College of Natural and Computational Science

Department of Plant Biology and Biodiversity Management

Vegetation Ecology of Sida Forest and Ethnobotany as well as the Distribution of *Piliostigma thonningii* in South Omo Zone, Southern Ethiopia

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June 2024

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A Dissertation Submitted to:

the Department of Plant Biology and Biodiversity Management

Presented in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy (Plant Biology and Biodiversity Management)

Addis Ababa University

Addis Ababa, Ethiopia

June 2024

ADDIS ABABA UNIVERSITY
GRADUATE PROGRAMMES

This is to certify that the Dissertation prepared by Mesfin Belete Hailemariam, entitled "*Vegetation Ecology of Sida Forest and Ethnobotany as well as the Distribution of Piliostigma thonningii in South Omo Zone, Southern, Ethiopia*" and submitted to the Department of Plant Biology and Biodiversity Management in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Plant Biology and Biodiversity Management) compiles with the regulations of the University and meets the accepted standards concerning originality and quality.

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DEDICATION

This dissertation is dedicated to my family: My mother W/o Ejigayehu Ayano, Brothers and Sisters, My wife Yetimwork Mamuye, and our lovely babies Makmas Mesfin and Bitania Mesfin who bring lots of happiness to my life**.** I would like also to dedicate this work to the local people of the study area who maintained the Sida Forest and generously shared their rich ethnobotanical knowledge in plant use, particularly their understanding, use, and management of the indigenous multipurpose tree, *P. thonningii* (Fabaceae).

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LIST OF ACRONYMS AND ABBREVIATIONS

ACB = *Acacia-Comiphora* Woodland and Bushland

ANOVA = Analysis Of Variance

AUC = Area Under the Curve

Av. P = Available Phosphorus

BD = Bulk Density

C/N = Carbon-to-Nitrogen ratio

Ca^{2+} = Exchangeable Calcium

CCA = Canonical Correspondence Analysis

CEC = Cation Exchange Capacity

CSA = Central Statistical Agency

CTW = *Combretum-Terminalia* Woodland and Wooded grassland

DAF = Dry evergreen Afromontane Forest and Grassland Complex

DBH = Diameter at Breast Height

EC = Electric Conductivity

EIAR = Ethiopian Institute of Agricultural Research

EPA = Environmental Protection Authority

ETH = National Herbarium of Addis Ababa University

FAO = Food and Agriculture Organization

FEE = Flora of Ethiopia and Eritrea

FEPA = Federal Environmental Protection Authority

GG = Gamo Gofa Floristic Region

H2 = Warm humid lowlands

ha = hectare

IBC = Institute of Biodiversity Conservation

IUCN = International Union for Conservation of Nature

K^{+} = Exchangeable Potassium

masl. = meter above sea level

m^2/ha = Meter square per hectare

MaxEnt = Maximum Entropy

MEFCC = Ministry of Environment, Forest and Climate Change

meq/100g = Milli Equivalent per 100 gram

Mg^{2+} = Exchangeable Magnesium

$mScm^{-1}$ = Milisimese per Centimeter

OC = Organic Carbon

OM = Organic Matter

RCP = Representative Concentration Pathway

RV = Riverine Vegetation

SA2 = Warm semi-arid lowlands

SDM = Species Distribution Modelling

SPSS = Statistical Package for Social Sciences

TN = Total Nitrogen

UNEP = United Nations Environmental Programme

USAID = United States Agency for International Development

USDA = United States Department of Agriculture

$\chi 2$ = Chi-square

ACKNOWLEDGMENTS

First and foremost, I would like to thank the Almighty God, who has been with me in all aspects of my life, and His unspeakable gift to everyday life and His help during this graduate study.

I would like to express my deepest gratitude and sincere appreciation to my advisers, Prof. Zerihun Woldu, Prof. Zemede Asfaw, and Dr. Ermias Lulekal for their guidance, support, suggestions, and effective follow-up of the research work from the time of proposal formulation to the enrichment of the dissertation.

I would like to acknowledge Wolkite University (WKU) for sponsoring me to pursue my PhD study. The postgraduate program office of Addis Ababa University is also acknowledged for funding research expenses. I would like to extend my acknowledgment to the McKnight Foundation Collaborative Crop Research Program (Legume Diversity Project) for providing training and grants used for field expenses. My thanks also go to the IDEA WILD for granting field equipment (such as a laptop computer, tablet mobile, clinometer, and compass).

I would like to thank the administrative heads of the two Districts (Benna-Tsemay and Hamer Districts) for their cooperation and assigning field assistants. I would also like to extend my deepest gratitude to the staff members of the National Herbarium (ETH), W/ro Shewangiziew Lemma, Ato Melaku Wondafirash, and Ato Wogie Abebe for their hospitality and cooperation in all aspects of the herbarium work. My special thanks go to the staff members of Wolkite Soil Testing Laboratory Ato Gizachew Demis, Ato Neja Bedru, Ato Murad Mohamed, Ato Fetu Nuriya, W/ro Kebebush Demissei, and all other laboratory technicians who offered their kind help in soil sampling and facilitating the soil analysis process, and their committed, active participation during laboratory work.

I want to express my heartfelt thanks to my wife W/ro Yetimwork Mamuye and our children Makmas and Bitania, for the love they offered me, their encouragement, and the patience they showed whenever they missed me while I was concentrating on my studies. I would also like to express my special thanks to my Mother, Brothers, and Sisters for their kindest support and prayers throughout the study period. Thus, without their support, and encouragement, this PhD work would not have come to this fruitful end.

Last, but not least, my special thanks are forwarded to all the local people of the study area, who maintained the forest and shared their rich ethnobotanical knowledge in plant use, their cooperation was instrumental in achieving my objectives of field data collection.

ABSTRACT

Vegetation Ecology of Sida Forest and Ethnobotany as well as Prediction of the Distribution of *Piliostigma thonningii* in South Omo Zone, Southern Ethiopia

Mesfin Belete Hailemariam, PhD Dissertation
Addis Ababa University, June, 2024

A study on the vegetation ecology and ethnobotany as well the predition of Piliostigma thonnigii was carried out in Sida forest in South Omo Zone, southern Ethiopia. The aim was to evaluate the status of the forest with variables governing species distribution pattern and further document the ethnobotanical uses and distribution of P. thonningii. Vegetation and environmental data were collected from 82 sample plots (each 20 m × 20 m) placed along twelve transect lines, which is 1km apart and 300m distance between plots. Height and DBH were measured for each woody species that had a height ≥ 2 m and DBH ≥ 2.5 cm. From ech plot a kilogram of composite soil samples were brought to the Wolkite soil testing laboratory for physicochemical analysis. Using stratified random sampling methods, 84 informants were sampled for ethnobotanical data collection focusing on P. thonningii. Structured and semi-structured interviews, guided field walks, and focus group discussions (six individuals in each Kebele) were used for ethnobotanical data collection. Thirty-six occurrence points and nine environmental predictor variables were used to predict the distribution of P. thonningii, which was modeled using MaxEnt (MaxEnt v. 3.4.1). Density, frequency, basal area, importance value index, and size class distribution were used to analyze the vegetation structure of Sida Forest. Hierarchical cluster analysis was used to compute and identify plant community types and CCA was used to analyze the relationship between plant communities and environmental variables. The Shannon-Wiener diversity index was used to compute species richness, diversity, and evenness. Sorensen's similarity coefficient was used to measure species similarities among the plant community types. Ethnobotanical knowledge held by informants was analysed using relevant descriptive statistical methods, Pearson's chi-square test, direct matrix and pair-wise ranking. The results of the study revealed that the study area harboured 254 plant species belonging to 180 genera and 82 families. Nine (3.5%) of the species are endemic. Fabaceae (26), Asteraceae (15), and Lamiaceaae (15) were the dominant families in terms of the number of species. Shrubs occupied the highest (35%) percentage followed by herbs (30%). The overall density of woody species was 682.32/ha. The highest density (324.39/ha) was found in the lower DBH class (2.5-10 cm), while the lowest (13.72/ha) was in the higher DBH class (> 60cm). DBH and height class distribution showed an inverted J-shape distribution. The frequency of woody species ranged from 1.2% to 42.7%. The basal area of woody species is 24.15 m^2/ha. The IVI value ranges from 0.13 to 14.62. Five plant community types were identified and the environmental factors such as elevation, slope, aspect, sand, pH, and disturbance were the major environmental factors determining plant species distribution and community formation. The Shannon-Wiener diversity indicates species diversity ranging from 3.25 to 4.44. Soresen's index of similarity showed the presence of the highest similarity between communities two and three (58.9%), while the least similarity was found between community one and community five (18.3%). The physicochemical properties of the soil such as OC, OM, TN, CEC, and exchangeable Mg^{2+} showed a positive correlation with elevation, while BD, pH, EC, Av. P, exchangeable Ca^{2+}, and exchangeable K^+ had a negative correlation with elevation. The results also showed that P. thonningii provides different functions to people's livelihoods. The results indicated that out of 862,247.05 ha of the total study area, 152,398.39ha (17.67%) was suitable for P. thonningii, of which 2,329.50 ha (0.27%) were highly suitable, 33,809.59 ha (3.92%) moderately suitable and 116,259.31ha (13.84%) was less suitable. Seasonality and annual range of temperature, solar radiation, and elevation had the highest contribution (69.4 %) in predicting P. thonningii distribution. Agricultural expansion, firewood collection and harvesting for fencing were the most threatening factors to Sida Forest in general and P. thonningii in particular. Field survey also confirmed that settlement, forest fire, and human encroachment were threatening factors to Sida Forest. Thus, Sida Forest requires urgent interventions that reduce the threat levels for the conservation of the forest in general and useful plants in particular.

Key Words/Phrases: *Piliostigma thonningii*; Plant communities; Sida Forest; Soil physicochemical properties; Species distribution modeling.

CHAPTER ONE

1. GENERAL INTRODUCTION

1.1. Background and Justification

Biodiversity is the total number, variety and variability among living organisms from all sources including inter alia, terrestrial, marine and other aquatic systems (IBC, 2009). The level of biodiversity indicates the health of the habitat. If an area has a high variety of life, it is said to be very healthy as it is capable of supporting life well, and communities with a greater number of species per functional group are more stable than communities with fewer species. Ethiopia is one of the biodiversity-rich country, hosting two (the Eastern Afromontane and the Horn of Africa biodiversity hotspots) of the world's 36 biodiversity hotspots (Mittermeier *et al.*, 2004; Noss, 2016). Biodiversity is an important element of natural resource, plays a vital role to human survival through the provision of ecosystem services and ecological processes and deliver a wide range of services, such as erosion control and reduced flooding; water purification and retention, they support food and health security by maintaining crop diversity and species, particularly play an important role in climate change adaptation and contribute to mitigation through the storage and sequestration of carbon (Mekonnen Daba & Sintayehu Dejene, 2018). Nearly half of the world's biodiversity hotspots are found in mountains (Korner, 2005).

Ethiopia is the fifth highest peaks mountain in Africa and more than 50 % of African mountains (land above 2000 meters) are found in Ethiopia (Friis *et al.*, 2010). The highlands of Ethiopia over 2,500 masl. covers 40 % of the country (Zerihun Woldu *et al.*, 1999). These diverse topographic features with a wide range of elevation, ranging from 125 meters below sea level (in Afar Depression- Kobar Sink) to 4533 meters above sea level (in Ras Dashen), edaphic and climate conditions create conducive environments for the occurrence and survival of wide diversity of biological resources, both in terms of flora and fauna (Zerihun Woldu *et al.*, 1999; Friis *et al.*, 2010; EBI, 2014; Sebsebe Demissew *et al.*, 2021).

The country is broadly divided into three major climatic zones: Cool highlands (> 2300 masl.), temperate highlands (1500-2300 masl.), and hot lowlands (<1500 masl.) (FAO, 2012). The rainfall distribution patterns are generally described as unimodal, bimodal, or scanty and erratic (EBI, 2014). The mean annual rainfall range from below 200 mm to above 2 800 mm, with the highest annual rainfall (above 2800 mm) in southwestern region, and the mean annual temperatures range from below 10 ^{o}C to above 30^{o}C (FAO, 2012; EBI, 2014). There are 60 soil types with an area coverage ranging from 1.4 (Dystric Cambisols) to 208,882 km^2 (Lithic Leptosols). Lithic Leptosols (18.46%), Humic Nitisols (11.90%) and Eutric Vertisols (10.18%) are the three major soil types (Belete Berhanu *et al.*, 2013). Ten soils textural classes in the country. The majority of the area was covered by sandy loam (30.51%), followed by loam (30.19%), clay (20.86%) and loamy sand (17.47%) (Belete Berhanu *et al.*, 2013). The heterogeneity of the resource resulted in diverse ecosystems inhabited with a great diversity of life forms (Zerihun Woldu, 1999) with high endemism. Ethiopia is the fifth largest country in terms of floral diversity in tropical Africa (EPA, 1997; EBI, 2014; Ensermu Kelbessa & Sebsebe Demissew, 2014). The flora of Ethiopia is highly diverse and contains an estimated number indigenous plant species of 4481, of which 19.9% are considered to be endemic (Sosef *et al.*, 2017).

Forests are widely known as the world's largest repositories of terrestrial biodiversity (FAO, 2014; FAO & UNEP, 2020), and nearly 90% of terrestrial biodiversity is found in the world's forests (Nestlé, 2013; FAO, 2014). The forest resources assessment reported by FAO (2010) puts Ethiopia among the countries with a forest cover of 10-30%. The country's forest cover is about 17.07 million hectares (FAO, 2020), which is about 15.7% (MEFCC, 2017). Forests and trees outside the forest play multiple roles to the well-being of humankind at local, national and global levels, by providing ecological, economic, and cultural services and are also used as a source of feed for both domestic and wild animals (Teshome Abate *et al.*, 2012). About 1.6 billion people (more than 25%) of the world's population rely on forest resources for their livelihoods (FAO, 2014). Contribute to crop production through nitrogen fixation, and humus development (Katila *et al.*, 2014), they provide food, medicine, fuel wood, timber, fodder, shade, and habitats for other organisms (Devendra, 1990; Kacholi, 2014; Langat *et al.*, 2016). They also provide a variety of environmental services, used as a source of income, and recreation (Devendra, 1990; IBC, 2009; Agustino *et al.*, 2011; Amogne Asfaw, 2014; EBI, 2014; Othow *et al.*, 2017).

Despite the diversified services of forest, the growing effect of human activities, land degradation, climate change, lack of sustainable utilization, proper management strategies create a pressure on forests, particularly on the vegetation and soil resources (Badege Bishaw, 2001; Teshome Soromessa *et al*., 2004; Kaky & Gilbert, 2016). The vegetation of Sida Forest was intact previously (information from community elders) and plays a crucial role in the livelihoods of the local communities, however, at present it is shrinking. This forest is surrounded by settlements (three

Kebele's: Kako, Chali, and Yirga), agricultural, and grazing lands, and influenced by various factors such as agricultural expansion, overgrazing, fire, human encroachment, and deforestation for firewood, charcoal, construction material, farm implements, and timber production. This action reduce the forest resources and led to environmental degradation and loss of key species, including *P. thonningii*. To take an effective management and conservation actions, detailed ecological studies are essential to understand the status of the forest. However, no work has been conducted to date on the vegetation ecology, population structure, regeneration status, soil physicochemical properties, use and distribution of species, like *P. thonningii*. Therefore, it is vital to assess the vegetation, soil physicochemical properties of the forest and indigenous ethnobotanical knowledge of the local communities on the use of key species, like *P. thonningii* and its distribution.

