, which have exposed the plants to external pressures, thereby limiting their ability to regenerate adequately.

The height of woody plant species reflects their various growth stages (Figure 4). The height class distribution in the Laga-Gur watershed exhibited a pattern similar to that of the DBH class distribution. Most individual plants were concentrated in the lower height class (1–5 m) across both micro-watersheds. For example, in Laga-Gur, 52% of individual plants were within the first height class (≤5 m), approximately 82% fell under the height class of (≤10 m), and the proportion of plants decreased progressively with increase in height class, making an inverted J-shape distribution as shown in Figure 4a. This pattern suggests that vegetation in Laga-Gur benefits from effective management interventions, resulting in robust reproduction and recruitment. Conversely, the trend in Laga-Jaldu differed significantly (Figure 4b). While the majority of trees (46%) were still within the first height class (≤5 m), a notable 47% of plants belonged to the higher height class (≥20 m), and only 5% fell within the intermediate height class (5–10 m). The low percentage of plants in this height class in Laga-Jaldu suggests selective cutting practices targeting individuals at this stage.

IV. Importance Value Index (IVI)

The species having the highest Importance Value Index (IVI) indicate their relative dominance and abundance compared to other species (see Supplementary Material Tables S4 and S5). Based on the IVI calculations, the most prevalent plant species in Laga-Gur are Eucalyptus globulus, Albizia gummifera, and Carissa spinarum, with IVI values of 18.87%, 18.41%, and 18.35%, respectively. In the Laga-Jaldu watershed, the most abundant species are Acacia abyssinica, Albizia gummifera, Croton macrostachyus, and Carissa spinarum, with IVI values of 19.27%, 18.58%, 18.48%, and 18.04%, respectively. Compared to these dominant species, the other species had significantly lower IVI values. Notably, Albizia gummifera and Carissa spinarum recorded the highest IVI values in both watersheds.

Table 3: Species density mean statistics (a) and t-test mean comparison (b) results of different plant communities in Laga-Gur and Laga-Jaldu watersheds

Woody Plant class	Watershed	(a) Mean statistics				(b) t-test mean comparison						95% CI of the difference	
		N	Mean	SD	SE	F	Sig	t	df.	Mean dif.	SE dif.	Lower	Upper
Tree/Shrub	Laga-Gur	12	63.25	8.476	2.447	19.372	0.000	14.815	22	38.667	2.61	33.254	44.08
	Laga-Jaldu	12	24.58	3.147	0.908								
Sapling	Laga-Gur	12	39.58	3.679	1.062	4.949	0.037	26.702	22	31.167	1.167	28.746	33.59
	Laga-Jaldu	12	8.42	1.676	0.484								
Seedling	Laga-Gur	12	23.92	3.423	0.988	2.365	0.138	17.045	22	20.333	1.193	17.859	22.81
	Laga-Jaldu	12	3.58	2.314	0.668								

SD = Standard Deviation, SE = Standard Error, df = degree of freedom, CI = Confidence Interval, N = number of quadrants

Table 4: Frequency of top five most frequently-occurring vegetation species in the study watersheds

Name of specie	No of quadrats	Frequency (%)
(a) Laga-Gur watershed		
Carissa spinarum L.	11	92
Croton macrostachyus Del.	10	83
Eucalyptus globulus Labill.	9	75
Albizia gummifera (J.F. Gmel.) C.A.Smith	8	67
Acacia abyssinica Hochst. Ex Benth.	7	58
(b) Laga-Jaldu watershed		
Croton macrostachyus Del.	10	83
Rhoicissus tridentata (L.f.) Wild & R.B.Drumm.	9	75
Lippia adoensis Hochst. ex Walp.	8	67
Albizia gummifera (J.F.Gmel.) C.A.Smith	7	58
Vernonia amygdalina Del.	6	50

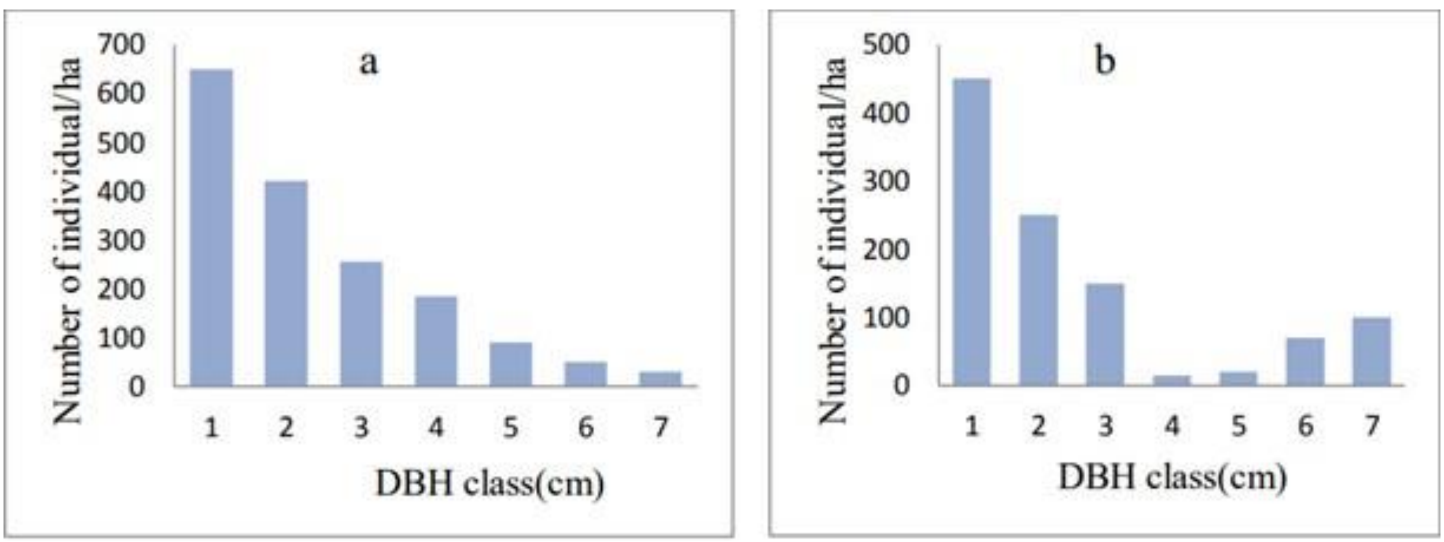

Figure 3: Distribution of individual vegetation by DBH class (cm) in Laga-Gur (a) and Laga- Jaldu (b) (DBH class: 1=2.5-10, 2=10.1-20, 3=20.1-30, 4=30.1-40, 5=40.1-50, 6=50.1-60, 7=60.1-70)

3.2.2 *Vegetation regeneration status*

The total population of plant communities within each vertical vegetation stratum in the study area is illustrated in Figure 5. The species-specific values in detail can be found in the Supplementary Material, Tables S2 and S3. In both micro-watersheds, the overall count of seedlings is smaller than that of saplings, while the total number of saplings is, in turn, fewer than that of trees or shrubs.

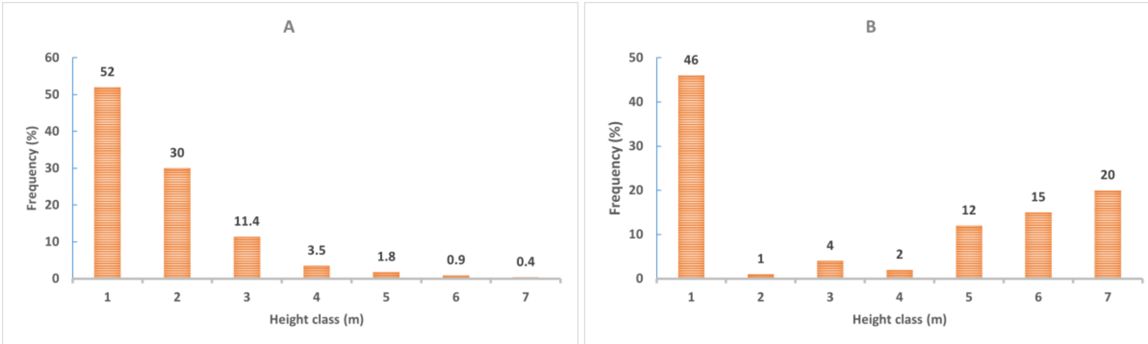

Figure 4: Percentage distribution of trees in height class (m) in Laga-Gur (a) and Laga-Jaldu (b) (Height class: 1 =1-5, 2=5.1-10, 3=10.1-15, 4=15.1-20, 5=20.1-25, 6=25.1-30, 7=30.1-35)

The overall proportions of seedlings, saplings, and trees/shrubs were 16.8%, 29.4%, and 53.8%, respectively. According to criteria from previous studies used to assess vegetation regeneration status, this pattern classifies the study area as having a "poor" regeneration status. However, the proportion of seedlings and saplings in the Laga-Gur micro-watershed is relatively higher than in the Laga-Jaldu micro-watershed (Figure 4), suggesting relatively better regeneration in the former. Tree and shrub species with a "fair" regeneration status include Bersama abyssinica, Dodonea angustifolia, Grevillea robusta, Lepidotrichilia volkensii, and Vernonia amygdalina in Laga-Gur (Figure 6), while only Albizia gummifera and Inula confertiflora exhibits this status in Laga-Jaldu (supplementary material Tables S2 and S3).

4 Discussion

It was found that variation in degree of watershed management intervention has brought effects on vegetation status of the study sites. This study was aimed to assess the impact of watershed management interventions on vegetation restoration by comparing two micro-watersheds in Ethiopia's central highlands. These watersheds share similar agro ecological and biophysical characteristics but differ in the extent of management practices. The findings revealed that key vegetation indices, including Shannon evenness (E), Shannon diversity index (H′), Species richness, population across vegetation strata (trees/shrubs, saplings, and seedlings), and density, were higher in the Laga-Gur watershed compared to the Laga-Jaldu watershed. This variation in woody plant species composition between the two micro-watersheds was attributed to varying management interventions.

Results showed that the number of species in the Laga-Gur micro-watershed was approximately 40% higher than in the Laga-Jaldu watershed. This was due to accelerated species colonization through ecological succession, which was facilitated by a more favorable environment created by improved watershed management practices and heightened community awareness of environmental conservation in Laga-Gur. Area closure has played a crucial role in ecosystem regeneration in Laga-Gur, leading to an increase in woody plant species, improved fodder availability for livestock, enhanced soil fertility, and the creation of habitats for wildlife. Additionally, this initiative has provided significant ecological and economic advantages to the local community. On the other hand, Laga-Jaldu micro-watershed exhibited lower woody plant species diversity due to vegetation degradation caused by deforestation for fuelwood collection, agricultural expansion, overgrazing, and the lack of good soil and water conservation (SWC) practices. The higher species evenness in Laga-Gur indicates a more balanced distribution of species, whereas the lower evenness in Laga-Jaldu suggests the dominance by a few species. This can be attributed to disruptive human activities and the selective removal of valuable plant species without replanting. Since dominance and evenness are typically inversely related, Laga-Jaldu is likely to have lower species diversity compared to Laga-Gur.

Research indicated that watershed management strategies are crucial for preventing ecosystem disasters and conserving natural resources. However, the benefits of rehabilitating degraded land take time to become visible to local communities. In this regard, studies emphasized that watershed management significantly aids in biodiversity conservation and enhances ecological productivity (Luck et al., 2009; Wagley & Karki, 2020). The findings of this research align with that of Asmamaw (2011), who observed that area enclosures supported greater species diversity, evenness, and richness compared to open grazing pastures due to more favorable conditions and reduced disturbances. Similarly, a study in Hawassa Zuria Woreda in southern Ethiopia by Tiki et al. (2015) showed that sustainable soil and water conservation practices improved the composition of woody plant species compared to open-grazing lands lacking such practices. In addition, Yaebiyo et al. (2015) found that well-managed watersheds exhibited higher density and diversity of woody plant species than less treated ones, highlighting the positive effects of integrated watershed management on the recovery of woody plant species. Practical examples also showed that many watershed management programs have been successful in restoring vegetation in degraded areas across Asian countries (Huang et al., 2024; Kang et al., 2024; Tang et al., 2022; C. Zhang & Li, 2016) .

