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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

Merkebu Belay [1], Belew Bekele [2*], Dadi Feyisa [2], Haile Ketema [3], Eshetu Yirsaw [3]

[1] Girar Jarso District Agriculture and Land Office, Department of Watershed and Forest Development, Fiche, Ethiopia
[2] Salale University, College of Agriculture and Natural Resource, Department of Natural Resource Management, Fiche, Ethiopia
[3] 3Dilla University, College of Agriculture and Natural Resource, Department of Natural Resource Management, Dilla, Ethiopia

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CORRESPONDING EMAIL

* belewbekele@yahoo.com

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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).

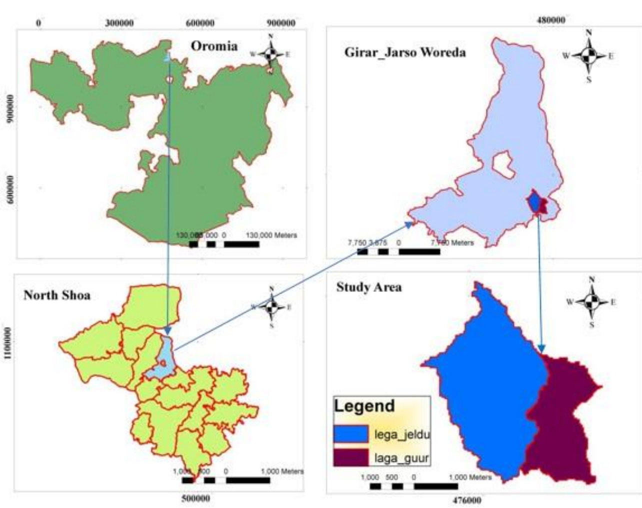

Figure 1: Location map of the study area

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/.

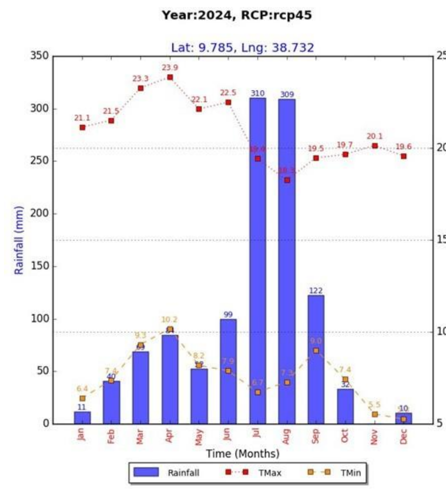

Figure 2: Climograph of the study area

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 m^2) for tree sampling, with a 50-meter gap between adjacent quadrats (Wassie et al., 2024). Additionally, five 5 m × 5 m (25 m^2) subplots for shrub sampling and five 1m * 1m (1 m^2) 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):

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

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):

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

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:

$$D_{Mn} = \frac{S}{\sqrt{N}} \quad (3)$$

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).

$$SSI = \frac{2C}{A + B} \quad (4)$$

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).

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

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

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

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

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

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

$$\text{BA} = \frac{\pi d^2}{4} \quad (10)$$

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

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

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

$$\text{IVI} = \text{RDO} + \text{RD} + \text{RF} \quad (12)$$

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 N	Mean	SD	SE	(b) t-test mean comparison F	Sig	t	df.	Mean dif.	SE dif.	95% CI of the difference 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