1.2. Literature Review

Forests of Ethiopia

Forest ecosystems are the world's largest repositories of terrestrial biodiversity (FAO, 2014). More than one-third of the total land area of the world is primary forest, i.e. forest of native species where there are no clearly visible indications of human activities and the ecological processes have not been significantly disturbed (FAO, 2010). According to FAO (2010), forests are defined as a piece of land area of more than 0.5 hectares, with more than 10 percent tree canopy cover and trees reaching a minimum height of 5 meters at maturity or trees able to reach these thresholds at maturity in-situ. However, Ethiopia adopted a new forest definition as land covering an area of 0.5 ha and above, attaining a height of more than 2m at maturity and a canopy cover of more than 20% or trees with the potential to reach these thresholds in situ. Based on FAO's definition of a forest, out of the twelve major vegetation types of Ethiopia (Friis *et al.*, 2010), the following six vegetation types are considered forests: i) *Acacia-Comiphora* woodland and bushland, ii) *Combretum-Terminalia* woodland and wooded grassland, iii) Dry evergreen Afromontane forest and grassland complex, iv) Moist evergreen Afromontane forest, v) Transitional rainforest, and vi) Riverine vegetation (FAO, 2012).

The country's forest cover is about 17.07 million hectares (FAO, 2020), which is about 15.7% (MEFCC, 2017). In the country there are about 58 most important high forest areas National Forest Priority Areas (NFPAs). Among the 58 NFPAs, 37 of them have been identified as protected forests (FAO, 2012). Species diversity index is one of the most important indices used for evaluating the sustainability of forest communities and is measured by recording the number of species and their relative abundance. A floristic description of community involves the analysis of species diversity, richness, evenness, and similarity (Whittaker, 1975). Species diversity is described based on two fundamental parameters, species richness (the total number of species) and species evenness (relative abundance of species) (Kent & Coker, 1992; Hamilton, 2005). Shannon Weiner diversity index (Shannon & Weaver, 1949) is the most commonly used index for comparing diversity between various habitats (Kent & Coker, 1992). Similarity indices measure the degree to which the species composition of the plots/samples or community is a like. Sorenson's coefficient of similarity is the most common similarity coefficient that relies on the presence or absence of data (Kent & Coker, 1992).

Vegetation types of Ethiopia

One of the biological resources is the natural vegetation where the floristic and faunistic elements with the abiotic components form dynamic ecosystems. Vegetation is the collection or assemblage of all populations of plant species growing together in a particular area or it is the total plant cover of an area (Van der Maarel & Franklin, 2012). Vegetation structure is the organization of individuals and the spatial pattern of growth forms in a plant community, especially in relation to their height, abundance, or coverage within the individual layer (Mueller-Dombois & Ellenberg, 1974). The vegetation of Ethiopia is classified into 12 major vegetation types (Friis *et al*., 2010). According to Friis *et al.* (2010) classification, the vegetation type of the study area mainly falls into *Acacia-Comiphora* woodland and bushland (ACB), *Combretum-Terminalia* woodland and wooded grassland (CTW), Dry evergreen Afromontane forest and grassland complex (DAF) and Riverine vegetation (RV). A brief description of these four vegetation types is provided by Friis *et al.* (2010).

Plant communities

In the natural vegetation, plants do not exist in isolation but rather grow in a mixture of co-existing populations, forming an association as a plant community (Kraft & Ackerly, 2014). A plant community is defined as a collection or assemblage of plants growing together in a particular location sharing a common environment that shows a definite association or affinity with each other, with animal populations, and with the physical environment, and is distinct from the adjacent assemblages (Kent, 2012). The existence of plant communities is due to the interaction between plant species and their environment (Chapin *et al.*, 2002). The environmental factors such as climate, topography, and edaphic are the most important in identifying plant species distribution and controlling the pattern of plant community formation (Liu *et al.*, 2003; Abella & Covington, 2006; Liu *et al.*, 2007; Toledo *et al.*, 2012; Fadrique & Homeier, 2016). Plant community type is characterized by the combination of sample plots having similar floristic composition (Mueller-Dombois & Ellenberg, 1974), and sample plots that make up a community are consistent in physiognomy and composition even though they are found in isolated locations (Van der Maarel, 2005). The dominant species which may be a single species or several co-dominant species is used in naming the plant communities (Kent & Coker, 1992).

Plant community data are multivariate in nature and their analysis requires multivariate techniques (McCune & Grace, 2002). Classification and ordination are the two main and basic techniques used to analyze the complex nature of plant communities (Mueller-Dombois & Ellenberg, 1974; Lepš & Šmilauer, 2003; Chahouki, 2013; Zerihun Woldu, 2017). Classification groups a set of vegetation samples (plots) together based on their attributes, and plant species composition (Kent, 2012). In classification, every individual in each group is more similar to the others in that group than to any individuals in any other group (Kent & Coker, 1992; McCune & Grace, 2002; Kent, 2012). The techniques in cluster analysis can be divided into two as hierarchical and non-hierarchical (Lepš & Šmilauer, 2003; Zerihun Woldu, 2017). However, hierarchical techniques are generally preferred to non-hierarchical (Kent & Coker, 1992). The result of hierarchical cluster analysis is shown in a dendrogram, called a tree diagram (Podani & Schmera, 2006; Zerihun Woldu, 2017) that could be cut at arbitrary heights to give a fixed number of clusters (Kent & Coker, 1992). In the structure of a dendrogram all the sample plots are listed on the X-axis and the Y-axis shows similarity or distance at which clusters are joined.

The hierarchical classification technique is further divided into two (Lepš & Šmilauer, 2003; Seefeld & Linder, 2007; Chahouki, 2013), namely agglomerative and divisive. The agglomerative hierarchical is the most preferred by ecologists (Kent & Coker, 1992). In the agglomerative clustering technique, the most similar objects are first joined to form the first cluster, which is considered an object, and the joining continues until all the objects are joined in the final cluster, containing all the objects (Lepš & Šmilauer, 2003; Seefeld & Linder, 2007; Chahouki, 2013). It is referred to as the “bottom-up method” since the clustering starts at the bottom and works upwards. Plots that are similar to each other are combined at low heights, whereas those that are more dissimilar are combined higher up the dendrogram (Kent & Coker, 1992).

Ordination expresses the relationships between samples, species, and environmental variables using ordination diagrams (McCune & Grace, 2002). Correlation analyses between environmental factors and ordination axes scores can be used to identify and describe environmental factors that influence species distribution patterns and species response to these variables (Kent & Coker, 1992; McCune & Grace, 2002). Canonical Correspondence Analysis (CCA) is the most appropriate method for the present study in assessing the relationship between vegetation and environmental data (Palmer, 2004; Chahouki, 2013; Zerihun Woldu, 2017). It incorporates the correlation and regression between floristic and environmental data within the ordination analysis (Chahouki, 2013). CCA is best suited to the community data sets where species response to the environment is unimodal and the important underlying environmental variables have been measured (McCune & Grace, 2002).

Plant population structure and regeneration status

Population structure is an indication of the stability and regeneration status of the forest vegetation (Kent, 2012). Population structure is characterized by the presence of a sufficient number of seedlings, saplings, and adults. Forest natural regeneration is the renewal of forests by means of natural biological processes (Wangchuk, 2007; Wang *et al.*, 2008). Size class distribution as DBH and height are used to evaluate the structure and regeneration of species. An inverted J-shape pattern indicates a stable population structure and healthy regeneration potential (Getachew Tesfaye *et al.*, 2002; Kebu Balemie & Fassil Kebebew, 2006), however, any population pattern other than an inverted J-shaped, indicates a disturbed forest (Motuma Didita *et al.*, 2010; Abyot Dibaba *et al.*, 2020). Forest can be restored with natural regeneration through seedling establishment and resprouting from cut stumps (Vieira & Scariot, 2006; Wang *et al.*, 2008). Various environmental factors, such as abiotic factors (light conditions, temperature, nutrients, wind, disturbances, and moisture), and biotic factors (intra and interspecific competition, fungal infection, and herbivory) affect the regeneration potential of a given forest (Nagamatsu *et al.*, 2002; Haileab Zegeye *et al.*, 2011).

Environmental factors affecting plant species distribution

The patterns of plant species distribution, abundance, diversity, and co-existence in a given area are not accidental but determined by changes in environmental factors, such as climatic, topographic, edaphic, and disturbance (Liu *et al.*, 2003; Abella & Covington, 2006; Tiwari *et al.*, 2010; Gholinejad *et al.*, 2012; Getaneh Gebeyehu *et al.*, 2019; Mengistu Teshome *et al.*, 2020).

Topographic attributes such as elevation (Zerihun Woldu *et al.*, 1989; Friis *et al.*, 2010), aspect, and slope indirectly influence the distribution and community formation by regulating micro-climatic and other environmental factors in the site such as soil conditions, hydrology, wind exposure, temperature, and fog frequency (Kreft & Jetz, 2007; Eiserhardt *et al.*, 2011; Poelking *et al.*, 2015). Species richness decreases with increasing elevation, largely in proportion to the available land area (Rana *et al.*, 2022), but species endemism increases with elevation, due to topographical isolation and speciation (Zerihun Woldu *et al.*, 1999; USAID, 2008; Schmitt *et al.*, 2013). The slope of an area determines vegetation composition and structure (Biru, 2003), and steep slopes, poorly support vegetation growth. Slope angle and aspect have fundamental effects on radiation income and temperature conditions (Barry, 2008).

Specific soil properties such as soil climate (moisture and temperature), soil texture, soil pH, and soil salinity determine species composition, richness, diversity, and plant community distribution in forest ecosystem (Zhang & Zhang, 2011; Schoonover & Crim, 2015; Maharjan *et al.*, 2022). The physicochemical properties of soil influence root distribution and the ability to extract water and nutrients (Bronick & Lal, 2005). Soil compaction influences the distribution of plants and more than 90% of roots were in the upper 40 cm of soil (Murphy & Lugo, 1986). Soil texture is an important factor in the soil–water potential– content relationship (Belete Berhanu *et al.*, 2013). Elevation determines the physicochemical properties of soil (Mulugeta Lemenih & Fisseha Itanna, 2004; Charan *et al.*, 2013; Saeed *et al.*, 2014; He *et al.*, 2016; Sierra *et al.*, 2017; Pourbabaei *et al.*, 2020; Weldemariam Seifu *et al.*, 2021; Gömöryová *et al.*, 2022; Han *et al.*, 2022). Species richness declined in both acidic and alkaline soils (Pausas & Austin, 2001). Soil processes and the availability of plant nutrients in the soil are largely controlled by soil pH (FAO, 2006). Disturbances influence species distribution and composition (Ermias Aynekulu *et al.*, 2016; Admassu Addi *et al.*, 2020; Dhar & Sarker, 2021), and increase with intermediate disturbances (Zhang, Xu, *et al.*, 2013).

Climatic factors affect plant species diversity, distribution, and community formations (Liu *et al.*, 2007; Ermias Aynekulu *et al.*, 2016), and climate change causes the species to track suitable climatic conditions and shift their distribution ranges either poleward or upward (Chen *et al.*, 2011; Maharjan *et al.*, 2022). Local climate changes and forest disturbances are the two most important factors influencing species diversity and distribution in a forest (Amare Mekonnen *et al.*, 2022). The growing effect of human activities and climate change creates an urgent need to understand the factors that determine the distribution of plants, identify prior conservation areas, and implement successful management plans (Dubuis *et al.*, 2011; Kaky & Gilbert, 2016). Species distribution modelling is a process where the occurrence records and environmental data of a species are used to predict the species potential distribution areas (Rodríguez *et al.*, 2007). Environmental variables such as rainfall and temperature, soil fertility, topography, and irradiance play a vital role in species distribution modelling (Toledo *et al.*, 2012; Amissah *et al.*, 2014; Dhakal, 2018). Among the various tools used to predict species potential distributions is the Maximum Entropy Model (MaxEnt) (Phillips *et al.*, 2006; Phillips, 2008; Fourcade *et al.*, 2014). MaxEnt is widely used and has the best predictive power using presence-only data, being less affected by small sample sizes than other methods (Rodríguez *et al.*, 2007; Wisz *et al.*, 2008). It is easily accessible, free to use, easy to learn, insensitive to sample size, and achieves high predictive accuracy with presence-only datasets and a small number of species-occurrence records and environmental variables (Phillips *et al.*, 2006; Merow & Silander, 2014; Araújo *et al.*, 2019).

Importance of forest and forest resources

Forests and trees outside the forests are essential to the well-being of humankind throughout the world by providing ecological, economic, and cultural services and are also used as a source of feed for both domestic and wild animals (Teshome Abate *et al.*, 2012). The science that studies these relationships between plants, people, and the environment is ethnobotany (Martin, 1995; Balick & Cox, 1996). People in different areas with different ethnic, religious, linguistic, and cultural backgrounds, with different age and gender groups, have their own specific knowledge about the use of plants (Balick & Cox, 1996). In Ethiopia, the variation in ethnicity, linguistic, religious, and social diversification led to varied plant traditions (Getachew Addis *et al.*, 2013). There are more than 40,000 useful plant species reported to fulfill a particular need of humans, animals, and the environment (Kor *et al.*, 2021).

In Ethiopia, different multipurpose indigenous tree species were reported by different authors (Misrak Tafesse, 2007; Biruktayet Assefa *et al.*, 2010; Wubalem Tadesse *et al.*, 2012; Takele Geta *et al.*, 2014; Dessalegn Ayele, 2017). One of the potential indigenous multipurpose tree species (Azene Bekele & Tengnäs, 2007; Kassahun Desalegn *et al.*, 2016; Almaz Ayenew, 2019) is *Piliostigma thonningii,* which is commonly found and used by the people of the South Omo Zone (Assegid Assefa & Tesfaye Abebe, 2011). *Piliostigma thonningii* is a deciduous tree widely distributed in tropical Africa and common in open woodland and wooded grasslands, often found in river valleys of sub-humid Africa at low to medium altitudes, with an altitude range between 500 to 2000 m (Hedberg & Edwards, 1989; Orwa *et al.*, 2009). In Ethiopia, it occurs in deciduous woodlands and wooded grasslands in most parts of the country (Figure 1). It is found growing as a wild uncultivated (Thulin *et al.*, 1989; Azene Bekele & Tengnäs, 2007).

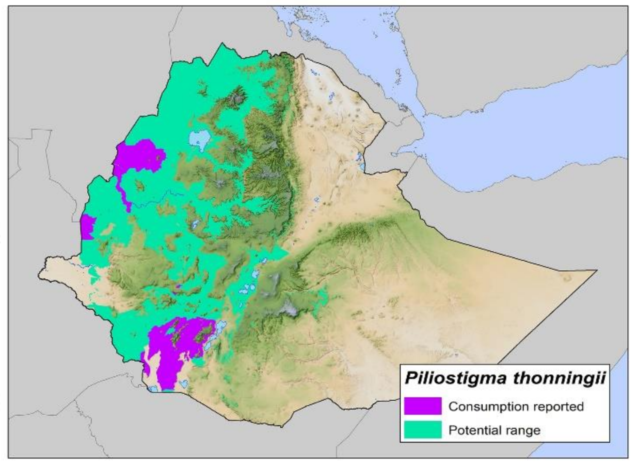



Figure 1.Distribution of *P. thonningii* in Africa (Debissa Lemessa, 2010) and in Ethiopia (Morgan Ruelle).

Piliostigma thonningii is used as a source of food for humans in the South Omo Zone (Assegid Assefa & Tesfaye Abebe, 2011; Mesfin Belete *et al.*, 2021). In other African countries, *P. thonningii* is used for various purposes other than food. *P. thonningii* is browsed by animals (Jimoh & Oladiji, 2005; Egharevba & Kunle, 2010; Jemiseye *et al.*, 2019). The leaves are eaten and chewed to relieve thirst (Jemiseye *et al.*, 2019). The wood is suitable for poles, firewood, charcoal, construction, household utensils, and farm implements (Thulin *et al.*, 1989; Orwa *et al.*, 2009; Chidumayo, 2018). The bark is used to make strings, ropes, and clothes (Thulin *et al.*, 1989; Orwa *et al.*, 2009; Egharevba & Kunle, 2010). Different phytochemicals are extracted from *P. thonningii*. It is used to treat various diseases (Ruffo *et al.*, 2002; Jimoh & Oladiji, 2005; Orwa *et al.*, 2009; Ukwuani *et al.*, 2012; Deshi *et al.*, 2014; Baldé *et al.*, 2016; Dluya & Dahiru, 2018; Jemiseye *et al.*, 2019; Musah, 2019).