Despite differences between the two watersheds, the Sorensen Similarity Index (SSI) showed that the plant species in both vegetation communities share about 51% similarity. Additionally, based on

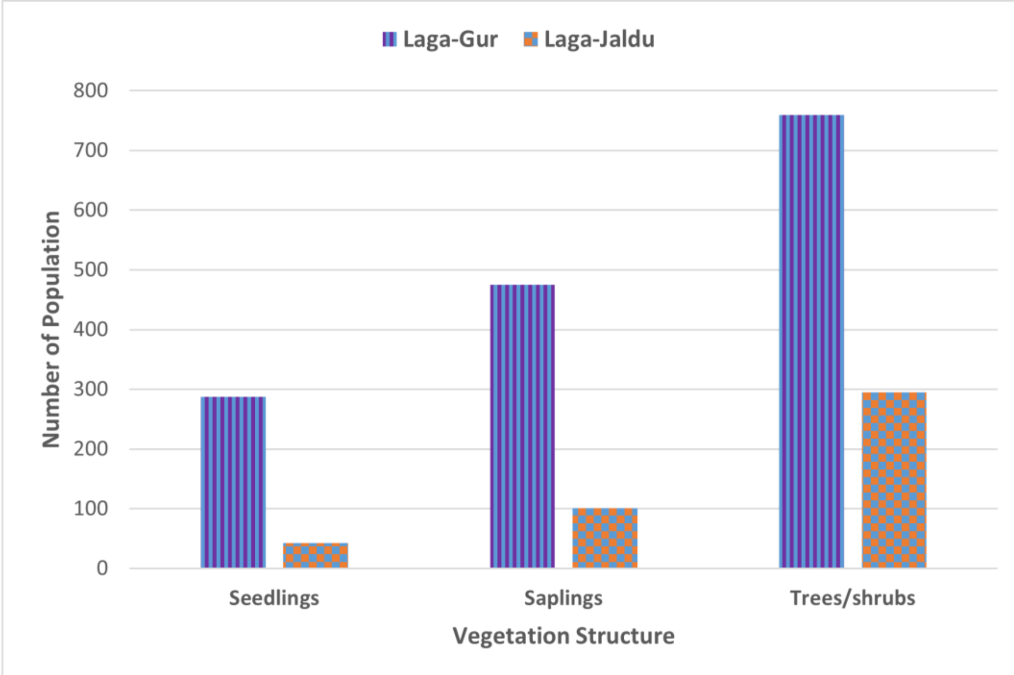

Figure 5: Structural distribution of vegetation community in the study area

the Importance Value Index (IVI), two out of the three most occurring species (Albizia gummifera and Carissa spinarum) were found in both watersheds. Among the top five most prevalent species, Croton macrostachyus and Albizia gummifera were common to both as well. These similarities in woody plant species composition between the two watersheds can largely be attributed to comparable biophysical factors such as climate, geographic location, altitude, and topography (Cheng et al., 2023; Hu et al., 2023; Watanabe et al., 2024). In contrast, the differences are mainly due to varying levels of management and conservation efforts. The greater density, frequency, abundance, and basal area of species in both watersheds are linked to their higher IVI values. Species with lower IVI values in both watersheds need more focused conservation and management, as their numbers and occurrence are comparatively low.

This study's findings indicated that the Fabaceae family exhibited the highest diversity and dominance in species across both micro-watersheds. This aligned with the results of Koricho et al. (2021), who identified Fabaceae as the most dominant tree family

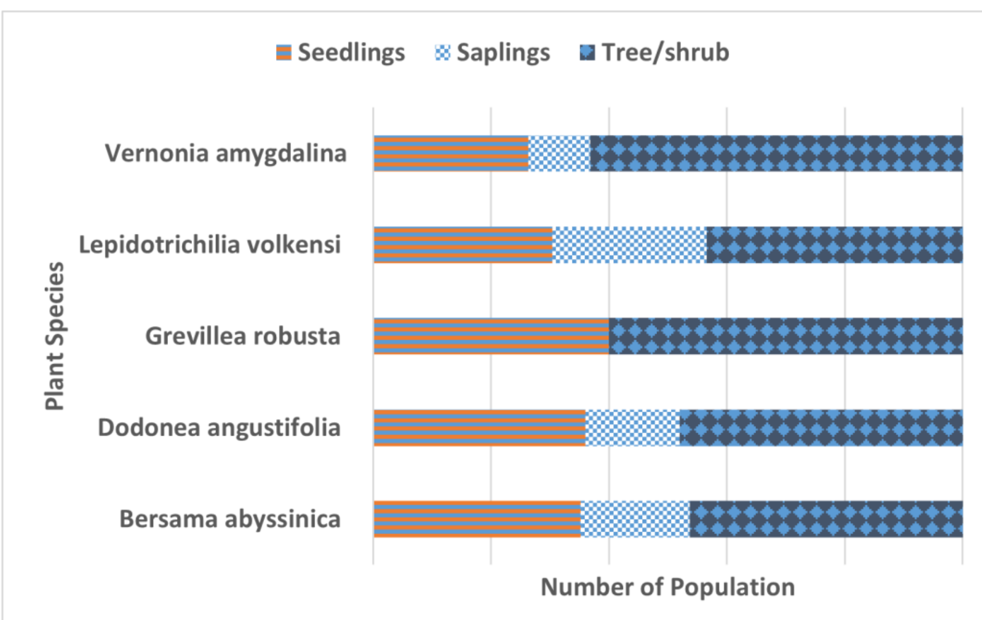

Figure 6: Plant species with 'fair' regeneration status in Laga-Gur micro watershed

in the Debre-Lebanos Monastery Church forest, Gebirehiwot et al. (2023) in the Hurubu natural forest, and Masresha et al. (2023) and Berhanu et al. (2017) in northern Ethiopia. However, concerning individual species status, this study contrasted with the research by Gebirehiwot et al. (2023), which highlighted Calpurnia aurea's strong regeneration and dominance in the nearby Hurubu natural forest located in the Degem Woreda of North Shewa zone. This variation could be due to differences in management strategies and local environmental factors.

Carissa spinarum, one of the species with the highest IVI in this study site, also known as conker berry or bush plum, is a hardy shrub valued for its adaptability to diverse environmental conditions, making it ideal for intercropping systems (Ahuja et al., 2024; Aragaw et al., 2021). Its thorny structure and unsuitability as firewood contribute to its capacity to endure disturbances. Recent research has underscored the importance of underutilized fruit crops like Carissa spinarum in arid and semi-arid regions due to their ease of cultivation, climate resilience, and hardiness (Ahuja et al., 2024; Meena et al., 2022). These qualities position such crops as beneficial for biodiversity, nutraceutical development, medicinal value, and sustainable agriculture (Ahuja et al., 2024; Sharma et al., 2023). Additionally, studies on indigenous fruits in Eastern Africa have highlighted Carissa spinarum's presence across various ecosystems, showcasing its contributions to local biodiversity and its potential for sustainable utilization (Chikamai et al., 2004). Research on tropical fruit trees and climate change further indicated that perennial species like Carissa spinarum possess adaptive traits that enhance their resilience, making them instrumental in promoting sustainable agricultural practices in the face of a changing climate (Aragaw et al., 2021).

Croton macrostachyus, known for its rapid growth and drought resistance, is also a non-palatable to animals. Furthermore, it helps improve soil quality, stabilizes moving sand dunes, restores degraded land, and provides shade for plantations. Similar studies found that Carissa spinarum and Croton macrostachyus were the most frequently occurring tree species in northern Ethiopia (Ayalew & Alemu, 2021; Berhanu et al., 2017), which was consistent with the findings of this study. The results of this study also aligned with those of Woldemariam et al., 2016, who identified Carisa spinarum as a dominant plant species in the Kumuli Forest in southern Ethiopia, and Woldearegay et al., 2018, who reported Albizia gummifera as a dominant species in the Yegof Forest in northeastern Ethiopia.

The distribution of individual plant species across various DBH and height categories in the Laga-Gur watershed displayed an inverted J-shaped curve, in which the number of individual vegetation decreased as the class size increased. In this watershed, mechanical and biological SWC efforts enhanced the regeneration of woody plant species, leading to a more balanced distribution at all stages and supporting natural regeneration. A greater proportion of woody species in the smaller diameter categories indicates better regeneration potential in Laga-Gur micro-watershed. In contrast, the plant population in the Laga-Jaldu watershed showed irregularities, with higher numbers in both the higher and lower height classes compared to the middle classes. This might be attributed to selective wood harvesting or the middle-diameter class being more susceptible to disturbances from livestock grazing. Species showing this trend could face future risks, as individuals might be harvested before reaching reproductive maturity, potentially causing a population decline. These findings were consistent with those of Asmamaw, 2011 , who found that woody plant species in protected areas had an inverted J-shaped distribution for DBH and height classes, while open areas did not exhibit such a pattern.

The results of overall vegetation regeneration status revealed a general order of seedlings < saplings < trees/shrubs in both micro-watersheds. According to criteria established by previous studies for assessing regeneration status, the study area falls under the "poor" regeneration category. This could be attributed to ongoing disturbances in Laga-Jaldu and the extended period required for vegetation recovery in Laga-Gur following management interventions. However, the higher proportions of seedlings and saplings in the Laga-Gur micro-watershed compared to Laga-Jaldu suggest a relatively better regeneration status in the former, likely due to improved conservation efforts and reduced external disturbances. Similar findings have been reported in Ethiopia, where better conservation correlates with enhanced vegetation regeneration. For example, Gebirehiwot et al., 2023 documented a satisfactory regeneration in the Hurubu natural forest, located in a comparable geographic region, but with more effective protection intervention. Other studies (Woldearegay et al., 2018; Woldemariam et al., 2016) observed variability in species reproduction and recruitment, with some species showing strong regeneration while others performed poorly under different degree of management intervention.

5 Conclusion

This research sought to evaluate the effects of watershed management initiatives on vegetation restoration by comparing two neighboring watersheds with different degree of management intervention. Data were collected through both field vegetation surveys and key informant interviews. The findings revealed that watershed management practices have significant potential to promote vegetation regeneration and improve the diversity of woody plant species. For example, key vegetation indices such as Species richness, Shannon evenness index (E), Shannon diversity index (H′), and the number of individuals across various vegetation strata (trees/shrubs, saplings, and seedlings), as well as their density, were higher in the well-managed Laga-Gur watershed compared to the less-managed Laga-Jaldu watershed. In Laga-Gur, the distribution of individual plant species across various DBH and height classes exhibited an inverted J-shaped curve, where numbers decreased as the class size increased. On the other hand, the plant population distribution in Laga-Jaldu appeared irregular, with higher numbers observed in both the lower and upper height classes compared to the middle classes. This indicates that watershed management practices have a positive impact on vegetation restoration. Despite these variations, the Sorensen Similarity Index (SSI) revealed that plant species in both watersheds shared around 51% similarity. Additionally, based on the Importance Value Index (IVI), two of the three most abundant or dominant species, Albizia gummifera and

Carissa spinarum, were common to both watersheds. The study also found that the Fabaceae family was the most diverse and dominant family in terms of species across both watersheds. The overall results regarding vegetation regeneration status indicated a general distribution of seedlings < saplings < trees/shrubs, suggesting that the current study area falls under the "poor" regeneration status category.

This study have limitations as it did not account for other location-specific natural factors, beyond management interventions, that could influence the distribution and occurrence of vegetation species. The data collection was conducted using micro-watersheds as study units, which covered a limited area and hence may not fully represent vegetation species that thrive across a broader agro ecological ranges. Despite such limitations, based on the results of this study, the following recommendations are suggested: Implementing watershed management interventions, such as biological and mechanical soil and water conservation (SWC) methods, are an effective strategy for restoring vegetation and supporting the regeneration of woody plant species in other less-treated watersheds. It is essential to assess and monitor the socioeconomic and environmental outcomes of watershed management practices to identify and implement necessary corrective measures after intervention. The lower Importance Value Index (IVI) for economically important woody plant species, along with the "poor" overall vegetation regeneration status in both micro-watersheds, underscores the need for enhanced conservation and better management approaches. Raising community awareness about sustainable resource use and nature conservation is essential. Furthermore, watershed planning and management should rely on informed decision making, which necessitate additional further research in the future. For instance, further studies related to socioeconomic contribution of watershed management intervention is important to make this study holistic.

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Availability of data and materials

All data generated or analyzed during this study are included in this manuscript [and its supplementary information files].

Competing interests

The authors declare that they have no competing interests.

Ethical declaration

This research was approved by Salale University Institutional Research Ethics Review Committee on 30th January 2024 through the approval Reference Number of SlU-IRERC-CANRS22/25. We confirm that the research was conducted in accordance with the principles embodied in the Declaration of Helsinki and in accordance with local statutory requirements. We also confirm that all participants were given written informed consent to participate in the study. Before starting the data collection process regarding views of key informants, all participants were informed about the study's title and purpose, the procedures involved, the participation being voluntary, potential risks and benefits, the confidentiality of the collected data, and contact information for any further inquiries. Accordingly, participants confirmed their voluntary agreement to participate in the study by signing the consent agreement form.

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Research Article

Smallholder farmers' vulnerability to climate change and variability in Gedeo Zone, Southeastern Rift Valley escarpments of Ethiopia

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Abstract

The Southern Rift Valley escarpments of Ethiopia are highly vulnerable to climate change, with smallholder farmers in the Gedeo Zone disproportionately affected. However, comprehensive studies on these impacts remain limited. This study investigated the socio-economic consequences of farmers' vulnerability to climate-related hazards using mixed methods. Data were collected from 384 farming households. Quantitative data were analysed through descriptive and inferential statistics, specifically the Propensity Score Matching (PSM) model, while qualitative data were examined thematically. Results revealed that 72.65% of smallholder farmers in the study area were highly vulnerable for impact of climate change, with food security and economic stability severely undermined. Although drought and temperature shifts were widely recognized, rainfall variability emerged as the most critical threat among vulnerable households. This heightened sensitivity translated into statistically significant reductions in household income ($p<0.001$), consumption ($p<0.001$), and agricultural production ($p<0.001$) compared to non-vulnerable farmers. Disparities in adaptive capacity were evident, as non-vulnerable farmers had significantly better access to credit and financial resources $p<0.001$) and moderately stronger social networks ($p<0.001$). Both groups, however, faced systemic barriers in accessing information and training. Specifically, vulnerable farmers' income, consumption and production decreased by 40, 19 and 47% ($p<0.001$) respectively lower than no-vulnerable farmers. The study revealed that coffee producing smallholder farmers in the study region are vulnerable to climate change. This calls urgent extension intervention focusing on scaling of accessible, tailored financial services and climate-adaptation funds.