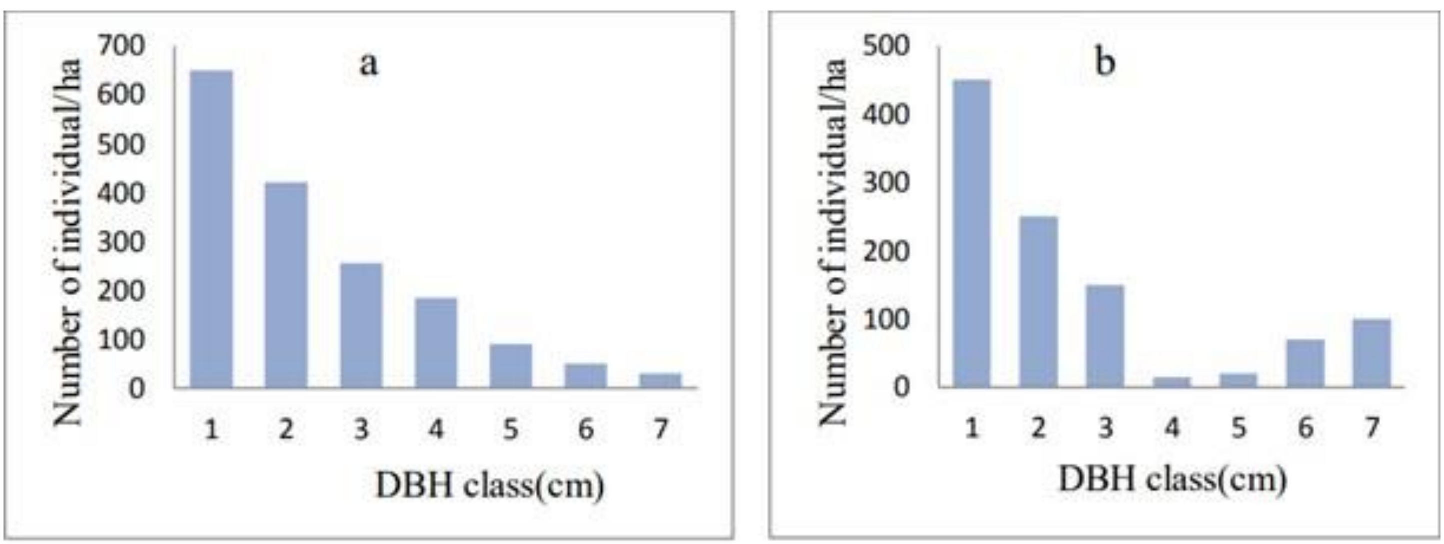

Figure 3: Distribution of individual vegetation by DBH class (cm) in Laga-Gur (a) and Laga- Jaldu (b) (DBH class: 1=2.5-10, 2=10.1-20, 3=20.1-30, 4=30.1-40, 5=40.1-50, 6=50.1-60, 7=60.1-70)

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.

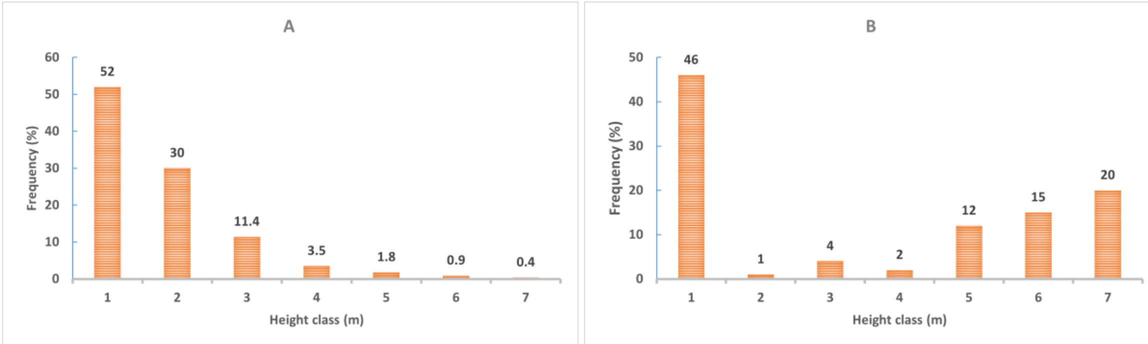

Figure 4: Percentage distribution of trees in height class (m) in Laga-Gur (a) and Laga-Jaldu (b) (Height class: 1 =1-5, 2=5.1-10, 3=10.1-15, 4=15.1-20, 5=20.1-25, 6=25.1-30, 7=30.1-35)

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).

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.