Threats to the Vegetation of Ethiopia

The world's forests have been decreasing from time to time because of increasing human activities and global climate change (Chen *et al.*, 2011). An increase in demands for forest products and forestland together with the increase in human population is putting pressure on the natural forests and causing loss of biodiversity (IBC, 2005; Husen *et al.*, 2012). The most common threats are habitat loss and fragmentation, agricultural expansion, deforestation, free livestock grazing, climate change, expansion of invasive species, and overexploitation (Teshome Soromessa *et al.*, 2004; Haileab Zegeye *et al.*, 2011; FAO & UNEP, 2020). Habitat loss and land degradation are the direct threats to biodiversity loss in the tropics (Haddad *et al.*, 2015), and the situation is well reflected in Ethiopia. About 420 million ha of forest was lost through deforestation between 1990 and 2020 (FAO & UNEP, 2020). The rate of deforestation increased in developing countries including Africa in the last 50 to 100 years (Othow *et al.*, 2017).

In Ethiopia, the major driver of deforestation is the expansion of agriculture in forest areas (FAO, 2017), about 80% of new agricultural land was created by converting forests, woodlands, and shrub lands in the years between 2000 to 2008 (Demel Teketay, 2012). This implies that forests and woodlands are shrinking both in size and species diversity (EBI, 2014). Charcoal production (Meles Teka, 2006; Solomon Chanie & Dereje Tesfaye, 2015), urbanization, forest fires (Feyera Senbeta & Demel Teketay, 2003), and climate change (Chen *et al.*, 2011) affect the high forests of the country.

1.3. Statement of the Research Problem

A significant proportion of Ethiopia was once covered by forests having wider coverage than at present, but gradually declined from the original 35-40% of the land area to 16% in 1952, further rapidly dropped to 3.6% by 1980, to 2.4% in 1992 (EFAP, 1994). However, the recent data on the forests of Ethiopia puts Ethiopia among the countries with forest coverage of 10-30% (FAO, 2010). The rate of forest cover loss in the country is 104,600 ha (0.8%) per year (FAO, 2010), and the annual deforestation rate is estimated at 92,000 ha (FAO, 2015). The loss of forest resources would have a great effect on the environment, biodiversity, and socio-economy of the communities in and around the forest (Sisay Nune *et al*., 2010). The most obvious factors contributing to the reduction of forest covers in the country include land degradation, expansion of invasive species and various human-induced factors such as expansion of agriculture, deforestation, overgrazing, fire, settlements, and overexploitation for various purposes such as firewood, charcoal, construction material, farm implements, and timber (Teshome Soromessa *et al.*, 2004; Haileab Zegeye *et al.*, 2011). The intensive action of these factors accelerated the decline of forest resources and led to environmental degradation. To take effective management and conservation actions, detailed ecological studies on plant species diversity, community types, and the environmental factors that govern the growth, survival, and distribution of plants are essential to understand the dynamics of the forest. Studies showed that understanding the species diversity, population structure, regeneration status of forest species and the associated environmental factors is an essential feature in providing basic information to plan successful management and conservation action for sustainable utilization (Kacholi, 2014; Alemayehu Yigeremu & Mesfin Woldearegay, 2022).

The vegetation of Sida Forest was influenced by various factors such as agricultural expansion, overgrazing, fire, human encroachment, and deforestation for firewood, charcoal, construction material, farm implements, and timber production, which lead to the loss of key species, including *P. thonningii*. There is no ecological information concerning the species composition, diversity, community types, regeneration status, and the physicochemical properties of the soil in the forest, and the ethnobotanical uses of *P. thonningii*, its potential distribution range, and the main environmental factors influencing the distribution of the forest species, including *P. thonningii*. Therefore, a detailed ecological study of the vegetation of Sida Forest, an ethnobotanical study and potential distribution range of *P. thonningii*, and the main environmental factors controlling the distribution of plant species are necessary to take effective forest and forest resource management and conservation actions.

1.4. Research Questions

The following were the main research questions, this study attempted to investigate:

1. What are the current floristic statuses of Sida forest look like?
2. What are the major plant community types in Sida Forest?
3. What are the major variables that determine plant community formation?
4. How soil physicochemical properties are related with one another and with elevation gradient?
5. What are the structural dynamics and regeneration status observed within the Sida forest?
6. How the ethnobotanical uses of *P. thonningii* differ in the two ethnic groups (Benna and Hamer)
7. How the climate scenario affect current and future distribution P. thonningii?
8. What are the major threatening factors of Sida Forest and *P. thonningii* in particular?
9. How the local people conserve Sida forest and *P. thonningii*?

1.5. Objectives of the study

1.5.1. General Objective

The general objective of this study was to investigate the vegetation ecology and soil physicochemical properties of Sida Forest, and to document the ethnobotanical use of *P. thonningii*.

1.5.2. Specific Objective

The specific objectives of the research were to:

1. To assess the floristic composition of Sida Forest;
2. To identify the plant community types in the study forest;
3. To compare the species richness, evenness, and diversity among the different plant community types;
4. To identify the major variables that determine plant community formation;
5. To analyzes vegetation structural pattern and regeneration statuses of selected woody species in the study forest;
6. To analyze the relationship between soil physicochemical properties and the forest's elevation gradients;
7. To document the ethnobotanical uses of *P. thonningii* by the local communities;
8. To identify the major threatening factors of the Sida forest as well as *P. thonningii*.
9. To assess the traditional conservation practices of local communities.

1.6. Structure of the Dissertation

This Dissertation consists of six chapters: the first chapter is the general introduction (this chapter), the next three chapters are research chapters (chapters 2-4), the fivth chapter is the general discussion, conclusion and recommendation (chapter 5), finally the references and appendices parts.

The first chapter (Chapter 1) starts with a general introduction encompassing a brief description of the background of the subject of investigation, followed by established research questions, and objectives.

The next three chapters (chapters 2-4) have their own specific introduction, objectives, methods, results, discussion, and conclusion. Each chapter focuses on specific points (objectives) as described below: The second chapter (Chapter 2) focuses on the ecological assessment of floristic composition, population structure, species diversity, community types, regeneration status of woody species, and the major environmental and disturbance factors that determine the distribution of plant species and community formation in the Sida Forest. The third chapter (Chapter 3) focuses on the impact of elevation on the distribution of soil's physicochemical properties along the Sida Forest's elevation gradients. The correlations between the soil variables and the elevation are briefly discussed. The fourth chapter (Chapter 4) targeted the use of plant species (*P. thonningii*), indigenous knowledge of plant use, the science of ethnontany, the role of indigenous knowledge in conserving plants, the status of *P. thonningii* in South Omo Zone; and threats to *P. thonningii*. The last chapter (Chapter 5) includes a general discussion based on the results of each chapter and its respective subsections, followed by conclusions and ending with appropriate recommendations of the whole work.

Chapter two: Manuscript

Ecological assessment of plant species diversity, vegetation structure, and the relationship between plant communities with environmental and disturbance factors in the Sida Forest, South Omo Zone, Southern, Ethiopia.

Mesfin Belete Hailemariam, Zerihun Woldu, Zemede Asfaw and Ermias Lulekal

Chapter three: Published

Mesfin Belete, Zerihun Woldu, Zemede Asfaw and Ermias Lulekal, 2021

Ethnobotany of an indigenous tree Piliostigma thonningii (Schumach.) Milne- Redh. (Fabaceae) in the arid and semi-arid areas of South Omo Zone, southern Ethiopia. Journal of Ethnobiology and Ethnomedicine, 2021, 17:44. https://doi.org/10.1186/s13002-021-00469-6.

Chapter four: Published

Mesfin Belete, Zerihun Woldu, Zemede Asfaw and Ermias Lulekal, 2023

Impact of Elevation Change on the Physicochemical Properties of Forest Soil in South Omo Zone, Southern Ethiopia. Applied and Environmental Soil Science, 2023. https://doi.org/10.1155/2023/7305618

Chapter five: Under review:

This study was conducted in South Omo Zone, one of the Administrative Zones in the Southern Regional State, Ethiopia, occupying a geographic location between 4° 31' to 5° 34' north latitude and 36° 09′ to 37° 03' east longitude. It is characterized by a wide elevation variation, ranging from 381 to 2410 m.a.s.l.. The capital town of the South Omo Zone is Jinka. According to the 2007 census, conducted by the Central Statistical Agency (CSA), the total human population of South Omo Zone is 573,435, of whom 286,607 are men and 286,828 women, with an area cover of 21,055.92 square kilometers. The study districts, Benna-Tsemay (Key Afer) and Hamer (Dimeka), are located at about 739 and 839 km from the capital city of Ethiopia, Addis Ababa, respectively. The study districts cover a total land area of 9496 km^2 (Hamer = 5742 km2 and Benna-Tsemay = 3754 km2).

The study area is characterized by a bimodal rainfall distribution pattern with the long rainy season begins from the end of March to the beginning of June, which is the cropping season and the short rainy season, which is important only for pasture, occurs between October and November. The average annual precipitation ranges from 754 mm (Hamer District) to 933 mm (Benna-Tsemay District) and the average annual temperature ranges from 20.7 °C (Benna-Tsemay District) to 22.9 °C (Hamer District). The topography of the study area is widespread in undulating with valleys and rolling, plateau, flat plains, and with different slopes. The common soil types of the highland plateau are chromic and eutric cambisols, with yellowish-red to dark-red eutric nitosols, and some orthic acrisols. The flat plains of the lowlands are covered by very fertile eutric fluvisols. The escarpments and steeply dissected sides contain shallow lithosols. The vegetation cover of the South Omo Zone is a mixture of *Acacia-Commiphora* woodland (at 1200 masl), *Combretum-Terminalia* woodland and wooded grassland (at 1500 to 1750 masl) and the dry evergreen afromontane forests are found at elevation greater than 1750 masl. on top of the mountain ridge. Most of the pastoral and agro-pastoral communities of the study area rely mainly on forest resources for livestock fodder, income, food, and medicine.

CHAPTER TWO

2. Ecological assessment of plant species composition, vegetation structure, regeneration status and factors determining plant species distribution in Sida Forest, South Omo Zone, Southern Ethiopia.

Mesfin Belete Hailemariam, Zerihun Woldu, Zemede Asfaw and Ermias Lulekal

Abstract

The investigation of species composition, vegetation structure, and community types are the key feature to understand the status of the forest. The aim of this study was to evaluate the vegetation status in relation to environmental factors that govern species distribution and community formation. A systematic random sampling method was used to collect vegetation and environmental data from 82 (20 m × 20 m) placed along twelve transect lines, which is 1km apart and 300m distance between plots. Height and DBH of adult plants were measured using Suunto Clinometers and measuring tape respectively, and percentage cover-abundances were visually estimated. Density, frequency, Basal area, importance value index, and size class distribution were used to analyze vegetation structure. The density ratio of age classes (seedlings and saplings) was used to determine the regeneration status. Hierarchical cluster analysis was used to classify the vegetation into plant community types. CCA was used to analyze the relationship between plant communities and environmental factors. Shannon-Wiener Diversity Index was used to evaluate species diversity and evenness. Soresen's similarity index was used to compare the species composition among the plant communities. A total of 254 plant species were identified and 9 species were endemic. Fabaceae (10.24%), Asteraceae (5.91%), Lamiaceaae (5.91%), Euphorbiaceae (4.72%), and Poaceae (4.33%) were the most dominant families. Shrubs occupied the highest (35 %) percentage followed by herbs (30%). The density of mature woody species was 682.32 individuals/ha. The frequency value ranges from 1.2% to 42.7%, and the basal area of woody species in the forest was 24.15 m^2/ha. The IVI value ranges from 0.13 to 14.62. The highest number of individuals was recorded in the lower DBH (47.5%) and height classes (42.5%) and the least was recorded in the higher DBH (1%) and height classes (1.3%). The DBH and height class distribution showed an inverted J-shaped pattern. The density of matured trees (1662) was greater than the density of seedlings (646) and saplings (339), showing a fair regeneration status. Five plant community types were identified. The results of CCA revealed that elevation, slope, aspect, sand, pH, and disturbances were the main environmental factors that determine plant species distribution and community formation. The highest species similarity was found between community two and three (58.9%), while the least similarity was found between community one and community five (18.3%). The results of this study help to understand the effect of environmental factors on plant community formation and provide important information to policy makers and stakeholders to plan conservation and management actions.

Key words/Phrases: Endemic species; Plant community, Population structure, Regeneration status, Sida Forest, Species diversity.

2.1. Introduction

Forests are a valuable natural resource that can provide a wide range of ecosystem goods and services, including environmental, economic, social, and cultural services and processes, such as carbon storage, nutrient cycling, erosion management, landscape protection, home to diverse species, and maintenance of ecological and ecosystem processes (IBC, 2009; FAO, 2010; Agustino *et al.*, 2011; Kent, 2012; FAO, 2014), which are essential to the survival and well-being of all humanity. About 1.6 billion people (more than 25%) of the world's population rely on forest resources for their livelihoods (FAO, 2014). Forest ecosystems are the world's largest repositories of terrestrial biodiversity (FAO, 2014), and nearly 90% of terrestrial biodiversity is found in the world's forests (Nestlé, 2013; FAO, 2014). Forests cover 31 percent (4.06 billion hectares) of the global land area (FAO & UNEP, 2020). Tropical forest occupies 52% of the total forest area in the world (Kacholi, 2014; Keenan *et al.*, 2015; Narayan & Anshumali, 2015)**,** of this, 42% is dry forest, 33% is moist forest, and 25% is wet and rain forest (Murphy & Lugo, 1986; Narayan & Anshumali, 2015). About 30% of the tropical forest cover is found in Africa, and the total African forest coverage is estimated to be 16% of the world's forests, which accounts for 21% of its total land area (FAO, 2006; Geldenhuys *et al.*, 2011). In Africa these forests are found in several countries, Central Africa (37%) and Southern Africa (28%), account for 65% of the forest and the other three sub-regions together account for the remaining 35% (West Africa and North Africa with 11% each; and East Africa 13%) (Geldenhuys *et al.*, 2011).

Ethiopia is one with the largest forest resources in the Horn of Africa, and one of the biodiversity-rich country, hosting two (the Eastern Afromontane and the Horn of Africa biodiversity hotspots) of the world's 36 biodiversity hotspots (Mittermeier *et al.*, 2004; Noss, 2016), and the fifth-largest floral diversity in tropical Africa (EPA, 1997; Motuma Didita *et al.*, 2010). The country is recognized as one of the top 20 Megadiverse countries in the world and one of the 12 global Vavilovian centers of origin and diversity of many cultivated crops (IBC, 2005). The vegetation types of the country range from tropical lowland rainforest in the southwest to the arid and semi-arid dry woodlands in the East, and the Afro-alpine forests in the north and southeast, and classified into twelve vegetation types (Friis *et al.*, 2010). The flora of Ethiopia is very diverse and contains an estimated number of indigenous plant species 4481, of which 19.9% are considered to be endemic to Ethiopia (Sosef *et al.*, 2017). This wide range of biological diversity and endemism is strongly associated with the ecological conditions, that is the great geographical variation and the wide range of elevations (EPA, 1997; Zerihun Woldu *et al.*, 1999; Friis *et al.*, 2010; Husen *et al.*, 2012; Abyot Dibaba *et al.*, 2014). The elevation of the country ranges from 125m below sea level at Dalol Depression (Afar) to 4533m above sea level Ras Dashen (Gondar) and possesses more land above 2000 m than any other country in Africa (Zerihun Woldu *et al.*, 1999; IBC, 2005; Friis *et al.*, 2010; Husen *et al.*, 2012; Sebsebe Demissew *et al.*, 2021).