KEYWORDS

Climate Change; farmers; variability; Vulnerability; Gedeo Zone, Ethiopia

1 Introduction

The complex interplay between global climate change and agricultural systems poses profound risks, particularly for smallholder farmers who are central to global food security (Intergovernmental Panel on Climate Change (IPCC), 2021). These farmers, concentrated in developing regions, are disproportionately exposed due to their reliance on rain-fed agriculture, limited resource access, and heightened vulnerability to extreme weather events (Food and Agriculture Organization (FAO), 2018; Müller et al., 2021). In Sub-Saharan Africa, where agriculture is predominantly rain-fed and institutional support remains weak, climate variability intensifies existing challenges of food insecurity and poverty (Abate et al., 2022; Niang et al., 2014). Ethiopia, with its economy heavily dependent on agriculture, is especially susceptible, frequently experiencing recurrent droughts, floods, and erratic rainfall that threaten millions of smallholder livelihoods (Gebreyesus et al., 2023; Tadesse et al., 2021). These shocks undermine food security and erode development gains, perpetuating cycles of poverty (Bedru et al., 2023; Worku and Singh, 2021).

The Gedeo Zone in southern Ethiopia represents a distinctive agro-ecological system, characterized by intensive multi-strata agroforestry dominated by enset and coffee (Dullo et al., 2022; Geda and Kebede, 2016. Despite its ecological richness, the zone faces mounting pressures from climate variability, including shifts in rainfall seasonality, intensity, and temperature, leading to crop failures, soil erosion, and resource degradation (Dullo et al., 2022; Osman et al., 2022. Smallholders, often cultivating small plots with limited access to inputs and credit, are highly sensitive to these impacts (Abate et al., 2022; Alemayehu and Bewket, 2017. Understanding their vulnerability defined by exposure to hazards, socio-economic sensitivity, and adaptive capacity is essential for designing effective, context-specific adaptation strategies (Deressa et al., 2009; Intergovernmental Panel on Climate Change (IPCC), 2021).

Critical resource gaps exacerbate vulnerability in the Gedeo Zone. Farmers lack affordable financial services necessary for investing in adaptive measures, purchasing inputs, or recovering from shocks (Abate et al., 2022; Dullo et al., 2022). This constraint limits adoption of climate-resilient technologies and livelihood diversification, increasing sensitivity to income and production losses (Bedru et al., 2023; Worku and Singh, 2021). Access to improved technologies such as drought-tolerant crops, efficient irrigation, and modern tools remains inadequate (Gebreyesus et al., 2023; Osman et al., 2022). Equally, farmers face deficits in localized climate information, early warning systems, and training in climate-smart practices, which are vital for informed decision-making and resilience building (Gebremariam et al., 2021; Nigussie et al., 2020; Tadesse et al., 2021. Institutional support, though present, is fragmented and under-resourced, limiting the reach of extension services and coordinated adaptation programs (Deressa et al., 2009; Simane et al., 2016).

Infrastructure deficiencies further constrain resilience. Limited market access, storage, and processing facilities reduce profitability, exacerbate post-harvest losses, and discourage production expansion (Dullo et al., 2022; Geda and Kebede, 2016). Moreover, inadequate support for integrated resource management has accelerated soil erosion, fertility decline, and water scarcity, intensifying climate-related risks (**osman2022smallholde**; Intergovernmental Panel on Climate Change (IPCC), 2021). Addressing these systemic gaps through targeted interventions, stronger institutions, and community empowerment is critical for fostering sustainable, climate-resilient livelihoods.

Although numerous studies have examined climate vulnerability among Ethiopian smallholders, disaggregated analyses within distinct agro-ecological zones such as Gedeo remain limited (Molla et al., 2020; Simane et al., 2016. Existing research generalizes vulnerability, overlooking intra-regional differences in socio-economic conditions, adaptive capacities, and livelihood outcomes (Gebremariam et al., 2021; Nigussie et al., 2020). Rigorous quantitative assessments that identify and measure drivers of vulnerability and their differential impacts on household income, consumption, and production are scarce (Tadese et al., 2020; Worku and Singh, 2021). Such granular insights are essential for moving beyond broad generalizations and informing precise, contextually relevant policy interventions (Bedru et al., 2023).

This study addresses these gaps by conducting a localized, comparative assessment of smallholder vulnerability to climate change in the Gedeo Zone. It systematically examines exposure, sensitivity, and adaptive capacity, differentiating vulnerable from non-vulnerable households through robust statistical analyses (Mean, Standard Deviation, T-value, p-value). The research quantifies disparities in socio-economic conditions and adaptive capacities, while measuring the direct impacts of vulnerability on household income, consumption, and agricultural production. Findings are expected to provide strong empirical evidence and actionable insights for targeted policy design, localized adaptation planning, and efficient resource allocation, thereby enhancing resilience and livelihoods in the Gedeo Zone and contributing to broader climate adaptation discourse.

2 Materials and methods

2.1 Description of study area

This study was carried out in selected districts within Gedeo Zone, Southern Ethiopia Regional State. Geographically, the Zone is located north of the equator from 5°53'N to 6° 27'N latitude and from 38° 8' to 38° 30'east longitude (Negash, 2010). On the main highway from Addis Ababa to Moyale towards Kenya, 365 kilometers from Ethiopia's capital city Addis Ababa. Slope gradient reaches up to 70% in some areas and almost 50% of the landscape is steep, with slope gradient above 10% (Mesele, 2011; Meteorological Climate and Technical Agency (MCTA), 2020). The majority of the soil type in the area is nitosol (Abiyot, 2013), typically made up of volcanic rocks. The Zone has three agro-ecological zones whose mid altitude agro-ecology occupies the largest area (62.2%) followed by high land (37.1%) and low altitude (0.7%) (Bogale, 2007). The study districts, namely Kochore, Yirgachefe and Wonago are one of the districts in the Gedeo Zone SNNPRS (Figure 1). Kochore district is found between 6'09' N latitude and 38'16'E longitude. Elevations range from 1,500 to 3,100 meters above sea level (masl), and the study area comprises two agro-climate zones: Dega (with elevations between 2,300 and 3,700 masl, accounting for 26%) and Weyna Dega (ranging from 1,500 to 2,300 masl, constituting 74%) according to Yibrah (2014). The average annual temperature falls between 25°C and 31°C, while the annual rainfall ranges from 1,000 to 1,200 millimeters.

Yirgachefe district is located between 6°09'N and 6°32'N and 38°08'E and 38°32E, with an altitudinal range of 1501–2500 masl (Negash, 2007). The annual rainfall ranges between 1200 and 1800 mm, with a bimodal distribution, and the mean annual temperature varies from 15°C to 20°C (Asnake, 2021). Wonago district is found between 6°20'E and 6°32'E, and 38°14'N and 38°24'N, with an undulated type of landscape and an altitude ranging from 1601 to 2875 masl. The district receives rainfall of 800 to 1400 mm per annum and annual temperatures ranging from 11°C to 29°C (Negash, 2007). All study districts are categorized as mid and highlands based on elevation, with a range of 1500–3700 masl.

2.2 Site selection

The study focused on three districts Kochere, Yirgachefe, and Wonago purposefully selected to capture the dimensions of vulnerability related to climate hazards, socio-economic sensitivity, and adaptive capacity. These districts lie within the coffee-producing belt of the Zone, where indigenous agroforestry practices are highly prevalent. From each district, three kebeles were randomly chosen: two from the midlands and one from the highlands, yielding a total of nine kebeles (six midland and three highlands). Specifically, Jeldo and Anchabi (midlands) along with Gololicha (highland, representing Woina dega and dega) were selected in Kochere. In Yirgachefe, Tutit and Wote (midlands) and Udesa (Woina dega) were included. Similarly, Deko and Hase Haro (midlands) and Wotiko (Woina dega) were chosen in Wonago. This stratified selection ensured representation across agro-ecological zones, thereby enabling a comprehensive assessment of smallholder vulnerability within the study area.

2.3 Research Design

A research design outlines the procedures for achieving research objectives and testing hypotheses (McDaniel & Gates, 2006). This study employed an explanatory research design to investigate how vulnerability components (independent variable) affect smallholder farmers' farming practices (dependent variable).

2.4 Research Approach

To achieve the study's objective, researchers used a mixed research approach, combining quantitative and qualitative methods. Quantitative data were collected via structured questionnaires from smallholder farmers, addressing vulnerability components like exposure, sensitivity, and adaptive capacity. Qualitative data were gathered through in-depth interviews and focus group discussions with a subset of the surveyed farmers. This comprehensive approach aimed to provide a deeper understanding of farmers' vulnerability.

2.5 Data type and sources

This study utilized both primary and secondary data. Primary data were collected through household surveys, key informant interviews, and focus group discussions. Secondary data were gathered from government reports, academic journals, published and unpublished materials, and websites.

2.5.1 Sampling techniques and sample size determination

Multiple-stage stratified sampling methods were used in the study. First, districts were selected due to high climatic change and variability. Second, the district is grouped by their agro-ecology (strata) on the basis of their elevation, where 1500–2300 masl is midland and above 2300 masl is high land. Third, kebeles were chosen from each agro-ecology stratum for data uniformity, and finally, households were randomly selected from selected kebeles using proportional sampling. The sample size of sampled households was determined following Yamane (1967) sampling techniques. The number of respondents included in the study was as follows:

$$n = \frac{N}{1 + N\ (e)\ 2} = n = \frac{9662}{1 + 9662\ (0.05)\ 2} = \frac{9662}{25.155} = 384 \quad (1)$$

Where n, N and e represent the sample size (number of respondents), total number of households and level of precision (allowable error, 5%), respectively. For sample size allocation at kebele level the proportional allocation formula was used as

$$ni = \frac{Ni\ x\ n}{N} \quad (2)$$

Where; ni = the sample size proportion of each kebele, Ni= the population proportion in the stratum (kebeles), n= the sample size of the districts and N = the total population of the districts.

2.6 Data collection methods

Surveys: Structured questionnaires administered to smallholder farmers involved demographic information, vulnerability components and socioeconomic conditions of farmers.

Key informants' interviews: To gather insights on the vulnerability of smallholder farmers in the Gedeo zone, key informants were selected based on knowledge or experience in agriculture, climate resilience, or rural development related to smallholder farming. individuals with direct experience working with smallholder farmers, such as extension workers, agricultural officials, and NGO staff

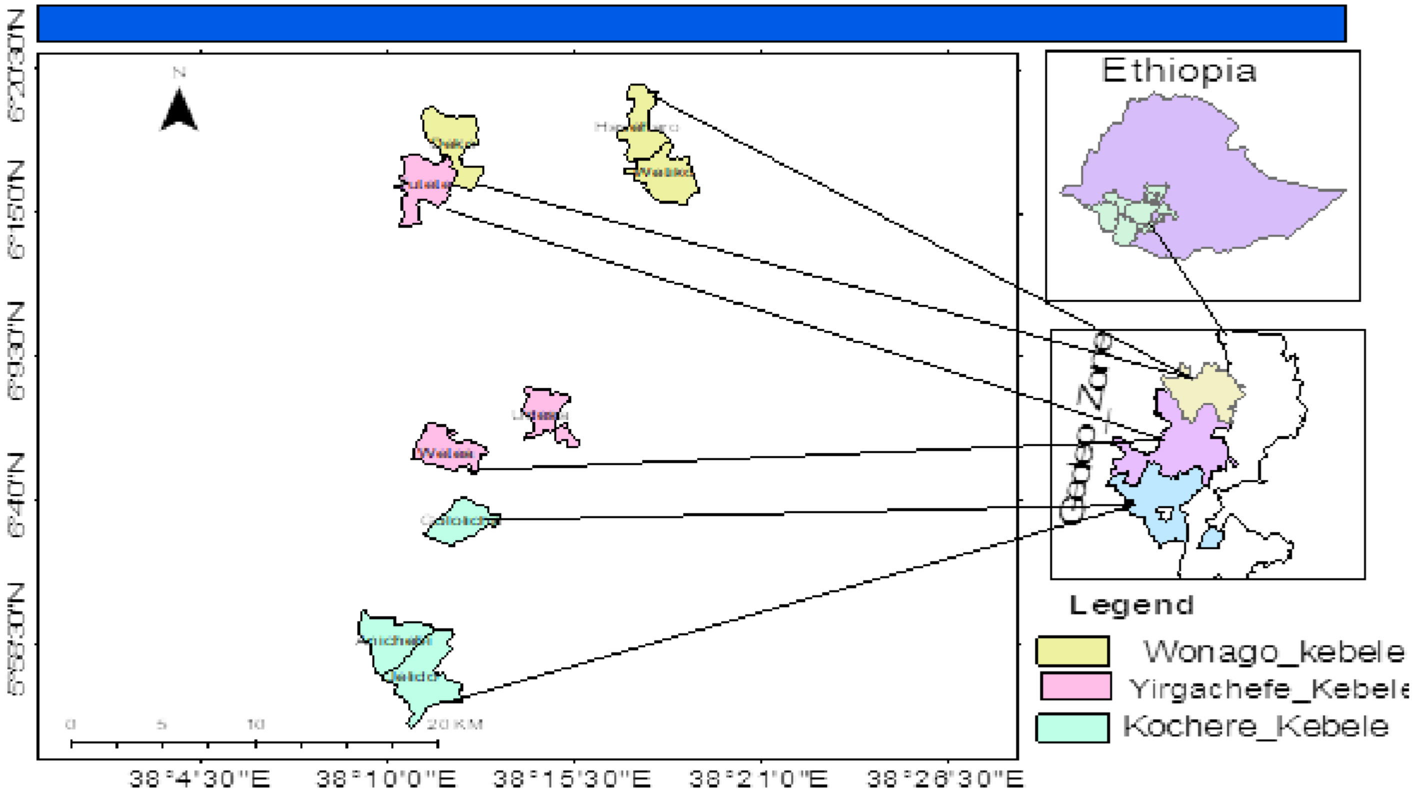

Figure 1: Location map of study area

Table 1: Total household and sample size of the study area

Name of districts	Name of Kebeles	Total households	Sampled households	
			Numbers	Percentage
Kochere	Jeldo	1073	43	11.19
	Anchabi	1024	41	10.79
	Gololcha	1253	50	13.02
Yirgachefe	Tutit	801	32	8.33
	Wote	970	39	10.15
	Udesa	1014	40	10.41
Wonago	Deko	1002	40	10.41
	Hase Haro	880	35	9.11
	Wotiko	1645	64	16.66
Total	**9**	**9662**	**384**	**100**

were preferred. Informants were to understand the local socio-economic context and agricultural challenges in the region. The selection included a diverse range of stakeholders, including farmers, community leaders, policymakers, researchers, and NGO representatives to ensure varied perspectives. We conducted 15 key informant interviews to gather diverse insights in a manageable manner, ensuring a rich data set for analysis. These interviews' perceptions about the vulnerability of farmers derived from climate change and variability engaged in this practice (Yin, 2018) .