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

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

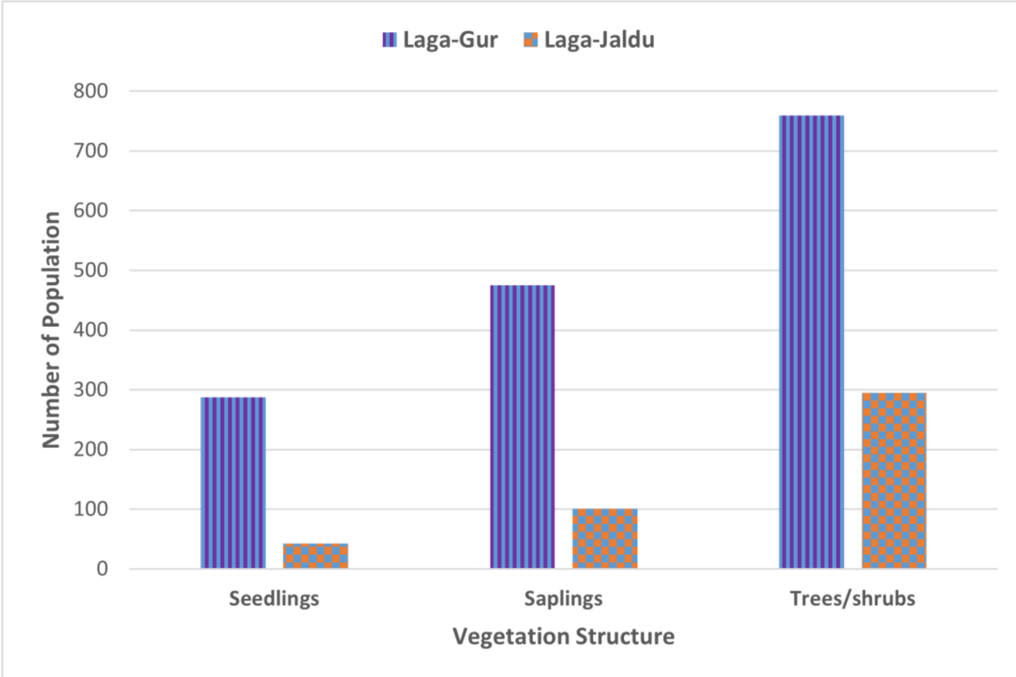

Figure 5: Structural distribution of vegetation community in the study area

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

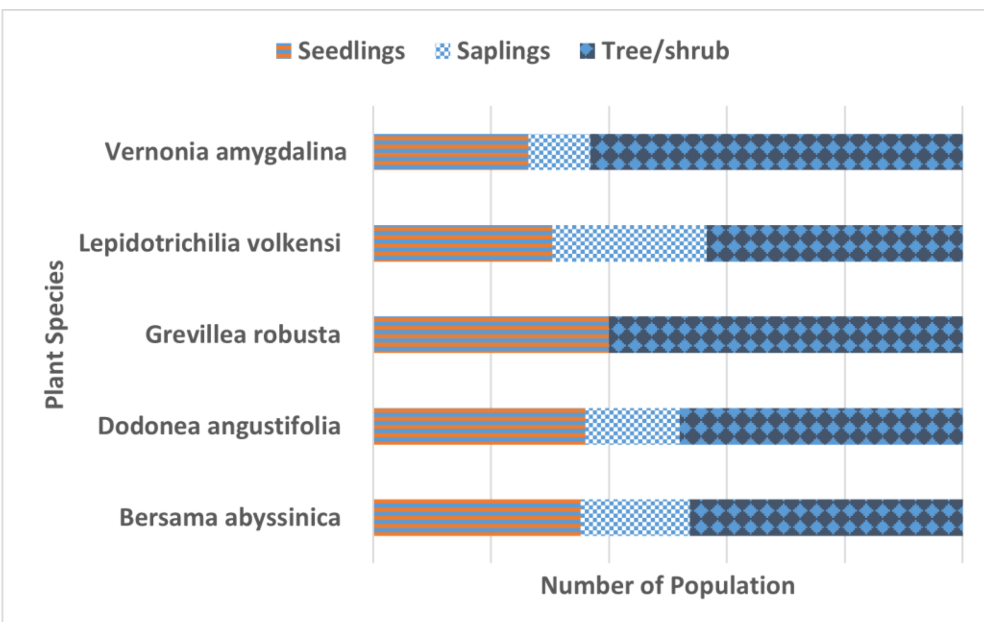

Figure 6: Plant species with 'fair' regeneration status in Laga-Gur micro watershed

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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