The most important environmental factors that affect plant species diversity and community formations are topographic and edaphic factors (Swaine, 1996; Kreft & Jetz, 2007; Eiserhardt *et al.*, 2011; Zhang & Zhang, 2011; Poelking *et al.*, 2015), elevation (Zerihun Woldu *et al.*, 1989; Friis *et al.*, 2010), disturbances (Ermias Aynekulu *et al.*, 2016; Getaneh Gebeyehu *et al.*, 2019; Admassu Addi *et al.*, 2020), and climatic factors (Liu *et al.*, 2007; Ermias Aynekulu *et al.*, 2016). The size and quality of forests in Ethiopia are declining at an alarming rate due to various threats, such as habitat degradation and deforestation. A significant proportion of Ethiopia was once covered by forests having wider coverage than at present, but gradually declined from the original 35-40% of the land area to 16% in 1952 (Breitenbach, 1963), further rapidly dropped to 3.6% by 1980 (Tewolde-Berhan Gebregzabher, 1991), and declined to 2.4% in 1992 (EFAP, 1994). However, the FAO (2010) report showed that Ethiopia forest cover is 10-30%. The country's forest cover is 17.07 million hectares, which is about 15.7% (MEFCC, 2017; FAO, 2020). The different factors contributing to the loss of the forests includes expansion of agriculture, deforestation, overgrazing, settlement, land degradation, expansion of invasive species, and overexploitation for various purposes such as firewood, charcoal, construction material, farm implements, and timber (Teshome Soromessa *et al.*, 2004; Haileab Zegeye *et al.*, 2011).

An ecological studies on the plant species diversity, population structure, regeneration status, and the associated environmental factors are essential features for successful management and conservation plan (Kacholi, 2014; Alemayehu Yigeremu & Mesfin Woldearegay, 2022). However, in Sida Forest, ecological studies have not been conducted so far. Therefore, the aim of this study was, to investigate the floristic composition, species diversity, and population structure of Sida Forest, to assess the regeneration status of woody species, to identify the plant community types, and to identify the factors that influence species diversity and distribution in each community types.

2.2. Materials and Methods

2.2.1. Description of the study area

This study was conducted in Sida Forest in the South Omo Zone, Southern Regional State of Ethiopia (Figure 2). In the South Omo Zone, there are eight districts, and the administrative center of the zone is Jinka. In this Zone, there are many ethnic groups, such as Hamer, Arbore, Benna, Tsemay, Turme, Mursi, Dasenetchi, and Karo tribes (Terefe Admasu *et al.*, 2010). The communities in the study District belong to the Benna and Tsemay ethnic groups. The Benna ethnic group inhabits the upper parts and practice shifting cultivation and animal husbandry, with some income from beekeeping and hunting, whereas the Tsemay ethnic group inhabits the lowland area and practices an agro-pastoral land use system, in which crop cultivation and livestock production are the most important (Reusing, 2000; Assegid Assefa & Tesfaye Abebe, 2011). The study District (Benna-Tsemay) is located 739 km south of Addis Ababa, the capital city of Ethiopia. Bena-Tsemay District is located at 5° 03′ to 5° 34′ N latitude and 36° 33′ to 37° 03′ E longitude, with an elevation range between 500 (Weyto valley) and 2400 (Kako mountain) m.a.s.l. According to the 2007 Census, conducted by the Central Statistical Agency (CSA), this Zone has a total human population of 573,435, of whom 286,607 are men and 286,828 women, with an area cover of 21,055.92 square kilometers. While, the human population of the study District (Benna-Tsemay) was 55,590, with a total land area cover of 3,754 km^2 (CSA, 2007; Enyew & Hutjis, 2015). However, the current (2018) unpublished report from the Benna-Tsemay District Agricultural Bureau shows 72,749 (36,262 male and 36,487 female). The communities of the study area rely mainly on dry forest resources for livestock fodder, income, food, and medicine. Their livelihoods are closely linked and interrelated to the existence of natural forest and woodland resources (Reusing, 2000). The main source of income was from the sale of livestock, followed by bee keeping (Terefe Admasu *et al.*, 2010).

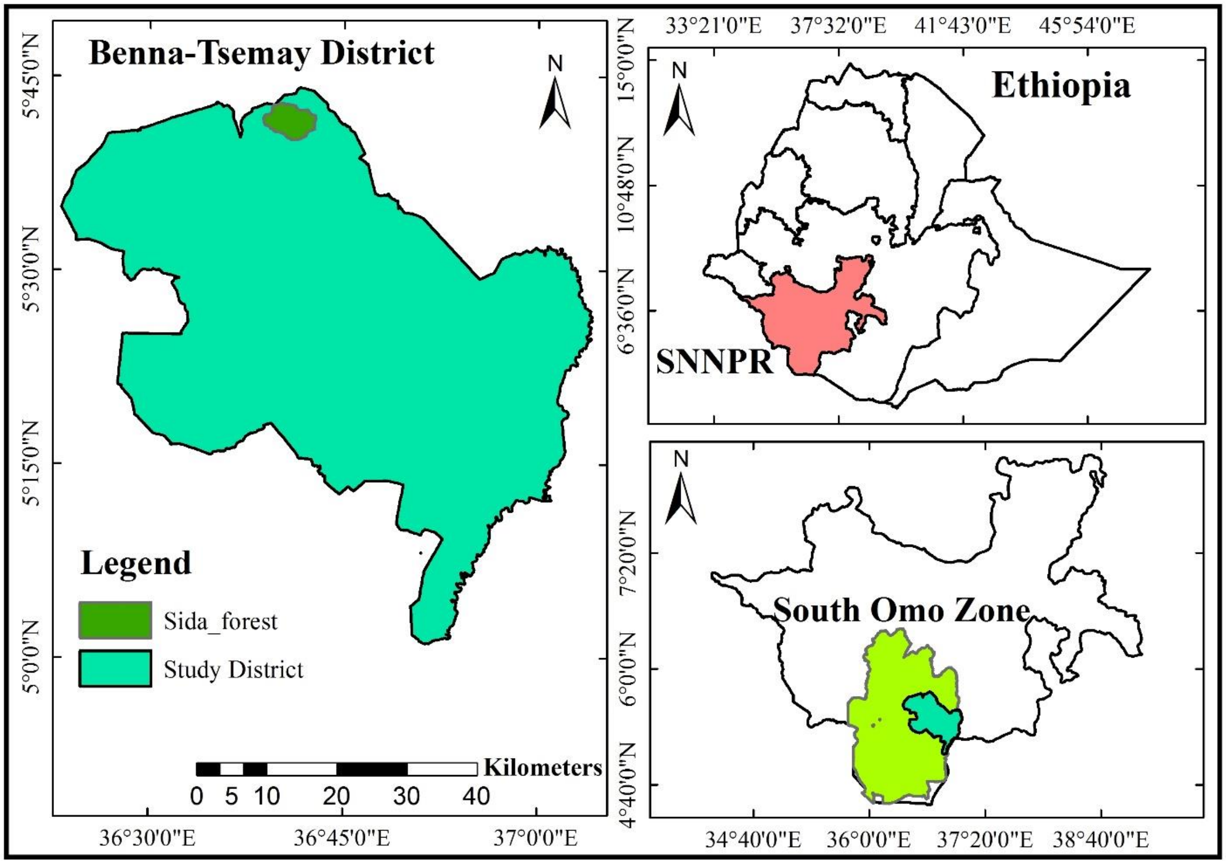


Figure 2. Map of Ethiopia showing South Omo Zone and the study District

The study area is characterized by semi-arid and arid climatic conditions, with a mean annual precipitation of 933 mm and a mean annual temperature of 21.7 °C. The rainfall is bimodal, with the dry season occurring from the beginning of December to the end of February, while the long rainy season occurs from the end of March to the beginning of June, and the short rainy season, occurs from October to November. The average monthly maximum temperature of the warmest month is 32.1 °C and the average monthly minimum temperature of the coldest month is 12.3 °C. In general, the study area has erratic, variable rainfall and temperature, with an average monthly temperature ranging from 12.3-32.1ºC (Figure 3).

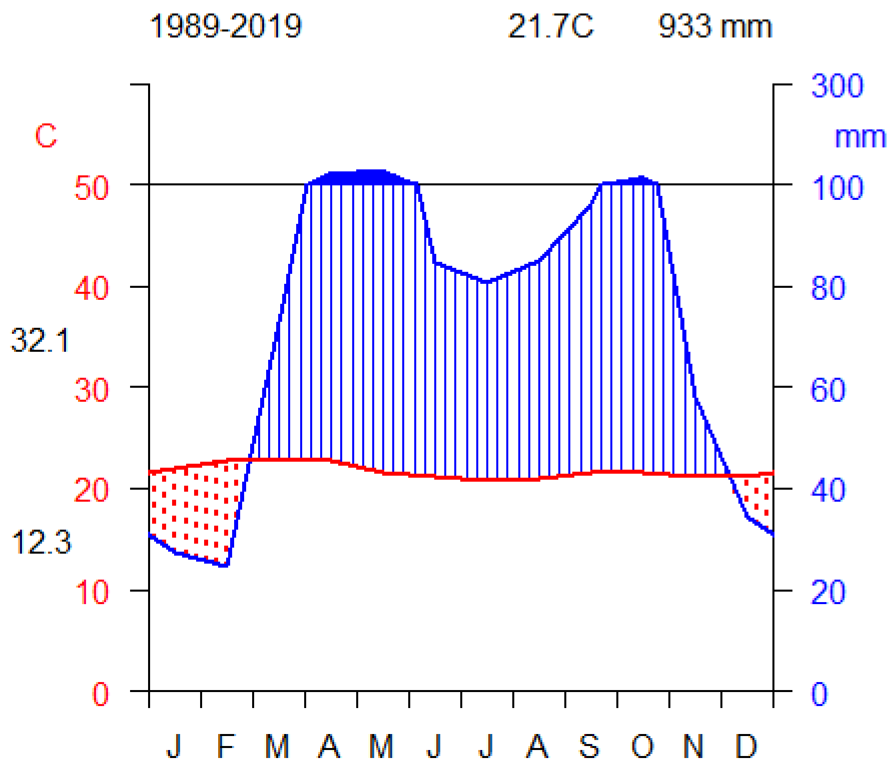


Figure 3. Climate diagram of the study District showing rainfall distribution and temperature variation from 1989 to 2019

The geology of the study area is characterized by the large plains belonging to the east-African rift valley system and containing Pleistocene and Holocene (Quaternary) deposits (Reusing, 2000). The hilly upper plateau landscape consists of granite and metamorphic rocks that have been continuously flattened towards the Rift Valley through natural erosion. The main soil types of the highland plateau are chromic and eutric cambisols, with yellowish-red to dark-red eutric nitosols, and some orthic acrisols. The flat plains of the lowlands are covered by very fertile eutric fluvisols. The escarpments and steeply dissected sides contain shallow lithosols with rock outcrops of granitic (igneous rock) and gneissic (metamorphic rock) material (Reusing, 2000).

The vegetation cover of the South Omo Zone is a mixture of *Acacia*, *Boswellia* and *Commiphora* woody species with herbs and grasses (Alemayehu Mulugeta & Tezera Getahun, 2002). *Boswelia-Commiphora* woodland dominates between 750-1150 masl. The transition zone between the *Acacia-Commiphora* (at 1200 masl.) and the *Combretum-Terminalia* (at 1500 masl.) contains small-leaf *Acacia* and broad-leaf *Combretum-Terminalia* woodland on higher (1500 to 1750 masl.) and moist parts. The dry evergreen afromontane woodlands are found at elevation greater than 1750 masl masl. on top of the mountain ridge (Reusing, 2000). The Sida Forest is located between 5°40′55″ and 5°42′04″ N latitude, and between 36°39′35″ and 36°41′07″ E longitude, with an elevation range extending from 1500 to 2400 masl. The topography of the study area is widespread in undulating with valleys and rolling, plateau, flat plains, and with different slopes. The vegetation type of study forest belongs to four vegetation types, namely *Acacia-Commiphora* woodland and bushland, *Combretum-Terminalia* woodland and wooded grassland, Dry Evergreen Afromontane Forest and grassland complex, and the Riverine vegetation (IBC, 2005, 2009; Friis *et al.*, 2010; EBI, 2014).

2.2.2. Sampling Design

A systematic random sampling techniques was used to locate sample plots and to collect the vegetation, and environmental data following Mueller-Dombois and Ellenberg (1974) and Kent (2012). A total of 82 sample plots of size 20 m x 20 m ($400m^2$) were laid systematically along twelve parallel transect lines (the longest transect is about 2.26 km and the shortest is about 1.30 km), following an elevation gradient. The first plot was laid randomly starting from the bottom to the top of the mountain, and the subsequent plots were established at 300 m intervals along the transect lines, which were 1000 m apart from each other. For the collection of woody (shrubs and trees) species, plots of 20m × 20m ($400m^2$) were laid, and five subplots of 2m × 2m ($4m^2$) were laid inside each plot, four from each corner and one at the center for the collection of herbaceous species, seedlings, and saplings of all woody species (Figure 4).

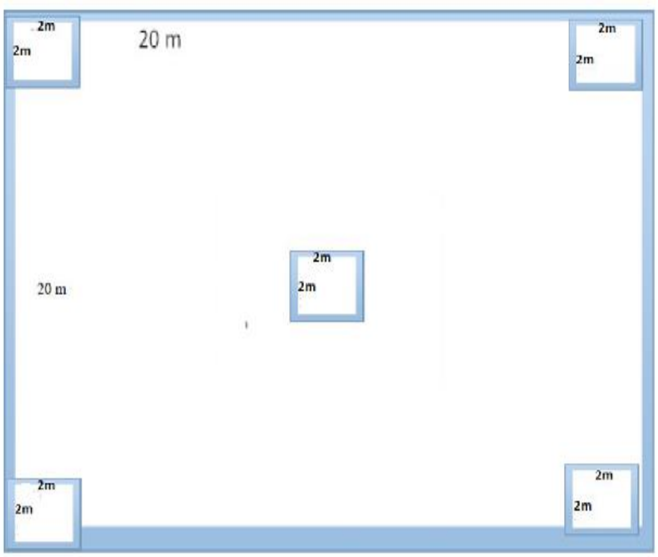


Figure 4. The design of the plot for vegetation and environmental data collection

2.2.3. Methods of data collection

Vegetation data collection

Vegetation data were collected from each sample plot and recorded using local names. Plant species occurring outside the plots, but within the study forest were also recorded as "present" however; these species were not used during data analysis. Height and Diameter at Breast Height (DBH) of adult plants were measured for each woody species that had a height ≥ 2 m and DBH ≥ 2.5 cm. Trees and shrubs with multiple stems below 1.3 m were treated as a single individual, and the circumference was measured separately and averaged. The height was measured using a Suunto Clinometer in an open forest, a calibrated long bamboo stick in a dense forest, and/or visually estimated, and the circumferences were measured using a meter tap. The circumferences were converted to DBH using the formula, $C = \pi DBH$ and $DBH = C/\pi$. The percentage canopy cover values of each woody species and cover-abundance of herbaceous species were visually estimated and converted into 1-9 cover-abundance classes of Braun-Blanquet scales as modified by Van der Maarel and Franklin (2012), 1 = (<0.5%), 2 = (0.5–1.5%), 3 = (1.5–3%), 4 = (3–5%), 5 = (5–12.5%), 6 = (12.5–25%), 7 = (25–50%), 8 = (50–75%), and 9 = (75-100%) cover of the total area. To assess the regeneration status of the forest, all seedlings and saplings of woody species were recorded. The regeneration status of woody species was assessed by employing a total count of seedlings (woody species of height < 1 m and DBH < 2.5 cm), saplings (woody species with height 1-2 m and DBH < 2.5cm), and woody species with a height of ≥ 2m and DBH ≥ 2.5 cm were considered as matured (Birhanu Kebede *et al.*, 2014; Geta Sileshi *et al.*, 2022).