Focus Group Discussions: focus groups discussions were conducted with smallholder farmers. Farmers who provided rich qualitative insights into the vulnerability of farmers derived from climate change and variability. The discussions were undertaken with 9 groups' of farmer's i.e. one group from each kebele. One group consists of 8 to 12 members

2.7 Methods of data analysis

The analysis and presentation of the study was both quantitative and qualitative. Quantitative data obtained through structured questionnaire were analyzed by descriptive statistics (such as frequency, percentages, means, Chi-squares and p-values) and inferential statistics specifically, multivariate probit regression model with the help of STATA software version 15.0. Qualitative data obtained through interviews and focus group discussions were analyzed thematically.

2.7.1 Measures of farmers Vulnerability to climate change and variability

Vulnerability of smallholder farmers was measured by exposure, sensitivity, and adaptive capacity of smallholder farmers. The vulnerability of a household Vi can be expressed mathematically as:

$$V_i = f(E_i, S_i, A_i) \quad (3)$$

Where:

V_i : Vulnerability of household i

E_i : Exposure of household i

S_i : Sensitivity of household i

A_i : Adaptive capacity of household i

Exposure: This refers to the degree to which farmers are subjected to climate-related hazards such as drought frequency, flood incidence, rainfall variability, temperature changes, impact on crop yields, livestock health and soil erosion.

Thus, the researcher can represent exposure as:

$$E_i = f(D_{\text{freq}}, R_{\text{var}}, T_{\text{chang}}) \quad (4)$$

Where,

D_{freq} : Drought frequency

R_{var} : Rainfall variability

T_{chang} : Temperature changes

Sensitivity: This indicates how susceptible farmers are to these hazards based on their socio-economic conditions. It reflects how changes in drought impact income, Food Security, and production. Thus, sensitivity can be represented as:

$$S_i = f(\text{Inc, FS, Prod})$$

Where,

Inc = households income

FSI = households food Security

Prod = households production

Adaptive Capacity: This reflects the ability of farmers to adjust their practices in response to changing conditions. It reflects farmers' Access to Information, Financial Resources, Social Networks, Training and Education, Access to Technology, Institutional Support and Community Engagement to adjust their practices in response to climate change impacts. Thus, Adaptive Capacity can be represented as:

$$AC_i = f(\text{Ainf, FR, SN, TE, Atech, IS, CE})$$

Where,

Ainf = Access to Information

FR = Financial Resources

SN = Social Networks

TE = Training and Education

Atech = Access to Technology

IS = Institutional Support and

CE = Community Engagement

2.7.2 Methods of characteristics of farmers vulnerability to climate change and variability

Vulnerability of smallholder farmers were characteristics based computed mean scores as 1.00 - 1.49 = very low, 1.50 - 2.49 = low, 2.50 - 3.49 = medium, 3.50 - 4.20 = high and 4.21 - 5.00 = very high. Accordingly, vulnerable farmers are those farmers exposed to different risks while non vulnerable farmers are relatively not vulnerable due to their adaptive capacity.

2.8 Model specification

Propensity Score Matching (PSM) Model: Investigating the impact of farmers' vulnerability to climate-related hazards on their socio-economic conditions

Propensity Score Matching (PSM) is a statistical technique used to control confounding variables when estimating the effect of a treatment or intervention. The core idea is to estimate the probability (propensity score) of receiving the treatment based on observed covariates and then match treated and untreated subjects with similar propensity scores. The derivation of the

The propensity score e(X) is defined as the conditional probability of receiving treatment given a set of observed covariates X:

$$e(X) = P(T = 1|X) \quad (5)$$

Where T is the treatment indicator (1 if treated, 0 otherwise)

After estimating the propensity scores using logistic regression or other methods, treated units are matched with control units that

Table 2: Variables definition and measurement

Variables	Variables Definition	Variables measurement
	Treatment Variable (FVCH)	
Farmers' vulnerability to climate-related hazards (FVCH)	Farmers' vulnerability to climate-related hazards (FVCH) refers to the degree to which a farming household is susceptible to, and unable to cope with	Binary (1 if Farmer's were vulnerable to climate-related hazards; 0 otherwise)
	Outcome Variables	
Households income	Total income generated by the household	Continuous (Monetary units, ETH Birr per year)
Households consumption	Total consumption expenditure of the household	Continuous (Monetary units, ETH Birr per year)
Households production	Total quantity of agricultural produce harvested by the household	Continuous (Kilograms per year)
	Independent Variables (Covariates)	
Age	Age of Household Head	Continuous (Years)
Gender	Gender of Household Head	Binary (1 = Male, 0 = Female)
household size	Number of members	Continuous
Total Farm Size	Total cultivated land area managed by the household	Continuous (Hectares)
Farming Experience	Number of Years Farming Experience of the household head	Continuous (Years)
Agro-ecological Zone	The specific agro-ecological zone where the farm is located	Categorical(1=Dega (highland), 2=Weina Dega (midland), 3=Kolla (lowland)
Initial Climate Exposure	Pre-existing conditions that might drive the need for adaptive capacity.	Ordinal scale (e.g., 1=Very Low, 5=Very High)
distance to the nearest market	Accessibility influences input costs and market access for outputs.	Continuous (Kilometers)
Climate Risk Perception	Household head's subjective assessment of the severity of climate change impacts	Ordinal Scale (e.g., 1=Low to 5=Very High)

have similar scores. This can be done using various matching techniques such as nearest neighbor matching, caliper matching, or kernel matching . Outcome Estimation: The average treatment effect on the treated (ATT) can be estimated as:

$$ATT = E[Y(1)|T = 1] - E[Y(0)|T = 1] \quad (6)$$

Where $Y(1)$ is the outcome for treated units and $Y(0)$ is the outcome for matched control units (Imbens, 2009).

Hypotheses of the study

Farmers' Vulnerability to Climate-Related Hazards (FVCH)

Null Hypothesis (H0): There is no significant relationship between farmers' vulnerability to climate-related hazards and household income, consumption, and production.
Alternative Hypothesis (H1): There is a significant relationship between farmers' vulnerability to climate-related hazards and household income, consumption, and production. Studies have shown that increased vulnerability to climate-related hazards negatively impacts agricultural productivity and household income (Mastrorillo et al., 2016) .

Household Income

Null Hypothesis (H0): Household income is not significantly affected by farmers' vulnerability to climate-related hazards.
Alternative Hypothesis (H1): Household income is significantly affected by farmers' vulnerability to climate-related hazards. Research indicates that vulnerable households often experience reduced income due to lower agricultural yields and increased costs of adaptation.

Household Consumption

Null Hypothesis (H0): Household consumption expenditure is not significantly influenced by farmers' vulnerability to climate-related hazards.
Alternative Hypothesis (H1): Household consumption expenditure is significantly influenced by farmers' vulnerability to climate-related hazards. Vulnerable households may increase consumption expenditures to cope with climate impacts, leading to higher overall consumption costs (Alderman Haque, 2006).

Household Production

Null Hypothesis (H0): There is no significant relationship between farmers' vulnerability to climate-related hazards and the total quantity of agricultural produce harvested.

Alternative Hypothesis (H1): There is a significant relationship between farmers' vulnerability to climate-related hazards and the total quantity of agricultural produce harvested. Vulnerability to climate change can adversely affect crop yields, thereby reducing overall agricultural production.

3 Results

3.1 Characteristics of farmers' vulnerability to climate-related hazards

Based on the vulnerability index analysis, there was a significant level of vulnerability among farmers to climate-related hazards, with 72.65% of respondents were vulnerable and 27.35% of respondents were none vulnerable to impact of climate change (Table 3). Most vulnerable farmners justified that they felt the impacts of climate change due to recurrent droughts, floods, and changing weather patterns, which undermine their food security and economic stability.

Table 3: Proportion of extent of farmers vulnerability status in the Gedeo Zone, Southeastern Rift Valley escarpments of Ethiopia

Farmers' vulnerability to climate-related hazards	Frequency	percent
Vulnerable farmers	279	72.65
Non-vulnerable farmers	105	27.35

3.2 Characterization of farmers climate-related hazards (Exposure) among vulnerable and none-vulnerable farmers

The results presented in Table 4 provide significant insights into the exposure to climate-related hazards among vulnerable and non-vulnerable farmers.

Drought Frequency: Vulnerable farmers reported a mean drought frequency of 3.83, classifying their perceived exposure as high, accompanied by a standard deviation of 0.79. In contrast, non-vulnerable farmers perceived drought frequency as medium with a mean of 2.51 and a standard deviation of 0.64. Despite notable difference in intensity, the Chi-square test (Chi2 = 19, p = 0.415) indicated no statistically significant difference between the two groups concerning drought frequency, suggesting that though vulnerable farmers sense the impact more intensely, the occurrence of drought events is generally pervasive across the farming community.

Flood Incidence: Both vulnerable and non-vulnerable farmers perceived flood incidence as medium, with means of 3.07 (Std. Dev. = 0.63) and 2.82 (Std. Dev. = 0.59) respectively. However, no statistically significant differences were reported between the two groups regarding their perceived exposure to floods. This suggests that floods, like droughts, are experienced across the community without a distinct perception gap between vulnerable and non-vulnerable farmers in terms of their occurrence. The medium perception indicates that while floods are a concern, they might not be as overwhelmingly frequent or impactful as other hazards for these farming communities.

Rainfall Variability: There was a tendence of differences on perceived responses on rainfall variability between vulnerable and non-vulnerable farmers (Chi2 = 23, p = 0.076), showing that rainfall variability is a profoundly impactful and differentiating factor for vulnerable farmers. This also makes it the highest perceived exposure indicator for vulnerable groups, highlighting their acute sensitivity to unpredictable rainfall patterns.

Temperature Changes: Both vulnerable and non-vulnerable farmers perceived temperature changes as high, indicating that the rising in temperatures are a universally perceived challenge within the farming community, irrespective of their vulnerability status. The respondents indicated that they observed the impact of high temperature on their crops, livestock, and overall farming systems.

Soil Erosion: Vulnerable farmers reported a mean score of 3.3 (high), while non-vulnerable farmers had a mean of 2.94 (medium), although the difference was not significant (Chi2= 2.7, p= 0.393)

3.3 Characterization of farmer's socio-economic conditions among vulnerable and non-vulnerable farmers

In-depth analysis of key socio-economic indicators (income, consumption, and production) that reflect the sensitivity of vulnerable and non-vulnerable farmer groups to external shocks, particularly climate-related hazards were conducted (Table 5). Household Income: There was significant difference between non-vulnerable and vulnerable farmers in terms of income ($p<0.001$). The mean household income of non-vulnerable farmers was 40% higher than the vulnerable farmers (Table 5), showing that non-vulnerable farmers possess considerably greater financial resources, which inherently reduces their sensitivity to economic shocks and allows for more robust adaptive capacity.

Household Consumption: The non-vulnerable farmers consumed by 19% higher than vulnerable farmers, which was significant ($p<0.005$), indicating a substantial difference in consumption levels between the two groups. Higher consumption levels among non-vulnerable farmers suggest better food security, improved nutritional status, and greater overall well-being. This in turn signifies lower sensitivity to economic and food system disruptions.

Household Production: Non-vulnerable farmers recorded a mean household production was by 47% higher than vulnerable farmers with significant variation ($p<0.001$). The marked differences show

Table 4: Perceived responses of farmers on climate hazards (Exposure) in the Gedeo Zone, Southeastern Rift Valley escarpments of Ethiopia

Exposure Indicators	Vulnerable (n-279)		Non-vulnerable (105)		Statistical value	
	Mean	Std. Dev.	Mean	Std. Dev.	Chi^2	p-value
Drought frequency	3.83	0.79	2.51	0.64	19	0.415
Flood incidence	3.07	0.63	2.82	0.59	4	0.133
Rainfall variability	4.24	0.86	3.75	0.72	23	0.076
Temperature changes	3.90	0.75	3.53	0.611	18	0.0952
Soil erosion	3.3	0.73	2.94	0.78	2.7	0.393

Table 5: Mean annual income (Ethiopian Birr), consumption (kg) and production (kg) of the studied vulnerable and non-vulnerable farmers in Gedeo zone, Southeastern Rift Valley escarpments of Ethiopia

Sensitivity Indicators	Farmers' vulnerability vulnerable (n-279)		Non-vulnerable (105)		Statistical value	
	Mean	Std. Dev.	Mean	Std. Dev.	Chi^2	p-value
Households' income	2699.77	0.67	4485.48	0.84	20	0.000
Households' consumption	2539.75	0.88	3128.29	0.83	21	0.000
Households' production	527	0.82	986	0.95	14	0.000

non-vulnerable farmers are substantially more productive, translating into greater self-sufficiency, higher market surplus, and reduced sensitivity to market and climate-induced production shortfalls.

3.4 Characterization of farmers ability to adjust climate related hazards (Adaptive Capacity) among vulnerable and non-vulnerable farmers

Results of the adaptive capacity indicators of vulnerable and non-vulnerable farmers in relation to their ability to adjust to climate-related hazards are shown in Table 6.

Access to Information: Both vulnerable and non-farmers perceived they received medium level of access to information, no significant differences were observed (P>0.05). suggests that access to relevant agricultural, climate, and market information remains a general challenge across the farming community, affecting both vulnerable and non-vulnerable farmers similarly in terms of perceived availability. The lack of significant difference implies that systemic issues in information dissemination or reception play, rather than a specific discriminatory barrier for the vulnerable.

Access to Credit Services: Non-vulnerable farmers perceived significantly high credit access compared to the non-vulnerable farmers (p<0.001). This significantly better access to credit for non-vulnerable farmers provides them with crucial financial flexibility to invest in adaptation measures, purchase inputs, or recover from shocks, thereby enhancing their adaptive capacity.

Financial Resources: Vulnerable farmers perceived their financial resources significantly lower compared to non-vulnerable farmers (p<0.001), showing that non-vulnerable farmers possess significantly greater financial capital. This stark difference directly impacts their ability to respond to climate shocks, invest in long-term adaptation measures, or cope with unexpected expenses.

Social Networks: Non-vulnerable farmers had significantly higher social networks compared to vulnerable farmers (p<0.001). While social networks are important for both groups, non-vulnerable farmers might more benefit from more extensive, diverse, or influential networks that provide enhanced access to information, labor, or collective action.

Training and Education: Both vulnerable and non-vulnerable farmers perceived their access to training and education as medium, no significance differences were reported. Similarity to access to training and education suggests more accessible agricultural and climate-related training and education for all farmers, irrespective of their current vulnerability status

Access to Technology: As expected, non-vulnerable farmers perceived significantly more access to technology than vulnerable farmers (p<0.001). However, the fact that both groups recorded low to medium scores, showing that technological access remains a general constraint, but is particularly acute for the vulnerable.

Institutional Support: Vulnerable farmers perceived their access to institutional support as medium (Mean = 3.11, Std. Dev. = 0.72), while non-vulnerable farmers reported slightly lower, also medium, access (Mean = 2.96, Std. Dev. = 0.67), but the difference was significant (p>0.001). This counter-intuitive finding suggests that vulnerable farmers, being the primary target of many government and non-governmental aid programs (e.g. Productive Safety Net Programme in Ethiopia), might be more aware of or actively engaging with these support systems, leading to a higher perceived access. It doesn't necessarily imply that the support received is sufficient to lift them out of vulnerability, but rather that they are more connected to existing institutional mechanisms.

Community Engagement: Vulnerable farmers perceived their community engagement significantly higher compared to non-vulnerable farmers ($p<0.001$), implying that vulnerable farmers have higher community engagement than non-vulnerable farmers. Similar to institutional support, this suggests that vulnerable farmers might rely more heavily on community networks for support, mutual aid, and collective action, leading to a higher perception of engagement. This often reflects their necessity to pool resources and rely on social capital in the face of limited individual resources. Table 6: Perceived responses of farmers for adaptive capacity indicators in Gedeo zone, Southeastern Rift Valley escarpments of Ethiopia

4 Discussions

Drought remains the most pervasive climatic stressor for smallholder farmers, particularly those reliant on rain-fed agriculture with limited livelihood diversification (Gebremariam et al., 2021; Gebreyesus et al., 2023). Evidence consistently shows that drought disproportionately affects vulnerable households, intensifying food insecurity and undermining rural livelihoods Bryan et al., 2013; Kabir et al., 2019). Socio-economically disadvantaged groups experience greater impacts due to weak financial buffers and inadequate infrastructure (Habib et al., 2020; Ray et al., 2021). Increasing drought frequency and severity across Sub-Saharan Africa further compounds these risks, destabilizing agricultural systems and deepening poverty traps (Niang et al., 2014; Zampaligré et al., 2019. Although statistical differences between vulnerable and non-vulnerable groups were not significant, variations in exposure likely reflect microclimatic differences and unequal adaptive capacities, shaping subjective experiences of drought impacts (Deressa et al., 2009).

The high drought burden underscores the urgency of resilience-focused interventions. Key strategies include adoption of drought-tolerant crop varieties, expansion of irrigation infrastructure, improved water harvesting, and accessible early warning systems (Adger, 2018; Bedru et al., 2023). While drought is a communal challenge, policy frameworks should prioritize vulnerable groups in resource allocation to strengthen adaptive capacity (Food and Agriculture Organization (FAO), 2018).

Flooding, though less frequent, remains a significant hazard in lowland and river basin areas, often exacerbated by deforestation and poor land management (Abera et al., 2021; Masika et al., 2017; Mwakapalila, 2017; Nigussie et al., 2020). Communities near major river systems and coastal zones frequently report moderate to high flood exposure (Nguyen et al., 2016; Phompila et al., 2020). Despite its localized nature, floods cause severe damage to crops, infrastructure, and livelihoods (Awoke et al., 2018). Interestingly, this study found no significant difference between vulnerable and non-vulnerable groups, contrasting with literature that highlights disproportionate impacts on poorer households due to weaker housing and farm infrastructure (Deressa et al., 2009; Zampaligré et al., 2019). Effective interventions include improved drainage, flood-resistant farming practices, community-based disaster risk reduction, and robust early warning systems (Mengistu & Dadi, 2023; UNISDR, 2015). Policies should emphasize preparedness and rapid recovery, particularly as climate change is expected to intensify flood risks (Intergovernmental Panel on Climate Change (IPCC), 2021).

Rainfall variability emerged as a critical stressor, with vulnerable farmers reporting very high exposure. Empirical evidence confirms shifts in rainfall regimes, including delayed onset, early cessation, and increased intensity of short rains (Bewket & Conway, 2007; Conway et al., 2007; Mekonnen et al., 2018). Erratic rainfall patterns drive agricultural risk and food insecurity, particularly for staple crops (Antwi-Agyei et al., 2018; Olofintoye et al., 2020). Such variability necessitates adaptive strategies, as demonstrated in rice-growing regions where altered monsoon patterns compel farmers to adjust to unpredictable conditions (Aguilar et al., 2020; R. Khan et al., 2021; Perez et al., 2018; Sriplung & Sompong, 2022). Although statistical differences between vulnerable and non-vulnerable groups were not significant, the practical reality remains resource-constrained farmers are more susceptible to immediate consequences such as crop failure and yield reduction (Deressa et al., 2009.

Rainfall variability emerged as a critical stressor, particularly for vulnerable farmers, demanding targeted adaptation strategies (Müller et al., 2021). Climate-smart practices such as conservation agriculture, drought-resistant crop varieties, efficient water management through small-scale irrigation and rainwater harvesting, and improved seasonal forecasting are essential to reduce risks and guide planting decisions Altieri et al., 2015; Gebreyesus et al., 2023; Nkonya et al., 2016). Policy frameworks should prioritize investments in agro-meteorological services and extension programs that strengthen farmers' capacity to cope with increasing rainfall unpredictability (Food and Agriculture Organization (FAO), 2018).

Temperature increases observed in this study align with regional climate change trends, marked by significant warming, heightened heat stress, and altered crop phenology (Gebreyesus et al., 2023; Intergovernmental Panel on Climate Change (IPCC), 2021). Rising maximum temperatures and more frequent heatwaves have reduced crop yields, impaired livestock health, and strained water resources (M. Khan & Hanjra, 2009; Rahman et al., 2019; Sow et al., 2020; Traoré et al., 2017). These changes necessitate shifts in growing seasons and adoption of heat-tolerant crop varieties (Hughes, 2011; Lobell & Gourdji, 2012). Although statistical differences between groups were not significant, the slightly higher mean for vulnerable farmers reflects their limited ability to invest in adaptive measures such as irrigation or shade structures, amplifying their sensitivity to temperature stress (Deressa et al., 2009).

Adaptation strategies to mitigate heat stress should include promoting heat-tolerant crops, adjusting planting calendars, integrating agroforestry for shade, improving livestock management, and expanding irrigation to counter evapotranspiration losses (Asfaw et al., 2022; Mekonnen et al., 2018; Thornton et al., 2014). Policies must support research into climate-resilient crop and livestock breeds, ensure their dissemination, and build farmer capacity to implement thermal adaptation measures (Food and Agriculture

Table 6: Perceived responses of farmers for adaptive capacity indicators in Gedeo zone, Southeastern Rift Valley escarpments of Ethiopia

Adaptive capacity Indicators	vulnerable (n-279)		Non-vulnerable (105)		Statistical value	
	Mean	Std. Dev.	Mean	Std. Dev.	*Chi*²	p-value
Access to Information	2.63	0.58	3.52	0.81	1.4	0.507
Access to credit service	3.42	0.79	4.05	0.73	18	0.000
Financial Resources	2.14	0.55	3.71	0.74	24	0.000
Social Networks	3.66	0.74	3.83	0.70	17	0.000
Training and Education	2.74	0.50	2.85	0.68	2	0.263
Access to Technology	2.47	0.43	2.62	0.65	5	0.030
Institutional Support	3.11	0.72	2.96	0.67	11	0.001
Community Engagement	3.47	0.66	3.28	0.69	16	0.000

Organization (FAO), 2018).

Income disparities identified in this study further reinforce vulnerability patterns. Low-income households consistently demonstrate reduced adaptive capacity, with limited ability to invest in resilience measures or recover from shocks (Abate et al., 2022; Bedru et al., 2023; Osman et al., 2022; Tadesse et al., 2021; Worku and Singh, 2021. Income poverty restricts access to credit and technologies, constraining livelihood diversification and heightening sensitivity to climate variability (Antwi-Agyei et al., 2018; Habib et al., 2020). Wealthier farmers, by contrast, are better positioned to adopt protective measures, underscoring income as a fundamental determinant of socio-economic sensitivity Intergovernmental Panel on Climate Change (IPCC), 2021; Nguyen et al., 2016; Niang et al., 2014; Ray et al., 2021).

Addressing income disparity requires policies that enhance vulnerable farmers' earning capacity. Key interventions include diversification into non-farm activities, improved market access, value-addition initiatives, and financial literacy and entrepreneurship training (Food and Agriculture Organization (FAO), 2018; Gebreyesus et al., 2023). Expanding microfinance and credit facilities, alongside risk transfer mechanisms such as crop insurance, can buffer households against shocks (Bryan et al., 2013). Social protection programs including conditional cash transfers and public works remain vital to provide safety nets for the most vulnerable (UNISDR, 2015).

Lower household consumption among vulnerable farmers observed in this study is a clear indicator of precarious food security, linking vulnerability to chronic food insecurity and poor dietary diversity (Dullo et al., 2022; Gebremariam et al., 2021; Haile et al., 2020; Molla et al., 2020; Nigussie et al., 2020. Consumption expenditure is widely recognized as a key metric for identifying food-insecure households, which are more sensitive to price shocks and climate impacts (Masika et al., 2017). Households with lower consumption are disproportionately affected by food price volatility and recurrent droughts, often resorting to coping strategies that erode long-term resilience (Zampaligré et al., 2019). Inadequate consumption reflects limited purchasing power and restricted access to essential goods and services (M. Khan and Hanjra, 2009; Ray et al., 2021). Thus, consumption patterns serve as a robust proxy for household welfare and socio-economic sensitivity (R. Khan et al., 2021).

Addressing this consumption gap requires multi-dimensional interventions. Strategies include improving access to affordable and nutritious food through local markets, promoting home gardens to enhance dietary diversity, and strengthening food assistance programs (Food and Agriculture Organization (FAO), 2018). Policies should also aim to increase purchasing power via direct income support or reduced costs of essential goods, while simultaneously boosting agricultural productivity to stabilize food supply (Müller et al., 2021). Investments in healthcare and education further contribute to improved consumption outcomes and reduced vulnerability (Intergovernmental Panel on Climate Change (IPCC), 2021).

Lower household production among vulnerable farmers is consistent with existing evidence, often attributed to smaller landholdings, limited access to inputs, poor soil fertility, and reliance on traditional farming methods (Gebreegziabher et al., 2011; Gebreyesus et al., 2023; Haile et al., 2020; Osman et al., 2022; Tadese et al., 2020. Low productivity undermines food availability and income, reinforcing vulnerability (Olofintoye et al., 2020; Traoré et al., 2017). Restricted access to modern technologies and extension services further heightens sensitivity to climate shocks (Aguilar et al., 2020; Perez et al., 2018). Disparities in land, capital, and technical knowledge directly correlate with household sensitivity to agricultural crises (Khang et al., 2021; Sriplung & Sompong, 2022).