During data collection, the growth forms and the local names of voucher specimens of each plant species were recorded, collected, pressed, dried, and brought to the National Herbarium (ETH) of Addis Ababa University for taxonomic identification and verification. The specimens were identified both in the field and later using the published volumes (1-8) of Flora of Ethiopia and Eritrea, and Honeybee Flora of Ethiopia (Fichtl & Admasu Adi, 1994), by comparing with the authenticated specimens housed at ETH and consulting experts (Ato Melaku Wondafirash, W/ro Shewangiziew Lemma, and Ato Wogie Abebe). The nomenclature of the plant specimens followed the Flora of Ethiopia and Eritrea and was confirmed by Dr. Ermias Lulekal.

Environmental data collection

The environmental variables (elevation, aspect, slope, and soil samples) were recorded from each sample plot. Geographical coordinates (latitude and longitude) and elevation were measured using

GPS, whereas slope and aspect were measured using a Suunto Clinometers (Steren 203- 661 Taiwan) and compass respectively. The value for aspect was coded according to Zerihun Woldu *et al.* (1989): N = 0; NE = 1; E = 2; SE = 3; S = 4; SW = 3.3; W = 2.5; NW = 1.3.

Soil samples were collected from five points (four from each corner and one from the center) of the main plot laid for vegetation data collection and a pit of 20cm × 20 cm was dug up to a depth of 30 cm using Soil Augur (Mohammadi *et al.*, 2019). The soil samples were mixed well to form a composite sample, and a kilogram of the sample was brought to the Wolkite Soil Testing Laboratory using sterile polythene bags for physicochemical analysis.

Ecological disturbances like grazing/browsing levels and impacts of humans (number of trees and shrubs cut, number of foot trails, signs of charcoal production, and number of seedlings trampled) were noticed and recorded from the sampled plots. The grazing and browsing levels was estimated following Zerihun Woldu and Backéus (1991) subjective five-level scales as 0 = nil; 1 = slight; 2 = moderate; 3 = heavy and 4 = destructive. The state of human interference was estimated following Zerihun Tadesse *et al.* (2017) and coded using a 0–3 subjective scale to record the degree of the impacts as 0= nil; 1= low; 2= moderate and 3= heavy.

2.2.4. Methods of Data analysis

Vegetation structure data analysis

Vegetation data were entered and summarized using Microsoft Excel spreadsheet version 2016. Graphs were drawn using an Excel spreadsheet. All individuals of woody species recorded in the sample plots were used in the analysis. The vegetation structure was determined by computing the following parameters, frequency, density, basal area, importance value index, DBH, and height class distribution of all plants.

Frequency**: -** is the probability or chance of finding a plant species in a given plot.

It was computed using the following formula:

$$\text{Frequency} = \frac{\text{No of plots where a species occurred}}{\text{The total no of plots laid in the study area}} \times 100$$

Relative frequency is the frequency of a given species expressed as a percentage of the sum of frequency values for all species present.

$$\text{Relative frequency (RF)} = \frac{\text{Frequency of a single species}}{\text{Frequency of all species}} \times 100$$

Based on the frequency values, woody species were classified into five frequency classes (%): 1) 0 - 20, 2) 21 - 40, 3) 41 - 60, 4) 61 -80, 5) 81-100.

Density:- is the count of individuals of woody species per unit area and calculated by converting the count from all plots into a hectare basis.

It was computed using the following formula:

$$\text{Density (D)} = \frac{\text{Total number of stems of a given species}}{\text{Sampled area in hectare (ha)}} \times 100$$

Relative density (RD) is the number of individuals of a species divided by the total number of individuals of all species;

$$\text{Relative density (RD)} = \frac{\text{Density of a single species}}{\text{The total density of all species}} \times 100$$

Basal Area**:** is the cross-sectional area of all of the stems in a stand at breast height (1.3 m above ground). Basal area explain the crowdedness of a stand of the forest. It is expressed in square meters/hectare. It also used to calculate the dominance of species.

$BA = \pi DBH^2/4$ or $BA = (DBH/2)^2 * \pi$

The analysis of dominance was made using basal area measurement.

Dominance (DO) was calculated as the sum of the basal areas (BA) of the individual woody species in m^2 per ha.

Relative Dominance: Basal area of a given species divided by the sum of the basal areas of all of the species × 100

$$\text{Relative Dominance (RDO)} = \frac{\text{Basal area of a single species}}{\text{Total basal area of all species}} * 100$$

Importance Value Index (IVI**):** is an important indicator for the ecological significance of a species, and combines data from three parameters (Kent & Coker, 1992). The importance value index (IVI) of each species was computed based on the formula:

IVI = Relative frequency (RF) + Relative density (RD) + Relative dominance (RDO).

Diameter at breast height (DBH) and height

Diameter at breast height (DBH) measurement was obtained from circumference (C), and calculated as follows:

$DBH=C/\pi$, where, DBH is diameter at breast height, C is circumference, and $\pi = 3.14$. DBH and heights were classified into different DBH and height classes following Abiyou Tilahun (2018).

The DBH class distribution of woody species was classified into seven DBH classes, (1) 2.5-10cm, (2) 10.1-20cm, (3) 20.1-30cm, (4) 30.1-40cm, (5) 40.1-60cm, (6) 60-80cm, (7) >80cm. On the other hand, the height of woody species was classified into seven height classes, (1) <5m, (2) 5.1-10m, (3) 10.1-15m, (4) 15.1-20m, (5)20.1-25m, (6) 25.1-30m and (7) >30m. The number of woody plant species within each DBH and height class were added and constructed to describe the population structure.

The vertical stratification was examined following the International Union Forestry Research Organization (IUFRO) classification scheme (Lamprecht, 1989). It categorizes the vertical structure of vegetation into upper (tree height > 2/3 of the top height, > 30 m), middle (tree height between 1/3 and 2/3 of the top height, between 15-30 m), and lower (<1/3 of the top height, <15 m) storey.

Vegetation classification:

Classification and ordination methods were used to describe the community types and to examine the relationship between community types and environmental variables (Lepš & Šmilauer, 2003; Chahouki, 2013; Zerihun Woldu, 2017). Plant community classification was computed through cluster analysis by using an agglomerative hierarchical clustering technique employed in R packages. The Similarity Ratio (SR) was measured using Ward‟s method. The data matrix contained 82 plots and 254 plant species collected from the sample plots. The SR eliminates the differences in total abundance among sample units and the Ward‟s method was used, because it minimizes the total within group mean of squares or residual sum of squares and is favorite as it produces nicely compact clusters (McCune and Grace, 2002). The plant community types from the cluster analysis were also analyzed in a synoptic table based on cover-abundance values. The community was named after the dominant tree or shrub species in that specific community with higher synoptic values. In each community type, the synoptic values of each species were further tested to find significant indicator values of the species performed in R using package labdsv (Zerihun Woldu, 2017).

Canonical Correspondence Analysis (CCA) was used to analyze the relationship between environmental variables and vegetation data by fitting the data into an ordination scatter plot and used to correlate the identified plant community types with environmental and disturbance factors (Chahouki, 2013).

Diversity analysis

Shannon-Wiener Diversity Index (H') was used to analyze the species diversity, species richness, and evenness of Sida Forest. The Shannon index is the most widely used in community ecology. The Shannon species diversity, richness, and evenness for each community type were computed in R, using R software (Zerihun Woldu, 2017), as indicated below:

$$H' = -\left(\sum_{1=1}^{s} p_i \ln p_i\right)$$

Where: H′= Shannon Diversity Index; s= the number of species Pi= the proportion of individuals or the abundance of the i^{th} species expressed as a proportion of total cover; ln= natural logarithm; Σ= Summation symbol.

Shannon evenness index (J) was calculated using the equation:

$$J = \frac{H'}{H'max} = \frac{-\sum_{i=1}^{s} PilnPi}{lnS}$$

Where, J = evenness, H' = Shannon –Wiener Diversity Index, H'max = Maximum Diversity index = lnS, S = total number of species in the sample. The values of J range normally between 0 and 1, where 1 represents a situation in which all species are equally abundant.

Species similarity analysis:

Similarity indices provide mathematical expressions for the similarity of communities (Mueller-Dombois & Ellenberg, 1974). The Sørensen's similarity index (Ss) was used to assess the floristic similarity between the five plant community types of the vegetation in the study area.

The index is given as: $Ss = \frac{2a}{2a+b+c}$

Where, a=number of species common to both communities;

b= number of species in community 1

c = number of species in community 2

Soil Data Analysis

All soil laboratory analyses (physical and chemical properties) were done following standard procedures. Accordingly, soil samples were air dried in a properly ventilated room on a plastic tray, and ground in a Wiley mill, to pass through a 2 mm sieve for all the soil parameters except for TN and OC passed through a 0.5 mm sieve to remove the root particles, rocks, and large organic materials. Then the sieved parts were labeled and stored in plastic bags until physicochemical analysis.

The analysis of soil texture classes was determined by the hydrometer method as described in Bouyoucos (1962) and Kalra and Maynard (1991) where hydrogen peroxide was used to burn OM and sodium hexametaphosphate solution was used as a dispersing agent to break up aggregates and disperse the mineral particles. The soil textural classes were determined using the soil textural triangle of the USDA system. Soil color (dry) was determined using the Munsell soil color chart (Color, 1994). Soil bulk density (BD) was determined using the core-sample method as described by Blake and Hartge (1986), where first soil samples were taken by a core sampler of known volume (height 5 cm and diameter 7.2 cm) weighed at field moisture condition. Then the soil samples were oven-dried at 105 °C for 24 hours until constant weight was obtained and the oven-dried sample was weighed again. Finally, the bulk density of the soil samples was computed by dividing the weight of oven-dried soil (g) by the volume (cm3) of the sampler.

$\mathrm{BD} = \frac{\mathrm{M2-M1}}{\mathrm{V}}$, Where: BD: dry soil bulk density (gm/cm3), M1: the weight of core (g), M2: the weight of core + oven-dried soil (g), and V: volume of the core (cm3).

The soil pH (pH-H2O) was measured potentiometrically using a digital pH meter (CP-501) in the supernatant suspension of 1:2.5 (soil: water ratio) as described by Webster (2008). The electrical conductivity (EC) of soils was determined in a soil: water ratio of 1:2.5 extract with the aid of a conductivity meter as described by Okalebo *et al.* (2002). The soil organic carbon (SOC) content was determined using the wet oxidation method, which involves the digestion of the OC in the soil samples with potassium dichromate ($K_2Cr_2O_7$) in a sulfuric acid solution as described by Walkley and Black (1934) and the percent soil organic matter was obtained by multiplying the percent SOC by Van Bemmelen factor (1.724). Total Nitrogen (TN) was determined following the Kjeldahl distillation method as described by Bremner (1982). The carbon-to-nitrogen ratio (C/N) was calculated from the ratio of soil organic carbon to total nitrogen. Available phosphorus was determined calorimetrically using a spectrophotometer (UV752(D)) after the extraction of the soil samples with 0.5 M sodium bicarbonate ($NaHCO_3$) at pH 8.5 following the Olsen method (Olsen, 1954). The cation exchange capacity (CEC) of the soil was determined titrimetric by repeated saturation using 1M ammonium acetate (NH_4OAC) followed by washing, distilling, and titrating as described by Chapman (1965), and the excess salt was removed using ethanol alcohol. The exchangeable base cations were extracted by saturating the soil sample using ammonium acetate (1M NH_4OAC at pH7) solution. Exchangeable Ca^{2+} and Mg^{2+} were determined from the extract using an atomic absorption spectrophotometer (AAS), while exchangeable K^+ was determined from the same extract using a flame photometer (CL 378) (Chapman, 1965).

Regeneration Status

The regeneration status of woody species in the forest was assessed based on the density ratio of age class (seedlings, saplings, and mature) of each woody species across all plots. The pattern of regeneration was analyzed using the following categories as described by Dhaulkhandi *et al.* (2008) and Tiwari *et al.* (2010). Pattern 1 = if the regeneration results of woody species show seedlings > sapling > adults, "good regeneration". Pattern 2 = if seedlings > or ≤ saplings ≤ adults, "fair regeneration", and Pattern 3 = if the woody species survive only in the sapling stages, "poor regeneration". Pattern 4 = if a woody species is present only in the adult stage, it is considered as "not regenerating" and Pattern 5 = "new regeneration" if the species has no mature but only seedlings or saplings stages. The assessments of seedling and sapling densities were used to prioritize conservation measurement.

2.3. Results

2.3.1. Floristic Composition

The results of the study revealed that the vegetation in Sida Forest had high species richness in different growth forms. A total of 254 plant species, belonging to 180 genera and 82 families were recorded from Sida Forest (Appendix 1). Out of these, 243 species were collected from the 82 sample plots and the remaining 11 species were collected from outside the plots but inside the forest and included in the floristic list of the forest. Of all the families, the highest number of species was recorded for the family Fabaceae represented by 26 species (10.24%) in 13 genera, followed by Asteraceae 15 species (5.91%) in 9 genera, Lamiaceaae 15 species (5.91%) in 10 genera, Euphorbiaceae 13 species (4.72%) in 8 genera, and Poaceae 11 species (4.33%) in 8 genera. These five dominant families together contributed 80 (32%) of the total species richness in the forest. The next six dominant families were Acanthaceae represented by 9 species (3.54%) in 4 genera, Rubiaceae 9 species (3.54%) in 8 genera, Solanaceae 7 species (2.76%) in 5 genera, Tiliaceae 7 species (2.76%) in 2 genera, Amaranthaceae 6 species (2.36%) in 5 genera, and Anacardiaceae 6 species (2.36%) in 3 genera, and constituted 44 (17%) of the total species richness. The remaining families (71 families) were represented by 5 and less than 5 species each and contributed 130 (51%) of the total species. The top fourteen families (Table 1) were the most important and contributed 139 (55%) of the species, this is more than half of the total species composition of the study forest.

Table 1. Top fourteen, species-rich families with their respective number of genera and species in Sida Forest

Family name	No. of genera	No. of species	Percent contribution (%)
Fabaceae	13	26	10
Asteraceae	9	15	6
Lamiaceae	10	15	6
Euphorbiaceae	8	13	5
Poaceae	8	11	4
Acanthaceae	4	9	4
Rubiaceae	8	9	4
Solanaceae	5	7	3
Tiliaceae	2	7	3
Amaranthaceae	3	6	2
Anacardiaceae	3	7	2
Capparidaceae	4	5	2
Moraceae	1	5	2
Vitaceae	3	5	2

New records to Gamo Gofa Floristic Region (GG)

The Sida forest is located in the Gamo Gofa Floristic Region of the Flora of Ethiopia and Eritrea. About 58 (22.83%) of the plant species, belonging to 53 genera and 36 families are new records to the Gamo Gofa Floristic Region of the Flora of Ethiopia and Eritrea (Appendix 2). Of this, 20 species were shrubs, 16 species were trees, 12 species were herbs, 6 species were climbers, 2 species were ferns and 2 species were grasses. Two species (*Millettia ferruginea* and *Gomphocarpus purpurascens*) were endemic plants documented as new records of this floristic region (GG).

Growth forms

Plant species of different growth forms (trees, shrubs, climbers and herbs) were recorded from the study forest. The analysis of the growth forms of plants recorded from the Sida Forest showed that herbs (91 species, 30%) and shrubs (90 speces 35 %) contributed the highest number of species followed by trees (56 species, 22%) and climbers (17 species, 7%) (Figure 5). Field observation in the study area also revealed that epiphytes were found in the forest. Trees and shrubs together contributed 146 (57%) of the floristic composition of the forest.

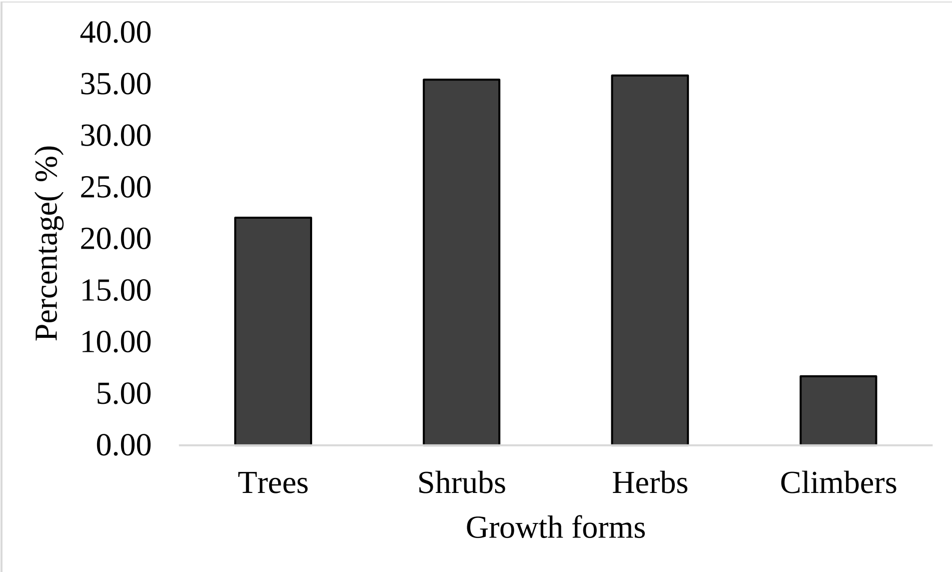


Figure 5. Growth forms of plant species collected from Sida Forest

Endemic plant species

Based on the endemic plant species of Ethiopia, out of the total plant species (254) collected from the study forest, 9 (3.5%) species belonging to 8 genera and 8 families were identified as endemic to Ethiopia (Table 2). From the endemic species, shrubs contribute 55.6%, herbs 22.2%, while trees and grasses contribute 11% each. Based on the IUCN criteria of level of threat, three species were assessed as nearly threatened (NT), four species were Not Evaluated (NE), one species was least concern (LC) and one species was vulnerable (VU). The presence of these endemic species shows the importance of the conservation of this forest.

Table 2. List of endemic plant species with their IUCN threat categories in Sida Forest

Species	Family	Habit	IUCN category
Acanthus senni	Acanthaceae	Sh	NT
Agrostis diffusa	Poaceae	G	NE
Aloe gilbertii	Aloaceae	Sh	NE
Aloe otallensis	Aloaceae	H	NE
Gomphocarpus purpurascens	Asclepiadaceae	H	NE
Lippia adoensis	Verbenaceae	Sh	LC
Gymnosporia addat	Celastraceae	Sh	NT
Millettia ferruginea	Fabaceae	T	NT
Tragia abortiva	Euphorbiaceae	Sh	VU

Note: T= Tree, Sh= Shrub, H= Herb, G= grass; NT= Near Threatened, LC= Least Concern, VU= Vulnerable, NE = Not Evaluated.

2.3.2. Vegetation structure of Sida Forest

Frequency

Based on the total frequency percentage, the species were grouped into the following five frequency classes: 1= 0-20; 2= 21-40; 3= 41-60; 4=61-80; 5=81-100 (Figure 6). The result of frequency class distribution showed that most (80.4 %) of the species were occurred in the lower frequency class (below 20% of frequency), whereas the least (2.2%) of the woody species were found in the higher frequency class (41-60% of frequency). It showed that there was a higher number of species in the lower frequency classes and a low number of species in the higher frequency classes. More than half 74 (80.4%) of the woody species in the study forest were rarely occurring species as they were recorded in less than 20% of the total studied plots, while 19.6% of the species were recorded in more than 20% of the total studied plots. About 9.78% (9) of the species occurred only in a single plot, while 11.96% (11) of the species occurred in two plots. The relative frequency of species ranged from 0.09 to 3.28%. The frequency values of the species in the study area ranged from 1.2% to 42.7% (Appendix 3). *Combretum molle* and *Vangueria madagascariensis* were the most frequently occurring species (42.7% of the sample plots each), followed by *Rhus vulgaris* (30.5%), *Croton macrostachyus*, *Discopodium penninervium*, *Terminalia macroptera* (26.8% each), *Podocarpus falcatus* and *Senna singueana* (25.6% each). Whereas the least frequent species in the Sida Forest occurring below 1.5% of the sampled plots were *Senegalia brevispica*, *Balanites rotundifolia*, *Bridelia micrantha*, *Dichrostachys cinerea*, *Diospyros scabra*, *Ficus ovata*, *Gardenia ternifolia*, *Grewia villosa* and *Searsia longipes* (1.2% each).

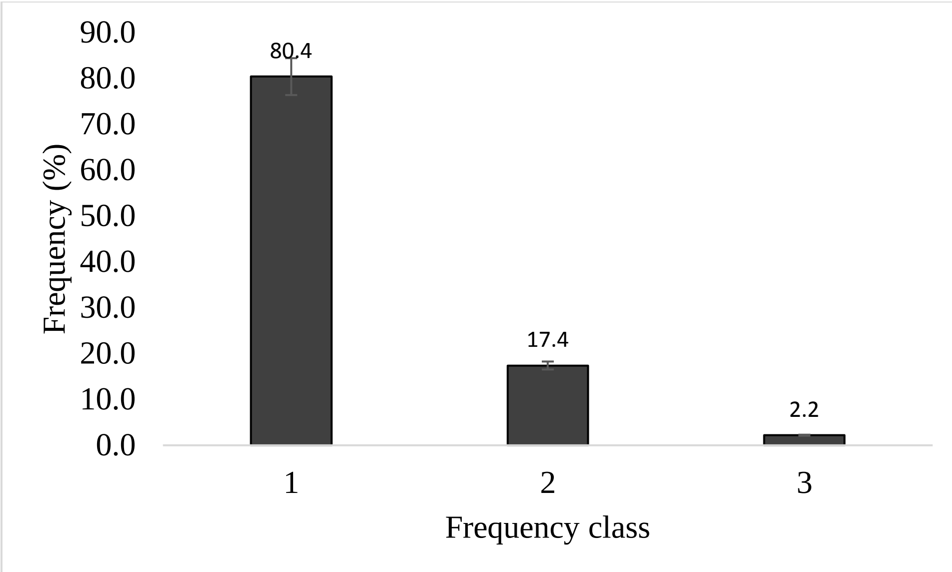


Figure 6. Frequency class distributions of woody species in the Sida Forest

The density of woody species

The results showed that the overall density of mature woody species in Sida Forest with DBH ≥ 2.5 cm and height ≥ 2m was 682.32 individuals/ha. The highest density of woody species was found in the lower DBH classes following a gradual decrease in the density across successive higher DBH classes. The highest 324.39 individuals/ha density of woody species was found with the lowest DBH class (2.5-10 cm), followed by the second DBH class (10-20cm) with a density of 174.39 individuals/ha. While the lowest density 13.72 individuals/ha was found in the highest DBH class (> 60cm). The relative density of woody species ranges from 0.03 to 3.48%, the highest relative densities were for *Syzygium guineense* subsp. afromontanum (3.48) followed by *Podocarpus falcatus* (3.26), *Combretum molle* (3.23), and *Vangueria madagascariensis* (3.03), while the lowest relative densities were for *Senegalia brevispica*, *Balanites rotundifolia* and *Bridelia micrantha* (0.03 each) (Appendix 3). The majority 612.8 individuals/ha of the species was found in the DBH class less than 2.5cm.

The top sixteen dominant woody species with abundance value above 100 individuals are given in Table 3. These dominant woody species were the most abundant species with a density of 685.37 stems ha-1 contributed to 52.92% of the total stem density. Whereas the remaining 76 woody species altogether accounted for a density of 609.76 stems ha-1 contributed to 47.08% of the total stem density in the forest.

Table 3.The density (D/ha) and relative density (RD) of the top sixteen dominant woody species with a DBH ≥ 2.5 cm in the Sida Forest

No.	Species	Abundance	D/ha	RD
1	*Syzygium guineense subsp. afromontanum*	208	63.41	3.48
2	*Podocarpus falcatus*	195	59.45	3.26
3	*Combretum molle*	193	58.84	3.23
4	*Vangueria madagascariensis*	181	55.18	3.03
5	*Calpurnia aurea*	144	43.90	2.41
6	*Phoenix reclinata*	139	42.38	2.33
7	*Discopodium penninervium*	132	40.24	2.21
8	*Croton macrostachyus*	127	38.72	2.13
9	*Osyris quadripartita*	124	37.80	2.08
10	*Maesa lanceolata*	120	36.59	2.01
11	*Terminalia brownii*	120	36.59	2.01
12	*Coffea arabica*	118	35.98	1.97
13	*Terminalia macroptera*	118	35.98	1.97
14	*Rhus vulgaris*	116	35.37	1.94
15	*Ficus thonningii*	109	33.23	1.82
16	*Eugenia bukobensis*	104	31.71	1.74
	Sub-total of 16 species	2248	685.37	
	The remaining 76 species	2000	609.76	
	Total	4248	1295.12	

Basal Area

The total basal area of the Sida Forest was calculated from DBH data (DBH ≥ 2.5 cm) and it was found to be 24.15 m^2/ha. The individual basal area of woody species ranges from 0.001 to 2.267 m^2/ha (Appendix 3). About 53.55% (12.93m^2/ha) of the total basal area was contributed by ten large-sized woody species such as *Podocarpus falcatus* (9.40%), *Ficus sycomorus* (7.86%), *Syzygium guineense* subsp. *afromontanum* (7.61%), *Combretum molle* (5.19%), *Ficus thonningii* (4.55%), *Hagenia abyssinica* (4.48%), *Diospyros mespiliformis* (3.82%), *Juniperus procera* (3.64%), *Croton macrostachyus* (3.58%) and *Ficus sur* (3.42%), whereas the least basal area was contributed by *Senegalia brevispica*, *Allophylus rubifolius*, *Ricinus communis* (0.001 m^2/ha each), *Grewia mollis,* and *Piliostigma thonningii* (0.002 m^2/ha each).

Importance Value Index (IVI)

Data obtained from the analysis of relative density (RD), relative frequency (RF), and relative dominance (RDO) was used to calculate the importance value index (IVI) of the species in the vegetation of Sida Forest. Twenty-one (22.83%) woody species having IVI greater than 4 constituted 140.72 (57.67%) from the total 244 IVI values of the vegetation studied (Table 4). The importance value index of woody species of the study area ranged from 0.13 to 14.62. The most ecologically important woody species in the forest with the highest importance value indices that contributed 26% of the total IVI were *Podocarpus falcatus* (14.62), *Syzygium guineense* subsp. *afromontanum* (12.68), *Combretum molle* (11.70), *Ficus sycomorus* (9.11), *Croton macrostachyus* (7.77) and *Ficus thonningii* (7.64). The remaining woody species contributed 74% of the total IVI. The woody species with the least IVI were *Senegalia brevispica* (0.13), *Grewia villosa* (0.17), *Gardenia ternifolia* (0.18), *Searsia longipes* (0.24), *Dichrostachys cinerea* (0.25) and *Piliostigma thonningii* (0.28), which contributed only 0.5% of the IVI (Appendix 3).

Table 4. Relative Frequency (RF), Relative Density (RD), Relative Dominance (RDO), and Important value index (IVI) of the top 21woody species in the Sida Forest

No.	Species	RF	RD	RDO	IVI
1	*Podocarpus falcatus*	1.970	3.264	9.391	14.62
2	*Syzygium guineense* subsp. *afromontanum*	1.595	3.481	7.606	12.68
3	*Combretum molle*	3.283	3.230	5.188	11.70
4	*Ficus sycomorus*	1.032	0.218	7.862	9.11
5	*Croton macrostachyus*	2.064	2.126	3.578	7.77
6	*Ficus thonningii*	1.313	1.774	4.551	7.64
7	*Vangueria madagascariensis*	3.283	3.029	0.428	6.74
8	*Terminalia brownii*	1.876	2.008	2.731	6.62
9	*Terminalia macroptera*	2.064	1.975	2.149	6.19
10	*Phoenix reclinata*	1.595	2.326	1.924	5.85
11	*Juniperus procera*	0.938	1.105	3.635	5.68
12	*Entada abyssinica*	1.407	1.322	2.602	5.33
13	*Hagenia abyssinica*	0.375	0.318	4.479	5.17
14	*Eugenia bukobensis*	1.595	1.741	1.721	5.06
15	*Rhus vulgaris*	2.345	1.941	0.439	4.73
16	*Calpurnia aurea*	1.782	2.410	0.396	4.59
17	*Discopodium penninervium*	2.064	2.209	0.104	4.38
18	*Osyris quadripartita*	1.595	2.075	0.701	4.37
19	*Diospyros mespiliformis*	0.281	0.134	3.821	4.24
20	*Maesa lanceolata*	1.501	2.008	0.633	4.14
21	*Ficus sur*	0.469	0.218	3.423	4.11

Diameter at breast height (DBH) class distribution

The general structural pattern of woody species in the Sida Forest was displayed using DBH and height (H) class distribution. A total of 2238 individuals of woody species with DBH ≥ 2.5 cm and height ≥ 2m were recorded in Sida Forest. The highest density of woody species was recorded in the lower DBH class and the density gradually decreased with increasing DBH classes. The highest 1064 (47.5%) number of individuals was recorded in the lower DBH classes and decreased at the higher DBH classes 23 (1%) (Figure 7). About 73.1% of individuals of woody species were found in the first two DBH classes (2.5-10 and 10.1-20cm). The remaining five DBH classes together contributed about 26.9%. The dominant woody species contributing to the lower DBH class were *Vangueria madagascariensis* 53(5%), *Combretum molle* 51(4.8%), *Syzygium guineense* subsp. *afromontanum* 49(4.6%), *Phoenix reclinata* 43(4%), *Calpurnia aurea* 38(3.6%), *Rhus vulgaris* 38(3.6%), *Terminalia macroptera* 38(3.6%), *Coffea arabica* 37(3.5%), *Senna singueana* 36(3.4%), *Maesa lanceolata* 35(3.3%), *Ziziphus mucronata* 33(3.1%), *Eugenia bukobensis* 31(2.9%), *Osyris quadripartita* 29(2.7%). Whereas *Ficus sycomorus* 8(34.8%), *Diospyros mespiliformis* 4(17.4%), *Podocarpus falcatus* 4(17.4%) *Ficus sur* 2(8.7%), *Ficus vasta* 2(8.7%), *Bridelia micrantha* 1(4.4%), *Hagenia abyssinica* 1(4.4%) and *Juniperus procera* 1(4.4%) were the dominant woody species contributing to the higher DBH class. However, the DBH class distribution of individual species was different from the cumulative DBH class distribution.