To enhance resilience, policies should prioritize access to climate-resilient seeds and fertilizers, expand irrigation technologies, and promote sustainable land management practices such as soil conservation and agroforestry (Altieri et al., 2015; Nkonya et al., 2016) . Strengthened extension services offering practical training in climate-smart techniques are essential (Food and Agriculture Organization (FAO), 2018). Collective farming initiatives and cooperatives can improve resource pooling, market access, and technology adoption (Asfaw et al., 2022). Securing land tenure rights further incentivizes long-term investments in productivity (Intergovernmental Panel on Climate Change (IPCC), 2021).

Medium access to climate and agricultural information, with no significant difference between vulnerable and non-vulnerable groups, reflects systemic inadequacies in extension services and information dissemination in Ethiopia (Alemayehu and Bewket, 2017; Bedru et al., 2023; Deressa et al., 2009; Gebremariam et al., 2021; Tesfaye and Mebit, 2021. Farmers often rely on traditional knowledge or informal networks due to poor access to formal meteorological services, limiting adaptive decision-making (Antwi-Agyei et al., 2018; Olofintoye et al., 2020). Even when information is available, barriers of accessibility, relevance, and interpretability persist (Nguyen et al., 2016; Ojha et al., 2019) .

Improving adaptive capacity requires strengthening extension services, diversifying communication channels (radio, mobile platforms, community meetings), and translating scientific forecasts into actionable advice (Bryan et al., 2013; Food and Agriculture Organization (FAO), 2018). Policies should invest in agro-meteorological services and build extension agent capacity to deliver tailored, context-specific information.

Credit constraints remain a major barrier for vulnerable farmers, limiting adoption of improved technologies and coping strategies (Abate et al., 2022; Dullo et al., 2022; Gebreyesus et al., 2023; Osman et al., 2022; Worku and Singh, 2021. Reliance on informal, high-interest loans exacerbates financial precarity (Habib et al., 2020; Ray et al., 2021). Restricted access to capital hinders investment in climate-smart agriculture and livelihood diversification (Sow et al., 2020; Traoré et al., 2017) . The significant difference observed in this study confirms financial capital as a critical determinant of adaptive capacity.

Expanding affordable credit access through tailored microfinance schemes, cooperatives, government-backed loan guarantees, and simplified procedures is essential (Food and Agriculture Organization (FAO), 2018). Innovative financial products, including climate-smart insurance, can enhance creditworthiness and resilience (Bryan et al., 2013).

Building the financial resilience of vulnerable farmers is essential for reducing climate-related risks. Key measures include promoting savings groups, expanding access to micro-credit, and establishing climate insurance schemes (FAO, 2019). Beyond direct financial access, policies should encourage diversified income streams, improve market integration for agricultural products, and implement social protection programs to provide safety nets against shocks (Müller et al., 2021) .

Social networks and community cohesion also emerge as critical non-financial assets for adaptation. They facilitate knowledge sharing, labor exchange, and collective coping mechanisms (Abate et al., 2022; Berhanu et al., 2014; Gebreyesus et al., 2023; Simane et al., 2016; Tesfaye and Mebit, 2021. Strong social capital enhances resilience by enabling collective responses to climate challenges (Antwi-Agyei et al., 2018; Zampaligré et al., 2019) . Community-based networks are particularly vital for disaster preparedness and recovery among vulnerable groups lacking formal support (R. Khan et al., 2021; Saroar and Alam, 2022) . The modest difference observed between groups suggests that non-vulnerable farmers benefit from broader networks, including ties to market actors and decision-makers, which provide additional adaptive advantages Deressa et al., 2009. Policies should therefore strengthen community-based organizations, promote farmer-to-farmer learning, and integrate traditional social structures into formal adaptation programs (Bryan et al., 2013; Food and Agriculture Organization (FAO), 2018).

Medium access to training and education across both groups highlights a systemic gap in knowledge and skill development crucial for climate adaptation (Bedru et al., 2023; Gebremariam et al., 2021; Haile et al., 2020; Nigussie et al., 2020; Tadese et al., 2020). Limited training in climate-smart agricultural techniques constrains adoption of resilient practices (Masika et al., 2017; Mwakapalila, 2017) , while inadequate farmer education programs hinder innovation uptake (Aguilar et al., 2020; Perez et al., 2018) . The absence of significant differences between groups indicates that both are underserved, though vulnerable farmers remain less equipped to capitalize on existing opportunities. Investment in comprehensive, context-specific training on climate-smart agriculture, water management, soil health, and livelihood diversification is therefore critical (Altieri et al., 2015; Food and Agriculture Organization (FAO), 2018).

Limited access to appropriate agricultural technologies such as improved seeds, irrigation equipment, and modern tools remains a well-documented constraint on productivity and adaptive capacity (Alemayehu and Bewket, 2017; Berhanu et al., 2014; Gebreegziabher et al., 2011; Nigussie et al., 2020; Osman et al., 2022). Affordability, knowledge gaps, and weak supply chains hinder adoption (Nkonya et al., 2016; Ray et al., 2021; Saroar and Alam, 2022; Traoré et al., 2017). The modest difference observed suggests that non-vulnerable farmers marginally overcome these barriers due to stronger financial resources or social networks. Policies should therefore prioritize making climate-smart technologies accessible and affordable, through subsidies, credit schemes, and strengthened supply chains for critical inputs such as drought-resistant seeds and efficient irrigation tools (Food and Agriculture Organization (FAO), 2018).

Interestingly, higher institutional support among vulnerable farmers reflects the design of development and humanitarian programs that deliberately target these groups (Bryan et al., 2013; Deressa et al., 2009; Gebreyesus et al., 2023; Simane et al., 2016; Tadesse et al., 2021). Vulnerable farmers are more likely to benefit from government and aid interventions, while non-vulnerable farmers often rely on market-based solutions. Humanitarian aid and social programs are thus channeled toward vulnerable populations, explaining their higher reported engagement (Intergovernmental Panel on Climate Change (IPCC), 2021; R. Khan et al., 2021. However, while institutional support is reaching its intended beneficiaries, policies must critically assess its effectiveness in enhancing adaptive capacity and reducing long-term vulnerability. Strengthening institutional coordination, ensuring flexible and needs-based support, and integrating aid with market mechanisms are essential to shift from short-term assistance toward sustainable resilience (Food and Agriculture Organization (FAO), 2018; UNISDR, 2015).

The higher community engagement observed among vulnerable farmers underscores the critical role of local social capital and collective action in coping and adaptation strategies (Abate et al., 2022; Bedru et al., 2023; Gebremariam et al., 2021; Osman et al., 2022; Tesfaye and Mebit, 2021). Community-based disaster risk reduction initiatives and informal networks often serve as the first line of defense for vulnerable populations. Strong social ties facilitate collective management of common resources and coordinated responses to environmental stress (Sow et al., 2020; Zampaligré et al., 2019). The significant difference found in this study suggests that while community engagement benefits all farmers, it is particularly vital for those with fewer individual resources. Policies should therefore strengthen existing community structures and indigenous coping mechanisms (Food and Agriculture Organization (FAO), 2018), foster participatory planning, and empower local leaders to enhance resilience (Bryan et al., 2013).

The negative impact of vulnerability on household income is well-documented. Vulnerable households, characterized by limited assets, poor market access, and reliance on rain-fed agriculture, consistently report lower and unstable income streams (Abate et al., 2022; Bedru et al., 2023; Dullo et al., 2022; Osman et al., 2022; Worku and Singh, 2021. Climate variability exacerbates these deficits, deepening socio-economic inequalities (Antwi-Agyei et al., 2018) . Low and inconsistent income restricts investment in adaptive measures (Habib et al., 2020), directly correlating with food insecurity and reduced resilience (Ray et al., 2021; Sow et al., 2020; Traoré et al., 2017) . Income thus emerges as a fundamental driver of vulnerability. Addressing disparities requires targeted interventions to diversify livelihoods, expand non-farm opportunities, and strengthen market linkages (Food and Agriculture Organization (FAO), 2018). Access to affordable credit, microfinance, and financial literacy training can empower households to invest in resilience (Bryan et al., 2013), while climate-smart agriculture can stabilize and increase incomes (Gebreyesus et al., 2023).

Significantly lower household consumption among vulnerable farmers highlights chronic food and nutritional insecurity. Vulnerable households often face poor dietary diversity and reduced access to basic needs (Dullo et al., 2022; Gebremariam et al., 2021; Haile et al., 2020; Molla et al., 2020; Nigussie et al., 2020). Lower consumption expenditures reflect struggles to meet caloric and nutritional requirements, especially during climate shocks (Masika et al., 2017; Mwakapalila, 2017). Income instability and limited market access further constrain consumption (Khang et al., 2021). Global assessments confirm that climate change disproportionately affects consumption patterns in vulnerable populations (Intergovernmental Panel on Climate Change (IPCC), 2021). Addressing these gaps requires integrated food security interventions: increasing production, improving market access, reducing food prices, and promoting nutrition education (Food and Agriculture Organization (FAO), 2018). Social safety nets such as food assistance and cash transfers provide immediate relief (UNISDR, 2015) , while investments in health and sanitation indirectly strengthen food utilization.

Lower household production among vulnerable farmers is a consistent finding, linked to limited access to inputs, poor soil fertility, rudimentary technologies, and heightened climate exposure (Gebreegziabher et al., 2011; Gebreyesus et al., 2023; Haile et al., 2020; Osman et al., 2022; Tadese et al., 2020). Low productivity undermines food availability and income, reinforcing vulnerability (Olofintoye et al., 2020; Traoré et al., 2017) . Farmers with restricted access to modern agronomic knowledge and technologies consistently achieve lower yields (Aguilar et al., 2020; Perez et al., 2018) . Production disparities intensify sensitivity to market and climate shocks (Khang et al., 2021; Sriplung and Sompong, 2022). Enhancing productivity requires improved access to climate-resilient seeds, fertilizers, efficient water management, and sustainable soil practices (Altieri et al., 2015; Nkonya et al., 2016). Strengthened extension services and tailored training programs are vital (Food and Agriculture Organization (FAO), 2018), while farmer cooperatives can improve access to inputs, markets, and shared technologies, collectively enhancing production capacity.

5 Conclusions

This study demonstrates that a substantial majority (72.65%) of smallholder farmers in the Gedeo Zone are highly vulnerable to climate-related hazards, with droughts, floods, and erratic weather directly undermining their food security and economic stability. Among these stressors, rainfall variability emerges as the most acute and differentiating hazard, disproportionately affecting vulnerable households and amplifying their sensitivity to climate shocks.

Our study reveals statistically significant disparities between vulnerable and non-vulnerable farmers across key socio-economic indicators. Vulnerable households consistently exhibit lower income, consumption, and production, confirming their heightened sensitivity to both climatic and economic shocks. In contrast, non-vulnerable farmers benefit from stronger adaptive capacity, largely due to better access to credit, financial resources and slightly stronger social networks However, both groups face systemic challenges in accessing timely information and training, highlighting structural gaps in extension and education services. These findings confirm that vulnerability directly erodes financial well-being, food security, and productivity, perpetuating cycles of poverty and fragility.

To effectively reduce vulnerability and build resilience in the Gedeo Zone, a comprehensive, integrated strategy should be implemented that combines accessible financial services, climate-smart agriculture, strengthened institutional and social support, diversified livelihoods, and targeted social protection. By addressing these dimensions simultaneously, farmers can enhance adaptive capacity, stabilize income and food security, and foster sustainable, climate-resilient livelihoods

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Availability of Data and Materials

All data generated or analysed during this study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no competing interests in relation to this study.

Authors Contributions

Tigistu Gezahegn: contributed to the conceptualization, data collection, formal analysis, investigation, project administration, visualization, and overall original manuscript writing.
Mesele Negash: played a key role in designing the methodology, supervising, validating, and reviewing the manuscript with constructive comments.
Eshetu Yirsaw: made significant contributions by reviewing, supervising, validating, and providing comments on the manuscript.

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Short Communication

Observation of an Atypical Hairless Free-Ranging Individual of Grivet Monkey (Chlorocebus aethiops), at Wondo Genet Patch of Forest, Southern Ethiopia

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Abstract

This study documents the observation of a highly unusual hairless female grivet monkey (Chlorocebus aethiops) at Wondo Genet College of Forestry and Natural Resources Campus, Ethiopia, a phenomenon not previously documented in free-ranging populations in the region. Following an initial report from local community members of a "strange looking" monkey, systematic field observations were conducted over a six-month period at two-week intervals to assess the individual's morphology, behavior, and interactions with conspecifics. The monkey displayed almost complete hairlessness, except for a small tuft on the tail, and weighed approximately 1.5 kg, substantively less than typical adults. Additionally, irregular white patches of depigmentation were present on the upper left flank, with no signs of dermal irritation or lesions. Behavioral observations revealed distinctly atypical foraging and social patterns. Unlike other troop members, the individual primarily foraged near office and training areas, avoided residential zones, and rarely engaged in grooming or close social interactions. Other monkeys initially avoided it, though selective tolerance from one adult male was occasionally noted. The hairless individual exhibited thermoregulatory behaviors, such as lying on sun-warmed rooftops during cooler mornings, presumably to mitigate cold stress due to the absence of fur. The findings suggest that common causes of hair loss, including infection, nutrition, stress, or over-grooming, are implausible explanations. Instead, hairlessness likely stems from an underlying genetic mutation or immunological dysfunction. This case underscores the importance of detailed documentation of rare morphological anomalies in wild primates; as these conditions may influence individual survival, social integration, and adaptive behaviors within both natural and human-modified environments.