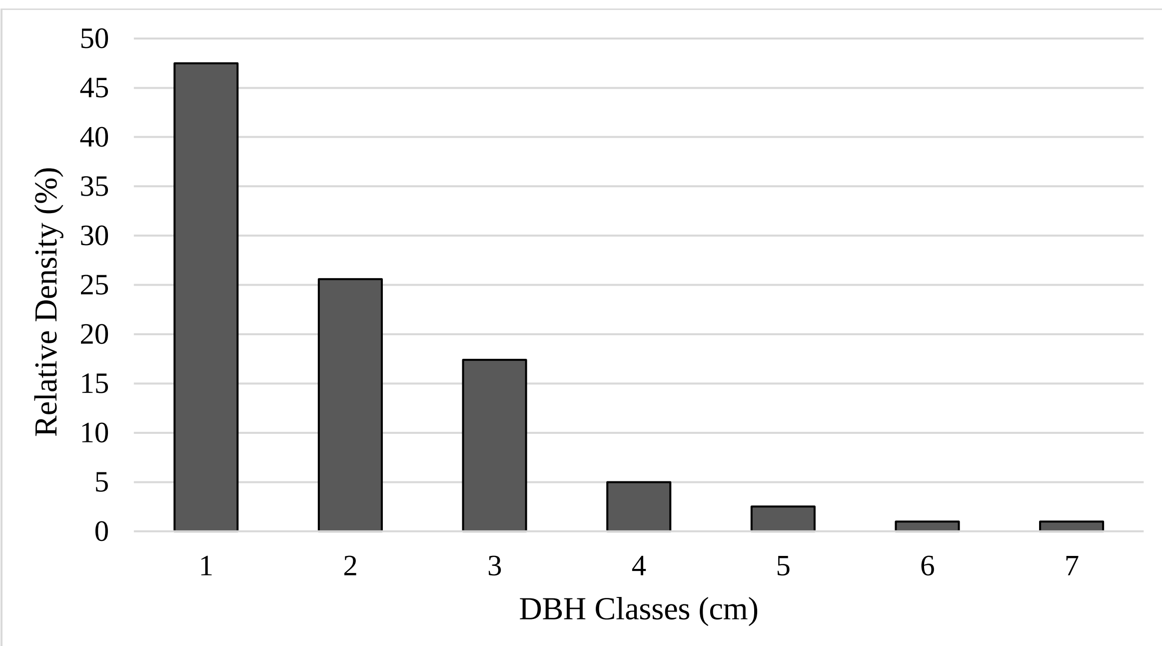


Figure 7. DBH class distributions of woody species in Sida Forest

Height class distribution of woody species

The results showed that the number of individuals in each successive height class decreased gradually starting from the lower height class to the highest height class. The cumulative height class distribution of all woody species has an inverted J-shape distribution pattern (Figure 8). The highest density 951 (42.5%) individuals of woody species were found in the lower height classes (< 5 m). About 76.8% (1,719 individuals) of woody species were found below a height of 10m, while the remaining 23.2% (519 individuals) of woody species were found above a height of 10.1m. Of this, 30 (1.3%) individuals were found above a height of 30.1m. The highest height class (>30.1m) constitutes the smallest proportions of individuals and is contributed by *Podocarpus falcatus* 7(23.33%), *Diospyros mespiliformis* 4(13.33%), *Juniperus procera* 3(10%), *Syzygium guineense* subsp. *afromontanum* 3(10%) *Ficus thonningii* 3(10%), *Ficus ovata* 2(6.7%), *Ficus sur* 2(6.7%), *Ficus sycomorus* 2(6.7%), *Ficus vasta* 2(6.7%), and *Hagenia abyssinica* 2(6.7%).

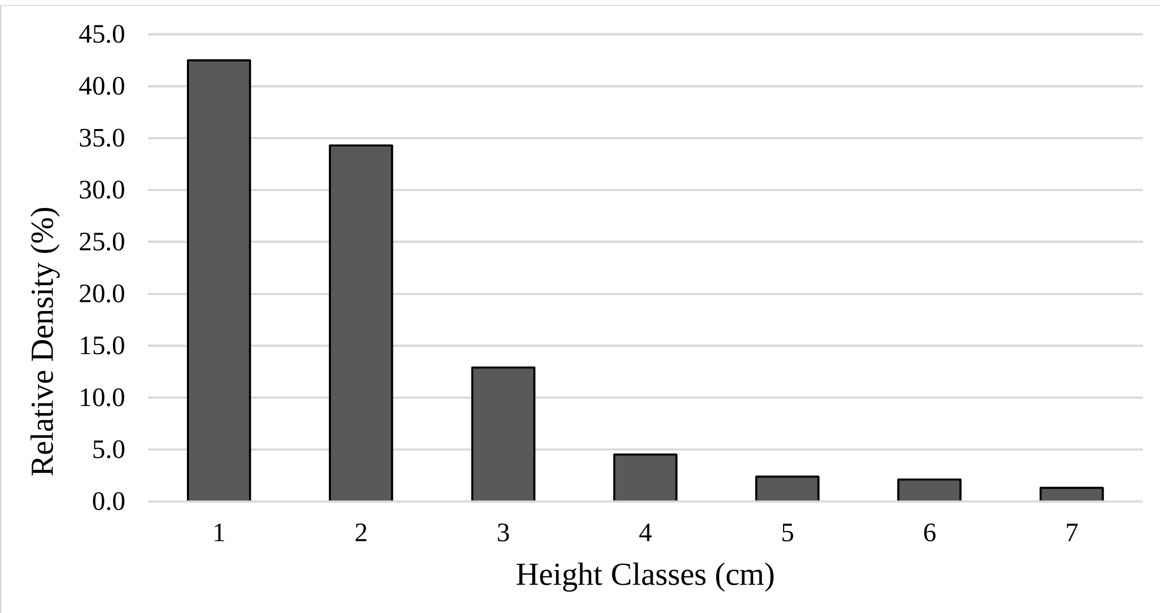


Figure 8. Height class distributions of woody species in Sida Forest vegetation

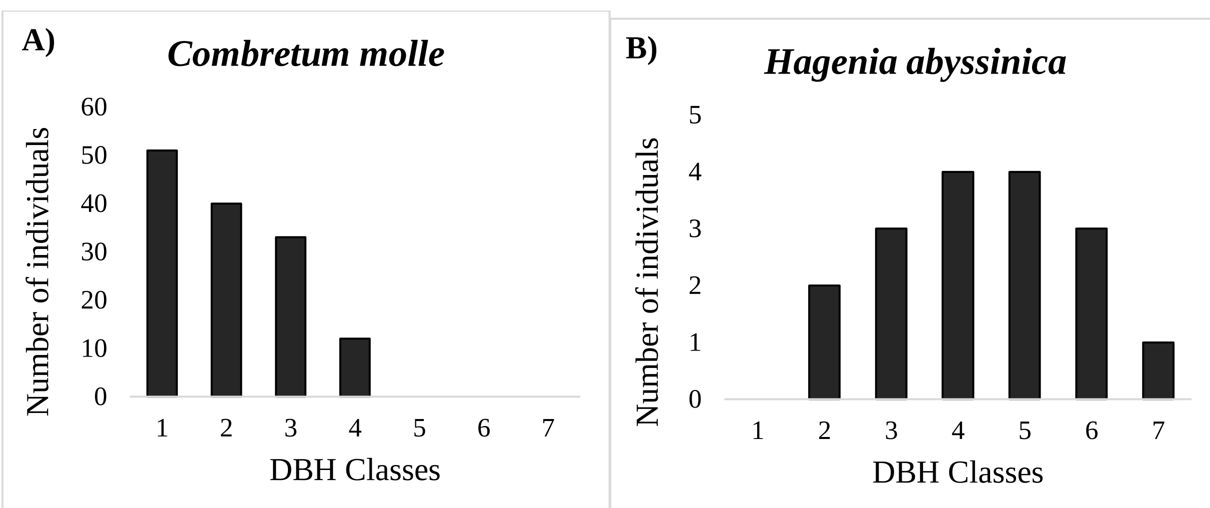
Population structure of selected woody species

The top ecologically important woody species were analyzed separately based on the value of the importance value index (IVI). The result on population structure revealed four general patterns and they were represented by four woody species which we think are better for demonstrating the result (Figure 9). The overall DBH class distribution of selected woody species showed various patterns of population structure, indicating variation among the species' population dynamics within the forest. The first pattern was an inverted “J” shaped distribution pattern represented by *Combretum molle* (Figure 9A). In this pattern, the species have a high density of individuals in the lower DBH class and the density gradually decreases with increasing DBH classes. The species in this pattern include *Acacia goetzei*, *Syzygium guineense* subsp. afromontanum, *Eugenia bukobensis*, *Grewia velutina*, *Lannea fruticosa*, *Maesa lanceolata*, *Maytenus arbutifolia*, *Millettia ferruginea*, *Olea europaea* subsp. *cuspidata*, *Osyris quadripartita*, *Phoenix reclinata*, *Schefflera abyssinica*, and *Terminalia macroptera*.

The second pattern was a bell-shaped (Gaussian-curve) distribution pattern represented by *Hagenia abyssinica* (Figure 9B). In this pattern, a higher number of species were found in the middle DBH classes and a lower number of species were found in lower and higher DBH classes. The species in this category were *Croton macrostachyus*, *Ficus thonningii*, *Mimusops kummel*, *Olinia rochetiana,* and *Terminalia brownii.*

The third pattern was a J-shaped distribution pattern, represented by *Dombeya torrida* (Figure 9C). In this pattern, the species have a higher proportion of individuals at the higher DBH classes and gradually decrease towards the lower DBH classes. The species in this pattern include *Acacia hockii*, *Bersama abyssinica*, *Cordia africana*, *Diospyros scabra*, *Entada abyssinica*, *Diospyros mespiliformis*, *Ficus ovata*, and *Ficus vasta.*

The fourth pattern was a Broken Inverted-J-shaped pattern, represented by *Podocarpus falcatus* (Figure 9D). In this pattern, individuals were absent at intermediate or higher DBH classes. They showed a higher density of individuals at the lower DBH classes and then decreased up to some limits and then increased up to some points and finally decreased, forming a kind of undulating or zigzag pattern as DBH increases. The species in this pattern includes *Juniperus procera.*



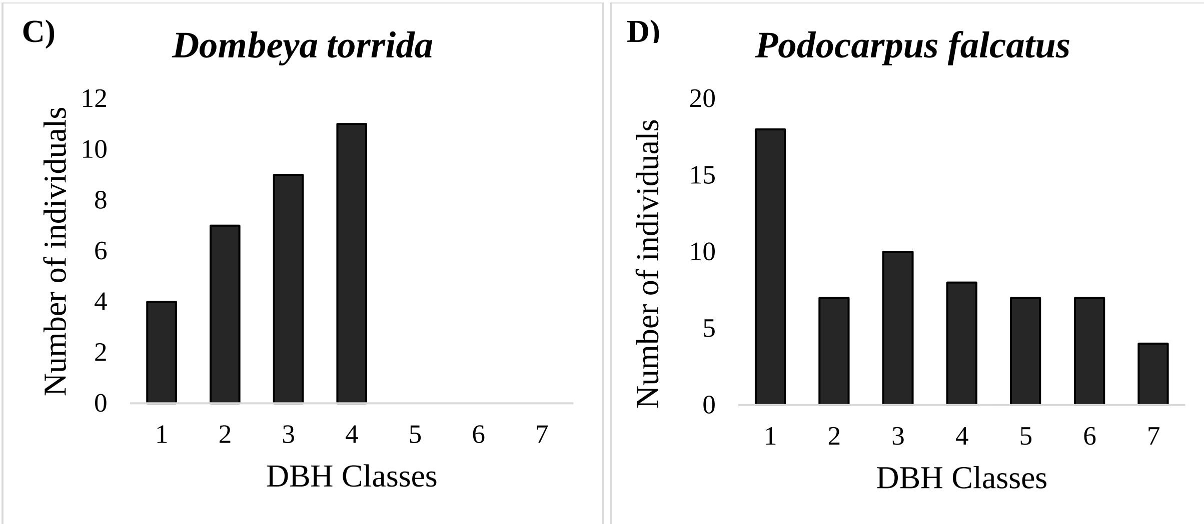


Figure 9. Population structure of selected woody species (A), *Combretum molle*, (B) *Hagenia abyssinica*, (C) *Dombeya torrida, and* (D) *Podocarpus falcatus*

Vertical structure

In this study tree heights greater than 30m were categorized as upper storey (height > 30 m), trees height between 15-30 m as middle storey, and trees heights less than 15 m were categorized as lower storey. The tallest tree in the upper storey (height of >30 m) accounted for only 2% of the total trees. Ten tree species represented this layer. The dominant trees contributing more than 10% to this layer were *Podocarpus falcatus* (23.33%), *Diospyros mespiliformis* (13.33%), *Juniperus procera* (10%), *Ficus thonningii* (10%), and *Syzygium guineense* subsp. *afromontanum* (10%), whereas, the middle storey (height of 15-30 m) contributed to 12% of the vertically stratified trees. Twenty tree species (37%) containing 199 individuals were found in this layer and the most dominant trees in this layer were *Croton macrostachyus* (4.02%), *Ficus sur* (4.02%), *Ficus sycomorus* (4.52%), *Ficus thonningii* (17.09%), *Hagenia abyssinica* (6.53%), *Juniperus procera* (4.52%), *Podocarpus falcatus* (13.57%) and *Syzygium guineense* subsp. *afromontanum* (20.60%) and the remaining contributes less than 4% each to this layer. Whereas a tree height of less than 15m forms the lower storey and is comprised of the largest percentage (86%) of trees in the Sida Forest. The lower storey contains almost all 51(94%) of the tree species and 1433 individuals of the species. The tree species in the lower storey contributing more than 3% to this layer were *Combretum molle* (9.21%), *Croton macrostachyus* (5.16%), *Phoenix reclinata* (5.65%), *Syzygium guineense* subsp. *afromontanum* (8.03%), *Terminalia macroptera* (6.56%), *Terminalia brownii* (5.44%), *Eugenia bukobensis* (4.68%), *Entada abyssinica* (4.40%), *Maesa lanceolata* (3.98%), *Ficus thonningii* (3.77%), and *Osyris quadripartita* (3.42%). The lower storey of the Sida Forest was found to contain a high number of individual species, whereas the upper storey was represented by very few individuals.

2.3.3. Plant community classification

The cluster analysis classified the vegetation of the study forest into five plant community types (Table 5) using agglomerative hierarchical cluster analysis (Ward's method) based on the cover-abundance value of the species on the study plots (Figure 10). Two or three dominant species with relatively high synoptic and significant indicator values in the group were used to name the communities and the indicator values of the species were considered significant if the respective probability values were less than 0.05 (Table 6).

Table 5. Distribution of plots and no of species of the five plant communities with their elevation ranges in Sida Forest

Community types	List of plots in each community	No. of plots	No. of species	Elevation range
C1	1,2,3,12,13,14,25,26,39,40,60,70	12	117	1505-1783
C2	4,5,18,19,21,24,28,29,30,31,33,34,43,55,56,59,61,62,63,64,69	21	159	1564-2310
C3	10,11,15,16,17,22,23,27,32,35,36,37,38,41,42,53,54,57,58,65,66,67,68,71,72	25	145	1640-2309
C4	6,7,8,9,44,45,51,52,73,74	10	92	1950-2228
C5	20,46,47,48,49,50,75,76,77,78,79,80,81,82	14	61	2092-2410

Description of the plant community types

Community 1: *Acacia hockii -Terminalia brownii* community type

This community type is distributed between the elevation ranges of 1505 - 1783 masl. and consists of 117 species in 12 plots. Out of these, 80 species were commonly shared with community two, 75 species with community three, 39 species with community four, and 20 species with community five. *Acacia hockii* and *Terminalia brownii* were the characteristic tree species in this community. Species including *Ficus sycomorus*, *Cordia africana*, *Grewia velutina*, *Combretum collinum*, and *Acacia goetzei* were also the dominant trees found in the tree layer. *Vangueria madagascariensis* was the characteristic shrub species in this community. *Calpurnia aurea*, *Acalypha fruticosa*, *Grewia velutina*, *Psychotria orophila*, *Stereospermum kunthianum*, *Senna singueana*, and *Ziziphus pubescens* were the dominant species in the shrub layer. The most dominant herb layer in this community was comprised of *Aloe gilbertii*, *Amaranthus spinosus*, *Commelina* *benghalensis, Hypoestes forskaolii*, *Ocimum urticifolium*, *Phyllanthus rotundifolius*, *Pupalia lappacea*, *Stachys aculeolata* and *Tagetes minuta*. *Adenia gummifera*, *Cardiospermum corundum,* and *Cissus petiolata* were the characteristics climber species of this community and *Andropogon distachyus* and *Eleusine jaegeri* were the grass species of this community. This community was found at the lower elevation.