Keywords: Alopecia; Ethiopia; feeding; monkey; primate; Wondo Genet.

1 Introduction

Ethiopia has 14 extant primate species and 23 distinct extant taxa (i.e., subspecies), including two endemic species – the Bale Monkey (Chlorocebus djamdjamensis) and the gelada (Theropithecus gelada) representing 33% of species–, and nine endemic taxa (Wallis, 2023). One species and five taxa are classified as globally threatened: two Endangered – Chlorocebus djamdjamensis ssp. djamdjamensis (Djam-djam Bale Monkey) and C. d. ssp. harennaensis (Harenna Bale Monkey) (Butynski & De Jong, 2025; Butynski et al., 2022; De Jong et al., 2022) – and three Vulnerable taxa – Cercopithecus mitis ssp. boutourlinii (Boutourlini's Blue Monkey), Erythrocebus patas ssp. pyrrhonotus (Eastern Patas Monkey) (Butynski & De Jong, 2025) and Theropithecus gelada ssp. gelada (Northern Gelada) (Fashing et al., 2019).

The Grivet Monkey (Chlorocebus aethiops) is distinguished from closely related species, particularly the Vervet monkey (Chlorocebus spp.), by its black facial skin with a white line above the eyes, black hands and feet (Butynski and De Jong, 2022) . Several authors note that the taxonomy and biogeography of Chlorocebus monkeys in Ethiopia are particularly complex and requiring further research (Wallis, 2023) . Currently, three subspecies are recognized: the common grivet C. a. aethiops, Matschie's grivet C. a. matschiei, and Hilgert's grivet C. a. hilgerti (Butynski et al., 2022) . The latter two are endemic to Ethiopia, with C. a. matschiei (Matschie's grivet) being found west of the Eastern Rift Valley at altitudes ranging from 440–3,000 m above sea level, and C. a. hilgerti east of the Rift Valley at altitudes from 1,100–3,000 m above sea level (Butynski et al., 2022; IUCN, 2025) .

Wallis, 2023 noted that African primates are facing three main threats: poaching, , 2) habitat loss, and disease. Any of these factors (or a combination thereof) can significantly impact local populations of primates and, when occurring at a large scale, can affect the conservation status of an entire species or subspecies (Wallis, 2023) . Herein, we report first documented case of a hairless grivet monkey exhibiting alopecia at the Wondo Genet Patch of Forest, southern Ethiopia.

Alopecia is a condition characterized by partial or complete hair loss in areas typically covered by fur. While alopecia can occur in both wild and captive animals, it is most frequently documented in captive settings (Zhang, 2011). Among non-human primates, alopecia has received limited research attention, despite growing concern among animal welfare specialists and regulators regarding its potential implications for health and psychological well-being (Zhang, 2011).

The etiology of alopecia in primates is varied and multifactorial. Documented factors include natural processes including seasonality and aging (Steinmetz et al., 2006), nutritional imbalances (Rushton, 2002), endocrine disorders (Diani et al., 1995) , immunological disorders (Wiedemeyer et al., 2004), genetic mutations and physiological changes during pregnancy or the postpartum period (A. A. Beisner and Isbell, 2009). Alopecia may also result from dermatological conditions such as bacterial or fungal infections, parasitic infestations, and atopic dermatitis (Martin and Elewski, 2003; Otberg et al., 2007; Ovadia et al., 2005). In captive environments, over-grooming, frequently associated with social stress or overcrowding, has been identified as a significant contributor to hair loss (B. A. Beisner and Isbell, 2008; Reinhardt et al., 1986).

Despite this broad spectrum of potential causes, alopecia in wild primates remains understudied and is generally regarded as rare. This knowledge gap complicates efforts to explain cases of hair loss observed in free-ranging individuals. Given increasing environmental changes ranging from habitat loss and poaching to disease outbreaks (Wallis, 2023), there is a pressing need to document such atypical cases and better understand their ecological, physiological, and behavioral underpinnings.

This study presents an atypical case of alopecia in a female grivet monkey (Chlorocebus aethiops) observed in the Wondo Genet Forest of Ethiopia, East Africa. In February 2023, we initiated documentation of the behavior and physical condition of a free-ranging, hairless grivet monkey within the Wondo Genet College compound. Observations continued until the animal's disappearance in October 2024. Our objectives were to document the individual's morphological features, foraging behavior, grooming activity, movement patterns, social interactions, and other associated behaviors, as well as to discuss plausible causes of its hair loss within the context of primate health and conservation.

2 Materials and methods

2.1 Study Site

All observations were carried out within the Wondo Genet College of Forestry and Natural Resources compound (38°36'30'' and 38°39'0'' E; 7°5'30'' and 7°7'30'' N), in the southern part of Ethiopia at about 250 km from the capital. The elevation of the area varies between 1,600 and 2,580 m asl. The college's campus covers 840ha of land, comprising of large areas of forested habitat, bushland and grassland areas, as well as residential, office, and dormitory quarters (Girma et al., 2012). Surrounding the campus are local community settlements. The dominant tree species in the natural forest and woodlands include Celtis africana, Pouteria adolfi-friedericii, Acokanthera schimperi, Albizia schimperiana, Millettia ferruginea and Afrocarpus falcatus. Some parts of the forest area are covered by exotic tree plantations (Girma et al., 2012). The Wondo Genet Forest is home to more than 19 large-sized wild mammal species, including endemic ungulates such as Tragelaphus buxtoni, and Tragelaphus scriptus meneliki; carnivores such as Canis aureus, Felis serval, Crocuta crocuta and Panthera pardus, and primates including Papio anubius, Chlorocebus aethiops, and Colobus guereza, which are the most abundant species in the area (Girma et al., 2012).

2.2 Observation method

Our study began following an informal report from local community members livening near the college campus. They reported seeing a "strange looking" monkey, unlike any species they had previously encountered in their lifetime. This initial account captured our interest. We conducted a preliminary literature review to investigate whether similar cases had been documented in Ethiopia. However, no published records describing such an occurrence were found. Based on the report, we attempted to locate the individual. After several attempts, we successfully observed the animal and identified it as a female grivet monkey (Chlorocebus aethiops). The individual displayed unusual morphological features, which distinguished it from other grivet monkeys.

We systematically monitored the hairless individual over a period of approximately six months, conducting observations at two-week intervals. This consistent monitoring schedule allowed us to record not only its physical condition but also its daily activity patterns, behavioral adaptations, and social interactions within the troop. Such regular monitoring sessions also allowed us to track subtle changes in its health and appearance over time. In October 2024, however, the individual abruptly disappeared from the study area. Despite repeated efforts to locate it during subsequent observation sessions, we recorded no further sightings. The exact cause of its disappearance remains uncertain, but we propose three plausible explanations for this outcome:

- **Predation** – The individual may have been killed by domestic dogs commonly found near the campus, or to wild carnivores inhabiting the surrounding forest.
- **Human-related mortality** – It is possible that local people deliberately killed the animal, either due to crop raiding or other forms of human–wildlife conflict.
- **Dispersal or emigration** – The monkey may have migrated to a different area, either independently or as part of broader troop movement, which is a natural behavior in many primate populations.

Although we initially considered capturing the monkey for detailed morphological measurements, skin biopsy, and blood sampling, we decided against this approach. Given the animal's skittish temperament, as well as the high risk of stress-induced mortality associated with capture and handling, we prioritized non-invasive observation. Accordingly, our method consisted of direct field observations and photographic documentation. On a weekly basis, we recorded the following behavioral and morphological aspects:

- **Morphological features:** external appearance and any observable anomalies.
- **Foraging behavior:** food items consumed and feeding strategies.
- **Grooming activity:** frequency and occurrence of self-grooming or grooming by conspecifics.
- **Movement patterns:** daily ranging and spatial use within the campus.
- **Social interactions:** responses to conspecifics and other animals, when applicable.
- **Other associated behaviors:** signs of stress, avoidance, or adaptation to human-dominated areas.

In addition to direct field observations, we conducted a comprehensive review of relevant literature to explore potential causes of hairlessness in free-ranging grivet monkeys. Our primary aim was to answer the question: what factors could cause the hair loss observed in the individual monkey at Wondo Genet? The review included examination of studies on genetic conditions, disease-related hair loss, environmental stressors, nutritional deficiencies, and social or behavioral influences that could contribute to alopecia in primates. By integrating insights from previous research with our own observations, we sought to identify plausible explanations for this unusual condition and place it in context within the broader understanding of grivet monkey biology.

3 Results and Discussion

This initial observation captivated our attention and prompted us to conduct a preliminary review of the literature to determine whether similar cases had been reported in Ethiopia. We found no published records or reports describing this phenomenon. Furthermore, during our survey, we encountered no other hairless individuals in the area apart from the one under our observation.

During the first week of observation, the hairless monkey gradually relocated its range toward the vicinity of the main office buildings on the campus. This movement appeared to be a behavioral response to two significant pressures. First, the animal was frequently harassed and chased by domestic dogs owned by members of the surrounding community, posing a constant threat to its safety. Second, negative perceptions among some local residents further exacerbated its vulnerability. Certain individuals regarded the monkey as "ugly" or associated its unusual appearance with bad spirits and misfortune, leading to hostile attitudes and occasional attempts to drive it away. The combined effect of these pressures likely influenced the animal's decision to seek refuge in areas with higher human activity on campus, where it experienced relatively less disturbance.

The observed individual was a completely hairless monkey, which distinguished it from previously reported cases of partial hair loss in other primates. For instance, hairless vervet monkeys observed in Umlalazi Nature Reserve exhibited alopecia accompanied by sparse hair coverage (Jenkins, 2015). Similarly, captive Japanese macaques (Macaca fuscata), a species closely related to grivet monkeys, have been documented exhibiting alopecia characterized by patchy hairless areas (Zhang, 2011). Notably, Japanese macaques are among the most extensively studied primates worldwide and are frequently referenced in research and breeding programs due to their ecological and behavioral significance (Institute, 2002; Kawai and Ohsawa, 1983. The complete absence of hair in the observed individual thus represents a distinct condition, differing from the partial or patchy hair loss described in these related cases.

3.1 Morphological features

The monkey with alopecia was estimated to weigh approximately 1.5 kg and measure 30 cm in length (from the top of the head to the base of the tail), noticeably smaller and lighter than typical adult members of its species. In comparison with other conspecific individuals, the hairless monkey exhibited several strikingly unusual morphological characteristics that clearly distinguished it from the rest of the troop (Figure 1). The normal Grivet monkeys have black facial skin, hands, and feet; a white line on the face just above the eyes; long, white whiskers on the cheeks; and a white tuft on the tip of the tail (Figure 2). In contrast, the observed monkey with alocepia was almost entirely devoid of body hair, with the exception of a small tuft of fluffy hair concentrated at the tip of its tail (Figure 3 and 4). Remarkably, throughout the entire duration of our monitoring period, the individual did not show any signs of hair regrowth, maintaining its hairless condition until the time of its disappearance. We did not observe any sign of sores or itching on its body including around the white patches. This persistent lack of fur suggests a chronic rather than a temporary condition, raising questions about possible underlying genetic, pathological, or environmental causes. The complete absence of body hair also exposed the underlying skin and accentuated its skeletal and muscular structure. This gave the individual a markedly different appearance and likely contributed to its social and ecological challenges within both the monkey troop and the surrounding human community.

Figure 1: The alopecia disease-infected grivet monkey individuals at Wondo Genet area (Photo: Yitayal Alemu, 2024).

Figure 2: The observed female hairless individual (picture on the left side) and a normal female member of the same species observed at the site (Photo: Yitayal Alemu, 2024).

Figure 3: White patches on the upper left flank of the hairless monkey (Photo: Yitayal Alemu, 2024).

The morphological condition of the hairless monkey reported here is unique compared to previous case reports that describes partial hair loss in other primates, unlike the complete hair loss observed in the present case. For instance, hairless vervet monkeys observed in Umlalazi Nature Reserve exhibited alopecia accompanied by sparse hair coverage (Jenkins, 2015). Similarly, captive Japanese macaques (Macaca fuscata), a species closely related to grivet monkeys, have been documented with alopecia characterized by patchy hairless areas (Zhang, 2011). The complete absence of hair in the observed individual therefore represents a distinct condition, differing from the partial or patchy hair loss described in these related cases.

3.2 Foraging behavior

Most other grivet monkeys at the Wondo Genet College Campus are frequently observed gathering in groups around cafeterias and residential areas, often snatching bread or other food from people. This hairless individual, however, did not exhibit such behaviors. Instead, she primarily foraged around the office and training buildings, feeding on leftovers from training refreshments where food was abundant. She was never observed venturing into residential areas. When sensing potential threats, she occasionally vocalized, signaling danger as her troop would.

The observed hairless monkey often wandered around office and training room areas, and rarely displayed the typical social or foraging behaviors seen in other members of its troop. Occasionally, however, like other grivet monkeys, she attempted to climb trees,

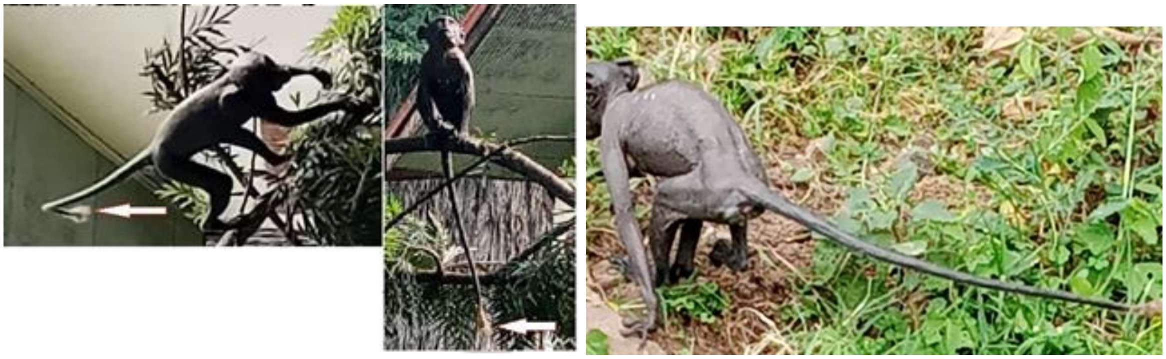

Figure 4: Only fluffy hair was observed around the tip of its tail (Photo: Yitayal Alemu, 2024

traverse electric lines between poles, and move across the rooftops of office buildings (Figure 4).

Troops of Grivet monkeys in the Wondo Genet College Campus usually gather in large groups around students' cafeterias and residential building areas and snatch bread and the like from people. The hairless monkey was not observed doing that. It never attempted to cross to residential areas. It was instead observed predominantly feeding on flowers, pods and fruits from plant sources, but sometimes seen scratching ground surfaces and feeding on insects. Like the normal grivet monkeys, the observed hairless monkey also fed both on the ground and on the trees (Figure 5 and 6).

3.3 Social interactions with other conspecific monkeys

When the hairless monkey was first observed in the area, it was clear that other members of the troop actively avoided social interaction with it, often moving away or fleeing in its presence. Over time, however, the troop gradually become somewhat accustomed to its presence, allowing it to move freely within the group, though they consistently maintained a reasonable distance. Direct social interactions such as grooming, close proximity, or mating attempts—were rarely observed between it and other group members (Figure 7). The only notable exception involved occasional close encounters, approximately one meter apart, with a single adult male near the office quarters. Interestingly, this same male was also observed spending timing with this individual at a greater distance, approximately three meters within relatively open grassland areas. This behavior suggests a degree of selective social tolerance rather than complete integration into normal troop dynamics.

3.4 Other Associated Behaviors

Early in the morning, when temperatures are relatively low, the hairless monkey exhibits behavior that is distinct from other members of the troop. Unlike its conspecifics, it is often observed lying alone on top of the office roof (Figure 8), presumably absorbing heat from the sun and the warmed surface. This behavior suggests that it may be experiencing discomfort or thermal stress during colder periods, likely due to its exposed, hairless skin. During cooler morning hours, she consistently remains isolated from other troop members, occupying buildings' corrugated iron rooftops. This solitary behavior and preference for elevated, sun-exposed surfaces may serve as a thermoregulatory strategy, highlighting the potential challenges posed by her hairless condition in coping with low ambient temperatures. Her reliance on artificial or sun-warmed surfaces for warmth indicates a behavioral adaptation to mitigate the physiological stress associated with cold exposure.

Most of the time, it wanders around office buildings, which appear to provide a sense of security and relative safety. These areas may offer protection from potential threats and harsh environmental conditions, such as exposure to cold, and also allow it to remain within sight of the troop while minimizing direct social interactions. Its preference for these built structures suggests a behavioral adaptation that balances the need for warmth, safety, and limited social engagement, reflecting the unique challenges posed by her hairless condition. Local residents informed us that they had never seen or heard of such kind of strange looking monkeys in their lifetime. We also haven't come across any literature or report from Ethiopia and elsewhere regarding this animal. Based on our discussions, many people dis like this strange looking animal mainly due to its unusual appearance. Consequently, they consider it as possible source of evil spirit.

3.5 Plausible Explanations for Hair Loss in the Observed Monkey

A central question raised by this case is: what caused the unusual hairlessness in the observed grivet monkey at Wondo Genet? Alopecia in non-human primates (NHPs) has been associated with a wide range of biological, environmental, and behavioral factors. However, closer examination of the animal's condition and behavior suggests that many of the common explanations can be ruled out in this particular case.

One well-documented cause of hair loss in captive primates is hair-pulling due to over-grooming (Institute, 2002; Reinhardt et al., 1986). Excessive grooming can create bald patches and even skin lesions, particularly when females over-groom their infants. However, this seems unlikely in this case, as the observed monkey rarely

Figure 5: The hairless monkey climbs trees and walking on electric lines (Photo: Yitayal Alemu, 2024).

Figure 6: Predominantly feeds on flowers, pods and fruits from plant sources, but sometimes seen scratching ground surfaces (Photo: Yitayal Alemu, 2024)

Figure 7: Social interactions and grooming behavior display of the observed monkey with other conspecific members (Photo: Yitayal Alemu, 2024).

interacted closely with other troop members and thus was not subjected to the kind of intense social grooming that could explain its complete hairlessness. Stress has also been linked to in primate alopecia, as elevated cortisol levels can disrupt hair follicle cycles and lead to shedding (Thom, 2016). Yet social stress is also an unlikely explanation here. The monkey was free-ranging, not in a confined captive environment where crowding and competition often heighten stress-induced alopecia (Figure 4).

Another common factor is aging, as older NHPs have a higher proportion of hairs in the telogen (resting) phase, leading to chronic telogen effiuvium and hair thinning (Lutz, 2021). This explanation can also be excluded, as this grivet monkey in question was a young individual, estimated at less than one year old.

Dermatological conditions: including bacterial and fungal infections, parasitic infestations, and skin allergies are frequently associated with alopecia in animals. These conditions usually present with signs such as scarring, lesions, inflammation, or persistent itching. However, this individual showed none of these symptoms. Instead, its skin appeared smooth, evenly pigmented, and clean-shaven in appearance (Figure 1), making dermatological causes less plausible.

Diet and nutrition: can also contribute to alopecia. In Gabon, for example, protein-deficient diets have been shown to cause hair loss

Figure 8: The hairless monkey lying on roof top of the building presumably sun-basking to keep warmth (Photo: Yitayal Alemu, 2024).

in captive gorillas, while in Madagascar, consumption of Leucaena leucocephala by ring-tailed lemurs resulted in hairlessness due to the toxic amino acid mimosine. Seasonal changes in food availability can also affect alopecia severity, as seen in rhesus macaques. However, these dietary factors are unlikely here because this monkey and other individuals in the troop shared the same free-ranging diet and environmental conditions, yet only one individual exhibited hairlessness. After eliminating these potential causes, the most plausible explanations for this case are immunologic disorder or a genetic mutation affecting hair development. Although mutations in hairless genes are rare among non-human primates (Novak and Meyer, 2009), they remain a possible cause given the complete and uniform absence of hair in the observed monkey.

4 Conclusions

In conclusion, although common causes of hair loss such as overgrooming, stress, aging, infections, and nutritional deficiencies can be largely ruled out in this case, the unusual hairlessness observed in this free-ranging grivet monkey at Wondo Genet is most plausibly caused an underlying immunological dysfunction or a rare genetic mutation. These factors may have disrupted normal hair growth and maintenance, leading to distinctive hairless condition. Further investigations, including genetic analyses and health assessments, are necessary to confirm the exact cause and better understand its implications for the individual and the population.

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Availability of data and materials

All data generated or analyzed during this study are included in this manuscript [and its supplementary information files].

Competing interests

The authors declare that they have no competing interests.

Ethical declaration

This research was approved by Salale University Institutional Research Ethics Review Committee on 30th January 2024 through the approval Reference Number of SlU-IRERC-CANRS22/25. We confirm that the research was conducted in accordance with the principles embodied in the Declaration of Helsinki and in accordance with local statutory requirements. We also confirm that all participants were given written informed consent to participate in the study. Before starting the data collection process regarding views of key informants, all participants were informed about the study's title and purpose, the procedures involved, the participation being voluntary, potential risks and benefits, the confidentiality of the collected data, and contact information for any further inquiries. Accordingly, participants confirmed their voluntary agreement to participate in the study by signing the consent agreement form.

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Journal of Forestry and Natural Resources (JFNR)

Authors Guideline

Abbreviation J. for. nat. resour.

ISSN 3005-4036

1. Editorial policy and Author's Guidelines

1.1. Background

The Journal of Forestry and Natural Resources (J. for. nat. resour., or JFNR) (JFNR) is a peer- reviewed online open-access published annually by the Wondo Genet College of Forestry and Natural Resources, Hawassa University. JFNR publishes original research findings in all subject-matter areas of forestry and natural resources. It seeks disciplinary and interdisciplinary research articles, review articles, featured articles, and short communication.

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1.2. Aims and Scope

Aims:

- serve as a communication medium among scientific communities in forestry, natural resources research, and other related fields
- publish original and innovative scientific works relevant to forestry and natural resources situation of Ethiopian as well as global problems
- encourage Ethiopian researchers, graduates, and postgraduate students to align their disciplinary and interdisciplinary researches in the direction of solving major problems in the areas of forestry and natural resources and conservation needs of the country, and
- serve as a platform to foster scientific knowledge sharing among researchers, scientists, policymakers, and practitioners working on sustainable forestry, green economy transition, issues of sustainable development goals, desertification, and dryland agriculture and forestry, combating desertification and drought, natural resource management, and conservation and other related topics.

Scope of the journal

The JFNR publishes scientific articles related to social, economic, policy, and environmental aspects: forestry, agroforestry, wildlife, soil, water and land resources, renewable energy, tourism, urban forestry, and greening, environmental science, GIS, and remote sensing.

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Submission system: Online

General contents of the journal JFNR uses the following format:

2.1. Research articles

These papers treat both disciplinary and interdisciplinary (thematic) types of researches encompassing basic and applied researches, graduate and postgraduate studies researches related to forestry and natural resources. JFNR will consider for publication articles from the regional and international forest and natural sources covering tropical and subtropical regions.

2.2. Review articles

Encompass critically reviewed scientific papers covering the state of the art knowledge in various aspects of forestry and natural resources. Review articles will be submitted by experts in the fields of forestry and natural resources with their expertise and experiences or invited by the editor-in-chief, associate editors, or editorial board.

2.3. Featured articles

These include topics in forestry and natural resources management, conservation, utilization, education, and non-conventional research articles.

Technical papers in the areas of forestry and natural resources development encompassing different aspects of socio-economics, policy issues, wildlife, environment, rehabilitation efforts and forestry and natural resources inventory and surveys, biodiversity conservation, processing and value addition of forest products, agroforestry, non-timber forest products, medicinal plants and their domestication and commercialization, integrated watershed management, green economy transition, green initiative related studies, climate change and development, land degradation and drought, aquatic ecosystem management, fisheries, etc.

2.4. Short communications

This includes articles of brief scientific notes on preliminary results, scientific observations, experimental techniques, and recent technological advances in forestry and natural resources. It also included information on specific cases and limited applications. Manuscripts for this column should not be more than six typed pages. They should have a brief abstract and not contain more than two figures and/or two tables.

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A critical evaluation of recently published books in any discipline of forestry and natural resource sciences will be published under this column.

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The peer-review process will follow double-blind where the manuscript will first be evaluated by the editor-in-chief or associate editors, followed by at least two reviewers. The names of the authors will be kept anonymous while sending them to the reviewers. At least one of the reviewers will be out of the staff of the publisher institute. If the reviewers recommend publication without any change(s) and the associate editors agree(s), the manuscript and the reviewer's comments are sent to the editor-in-chief who will notify the author accordingly. If the reviewer and the associate editor recommend that the manuscript could be published after revision, the editor-in-chief will return the manuscript to the author for minor or major revision. If the reviewer and the associate editor recommend that the manuscript be rejected, the associate editor sends the manuscript and the reviewers' comments to the editor-in-chief, and the editor-in- chief will check the comments forwarded by reviewers and associate editor to make a decision and return to the authors. If very different comments and decisions are observed between or among reviewers, a third or fourth reviewer will be invited to resolve the issue. The author whose manuscript is released has the option of appealing to the editorial board. The first review process will take 6-8 weeks.

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And also, the way references are presented both in the text and reference lists. Reviewers are expected to give their comments and suggestions clearly (referring to the line numbers in the paper) to the authors to assist the author (s) to address all comments and suggestions given. Language correction is not part of the review process but suggestions can be made by reviewers.

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The manuscript should be prepared in Times New Roman with 11 font sizes, double space, and 2.5 cm marginal indentions on all sides. The maximum number of words should be 8000. The first page should contain the full title of the manuscript, the name(s) of the author(s) including address (es), and the institution(s) in which the research was carried out. For ease of communication, authors are requested to include their email addresses. For manuscripts with multiple authors, an asterisk should indicate the author to whom all correspondence is to be addressed.

Second and consecutive paragraphs after a heading should be indented while the first paragraph after a heading should start flush left. No space should be left between two consecutive paragraphs. Scientific names should be written in full when mentioned for the first time in the text. They should be italicized. Subsequent citations should abbreviate the genus name.

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Information that explains whether and by whom the research was supported

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Paper in proceedings

Tesfaye Awas, Sebsebe Demissew (2009) Ethnobotanical study of medicinal plants in Kafficho people, Southwestern Ethiopia. In: Svein Ege, Harald Aspen, Birhanu Teferra and Shiferaw Bekele, Trondheim (Eds.), Proceedings of the 16th International Conference of Ethiopian Studies. Addis Ababa, Ethiopia.

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