Community 2: *Albizia gummifera-Croton macrostachyus* community type

This community type was distributed between the elevation ranges of 1564 - 2310 masl. and consists of 159 species in 21 plots. Out of these, 80 species were shared with community one, 96 species with community three, 69 species with community four, and 38 species with community five. *Albizia gummifera* and *Croton macrostachyus* were the characteristic tree species in this community. Species including *Diospyros abyssinica*, *Diospyros mespiliformis*, *Millettia ferruginea*, *Entada abyssinica*, *Eugenia bukobensis*, *Ficus sur*, and *Ficus vasta* were also the dominant trees found in the tree layer of this community. *Coffea arabica* was the characteristic shrub species in this community. *Acanthus sennii*, *Discopodium penninervium*, *Dodonaea angustifolia*, *Grewia tenax,* and *Lippia adoensis* were also the dominant species in the shrub layer. The most dominant herb layer of this community was comprised of *Physalis peruviana*, *Solanum americanum*, *Triumfetta rhomboidea*, *Commelina diffusa*. *Chasmanthera dependens*, *Cissampelos mucronata*, *Momordica foetida*, *Rhoicissus tridentata*, and *Zehneria scabra* were the characteristics climber species of this community and *Eragrostis longifolia* and *Panicum maximum* were the grass species of this community.

Community 3: *Combretum molle* - *Terminalia macroptera* community type

This community type was distributed between the elevation ranges of 1640 - 2309 masl. and consists of 145 species in 25 plots. Out of which 75 species were shared with community one, 96 species with community two, 58 species with community four, and 25 species with community five. *Combretum molle*, *Entada abyssinica* and *Terminalia macroptera* were the characteristic tree species in this community. Species including *Lannea fruticosa*, *Nuxia congesta*, *Osyris quadripartita,* and *Schefflera abyssinica* were also the dominant trees found in the tree layer of this community. *Rhus vulgaris* was the characteristic shrub species in this community. *Carissa spinarum, Clerodendron myricoides, Dodonaea angustifolia,* and *Ziziphus mucronata* were the dominant species in the shrub layer. The dominant herb layer of this community included *Becium obovatum*, *Bidens schimperi*, *Cyperus longibracteatus*, *Guizotia scabra* and *Triumfetta cordifolia*.

Clematis simensis, *Dioscoria bulbifera*, *Periploca linearifolia* and *Vatovaea pseudolablab* were the characteristics climber species of this community and *Agrostis diffusa*, *Digitaria abyssinica*, and *Panicum porphyrrhizos* were the common grass species of this community.

Community 4: *Juniperus procera - Podocarpus falcatus - Maesa lanceolata* community type

This community type was distributed between the elevation ranges of 1950 - 2228 masl. and consists of 92 species in 10 plots. Out of these, 39 species were shared with community one, 69 species with community two, 58 species with community three, and 35 species with community five. *Juniperus procera*, *Podocarpus falcatus*, and *Maesa lanceolata* were the characteristic tree species in this community. Species including *Agarista salicifolia* and *Eugenia bukobensis* were also the dominant trees found in the tree layer of this community. *Myrsine africana* was the characteristic shrub species in this community. *Clutia abyssinica*, *Gymnosporia addat*, *Rhamnus prinoides*, *Rubus steudneri* and *Vernonia amygdalina* were the dominant species in the shrub layer. The dominant herb layer in this community consists of *Achyranthes aspera*, *Bidens pilosa*, *Justicia heterocarpa*, *Lobelia giberroa*, and *Rhynchospora corymbosa*. *Aspargus africanus*, *Cyphostemma niveum* and *Jasminum abyssinicum* were the characteristics climber species of this community and *Eragrostis virescens* and *Sporobolus africanus* were the common grass species of this community, while *Cheilanthes hirta*, *Pseudocyclosorus pulcher,* and *Pteridium aquilinum* were the ferns common to this community.

Community 5: *Ficus thonningii - Phoenix reclinata - Syzygium guineense* subsp. *afromontanum* community type

This community type was distributed between the elevation ranges of 2092 - 2410 masl. and consists of 61 species in 14 plots. This community was found at the highest elevation. Out of these 20 species were shared with community one, 38 species with community two, 25 species with community three, and 35 species with community four. *Ficus thonningii*, *Phoenix reclinata*, and *Syzygium guineense* subsp. *afromontanum* was the characteristic tree species in this community. Species including *Hagenia abyssinica*, *Ficus sur*, *Maytenus arbutifolia* and *Mimusops kummel* were also the dominant trees found in the tree layer of this community. The common species in the shrub layer of this community include *Bersama abyssinica*, *Brucea antidysenterica*, *Maytenus undata*, and *Teclea nobilis*. The most dominant herb layer in this community comprised *Hypoestes aristata*, *Lobelia giberroa*, *Rumex abyssinicus*, and *Scadoxus multiflorus*. *Landolphia buchananii* was the characteristic climber species of this community and *Oplismenus hirtellus* was the common grass species of this community, while *Asplenium theciferum* and *Dryopteris schimperiana* were the common ferns found in this community.

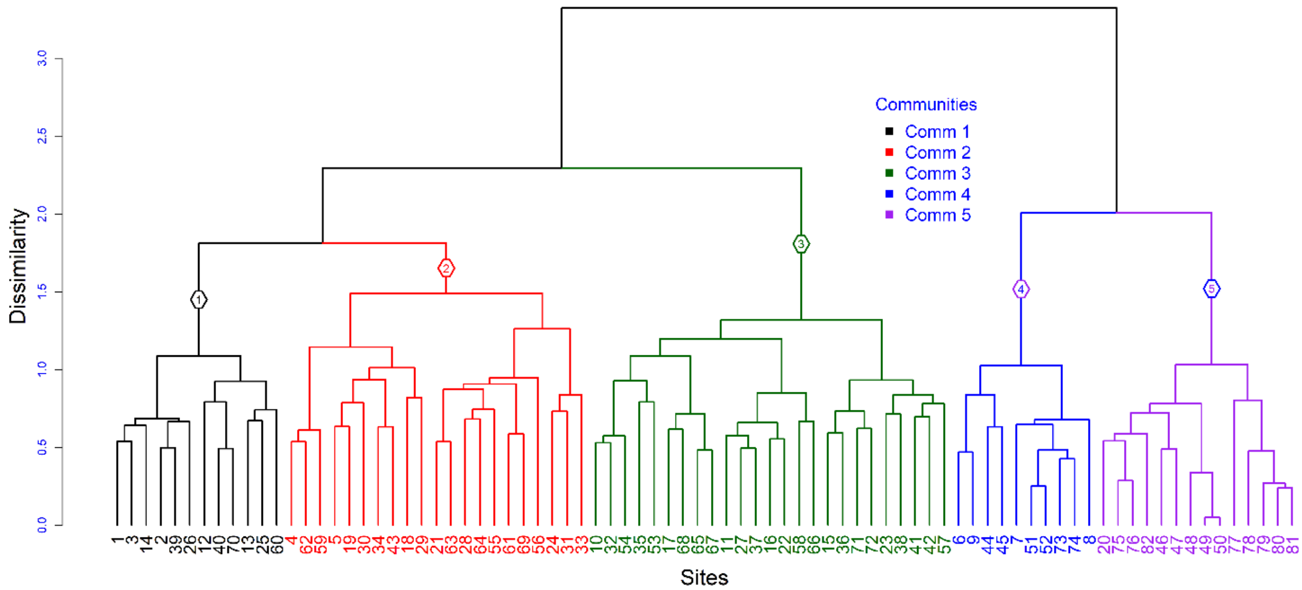


Figure 10. Dendrogram of the vegetation data obtained from hierarchical cluster analysis of Sida Forest using Ward's method.

Table 6. List of indicator species with synoptic cover-abundance values, having a value of ≥1 at least in one of the community type (C1—C5) and their significance (P < 0.05)

Species	Indicator Values (%)					Synoptic Values					
	C 1	C 2	C 3	C 4	C 5	C 1	C 2	C 3	C 4	C 5	P-value
Acacia goetzei	26.9	2.4	9.4	0	0	1.64	0.73	1	0	0	0.01
Acacia hockii	**44.1**	0.1	8.4	0	0	3.55	0.05	1	0	0	**0.001**
Acalypha fruticosa	47.7	0.2	0	0	0	1.09	0.05	0	0	0	0.001
Albizia gummifera	0	**31.4**	0.2	0	0	0	1.86	0.12	0	0	**0.001**
Bersama abyssinica	0.9	0.3	0	1.2	35.6	0.27	0.14	0	0.3	1.71	0.001
Calpurnia aurea	40.4	14.9	0.4	0	0	2.55	1.55	0.2	0	0	0.001
Carissa spinarum	7.6	2.7	22.2	3.3	0.3	0.91	0.5	1.56	0.6	0.14	0.053
Clerodendron myricoides	4.7	0.3	23.8	0	0	0.18	0.27	1.16	0	0	0.021
Clutia abyssinica	3.2	0.2	8.3	23.2	0	0.45	0.09	0.64	1	0	0.024
Coffea arabica	1	39.1	0	1.4	0	0.27	1.55	0	0.3	0	0.001
Combretum collinum	24.3	0	3.2	0	0	1.18	0	0.4	0	0	0.008
Combretum molle	14.8	1.3	**58.8**	0.4	0	2	0.68	5.24	0.3	0	**0.001**
Cordia africana	17.8	11.1	0	0	0	1.55	1.18	0	0	0	0.038
Croton macrostachyus	9.1	**31**	0.4	1.8	2.1	1.09	3.59	0.32	0.6	0.64	**0.006**

Diospyros mespiliformis	0	19	0	0	0	0	1.32	0	0	0	0.016
Discopodium penninervium	0.4	13.9	5.5	12	0.4	0.18	1.27	0.84	1.1	0.21	0.27
Dodonaea angustifolia	1.1	1.9	23	1	0	0.27	0.36	1.12	0.2	0	0.014
Dracaena afromontana	0	1.3	0	5.8	16.4	0	0.23	0	0.5	1	0.057
Ekebergia capensis	1.8	0.6	0	0	14.2	0.45	0.23	0	0	1.29	0.063
Entada abyssinica	0.9	2.2	32.6	0	0	0.36	0.45	2.32	0	0	0.003
Eugenia bukobensis	0	1.2	1.2	37.5	8.6	0	0.41	0.36	1.9	0.86	0.002
Ficus sur	0	3.5	0	0	13.5	0	0.64	0	0	1.14	0.066
Ficus sycomorus	24.8	5.2	0.1	0	0	2.82	1.14	0.56	0	0	0.005
Ficus thonningii	0	0	0	3.4	**71.3**	0	0	0	1.1	5.43	**0.001**
Ficus vasta	0	19	0	0	0	0	1.23	0	0	0	0.014
Grewia tenax	12	29.3	0.1	0	0.3	1	1.86	0.12	0	0.14	0.003
Grewia velutina	25.1	1.6	2.7	0	0.4	1.91	0.82	0.6	0	0.21	0.007
Gymnosporia addat	0.3	7.3	0	27.3	1.5	0.09	0.59	0	1.1	0.21	0.008
Hagenia abyssinica	0	0	0	0	28.6	0	0	0	0	1.71	0.002
Juniperus procera	0	0	0	**46.7**	6.3	0	0	0	4.5	1.29	**0.001**
Lannea fruticosa	11.8	0	18.9	0	0	1.45	0	1.48	0	0	0.041
Maesa lanceolata	0	1	0	**58.5**	8.5	0	0.45	0	**5**	1.36	**0.001**
Maytenus arbutifolia	0	0.6	0	2.6	17.8	0	0.23	0	0.5	1.21	0.035
Maytenus undata	0	0	0	0	42.9	0	0	0	0	1.43	0.001
Millettia ferruginea	0	20.6	0	1	2.6	0	1.36	0	0.2	0.36	0.028
Mimusops kummel	0	0	0	0	0.214	0	0	0	0	1	0.009
Myrsine africana	0	8.2	1.1	61.4	0.4	0	0.95	0.36	2.5	0.21	0.001
Osyris quadripartita	1.5	0	28.5	9.5	0	0.36	0	2.24	1.2	0	0.003
Phoenix reclinata	0	0.5	0	4.5	**68.2**	0	0.32	0	0.9	4.79	**0.001**
Podocarpus falcatus	0	0	0	**67.4**	25.6	0	0	0	7.4	3.57	**0.001**
Psychotria orophila	17	6.9	0.2	2.8	0	1.18	0.59	0.12	0.3	0	0.078
Rhus vulgaris	0	6.4	31.4	1	0	0	0.77	1.88	0.9	0	0.005
Senna singueana	19.8	1.9	22.5	0	0	1.36	0.41	1.48	0	0	0.028
Stereospermum kunthianum	27.6	0.6	4.4	0	0	1.18	0.18	0.36	0	0	0.005
Syzygium guineense subsp. *afromontanum*	0	0	0	4.7	**84.2**	0	0	0	1.3	6.93	**0.001**
Terminalia brownii	**63.2**	0.1	7.7	0	0	6	0.18	1.56	0	0	**0.001**
Terminalia macroptera	1.7	2.7	**41.7**	0.6	0	0.55	0.68	3.44	0.3	0	**0.001**
Vangueria madagascariensis	62.4	17.7	2.7	0.2	0	5.45	2.27	0.72	0.2	0	0.001
Ziziphus mucronata	11.6	1.7	17.4	1	0	1.18	0.36	1.36	0.3	0	0.08

*Bold = species score high cover-abundance and significant values (P value) used for community types.

2.3.4. Ordination analysis

Relations between environmental factors and the plant community types

The correlation of environmental variables with community types and their influence on the distribution of vegetation in the study area was analyzed using the Canonical Correspondence Analysis (CCA) technique. Eighteen environmental variables (Appendix 4) were used in the ordination analysis (altitude, slope, aspect, disturbance, sand, clay, silt, pH, EC, OC, OM, TN, AvP, CEC, Ca^{++}, Mg^{++}, $K^{+,}$ and BD). The Canonical Correspondence Analysis (CCA) result showed that out of 18 environmental variables, six (altitude, slope, aspect, disturbance, sand, and pH of the soil) were found to be significant in explaining the patterns of plant community formation in Sida Forest and had a strong influence on species composition and distribution. From the ordination diagram (Figure 11), it can be seen that elevation, disturbance, OC, and sandy soil were strongly associated with species composition and distribution as indicated by the long arrow suggesting that they are the main environmental factors responsible for the variation of vegetation in the study area. The five community types were isolated following the arrows of the environmental variables. Community type one (*Acacia hockii -Terminalia brownii*) occurs at the lower elevation and is positively correlated with aspect, disturbances, and pH, however, it is negatively correlated with altitude and slope. Community type two (*Albizia gummifera-Croton macrostachyus*) was found in scattered form and affected by different factors including aspect, slope, pH, and sand. However, slope and pH were strongly influencing the distribution of species in this community. Community three (*Combretum molle - Terminalia macroptera*) is positively correlated with altitude, slope, and sandy soil. Altitude has a strong influence on the distribution of species in this community. Whereas community four (*Juniperus procera - Podocarpus falcatus - Maesa lanceolata*) positively correlated with disturbance, aspect, and sandy soil texture. The distribution of species in this community was strongly influenced by sandy soil. Community five (*Ficus thonningii - Phoenix reclinata - Syzygium guineense* subsp. *afromontanum*) occurred at a higher elevation and positively correlated with elevation and slope. The distribution of species in this community is strongly influenced by elevation.

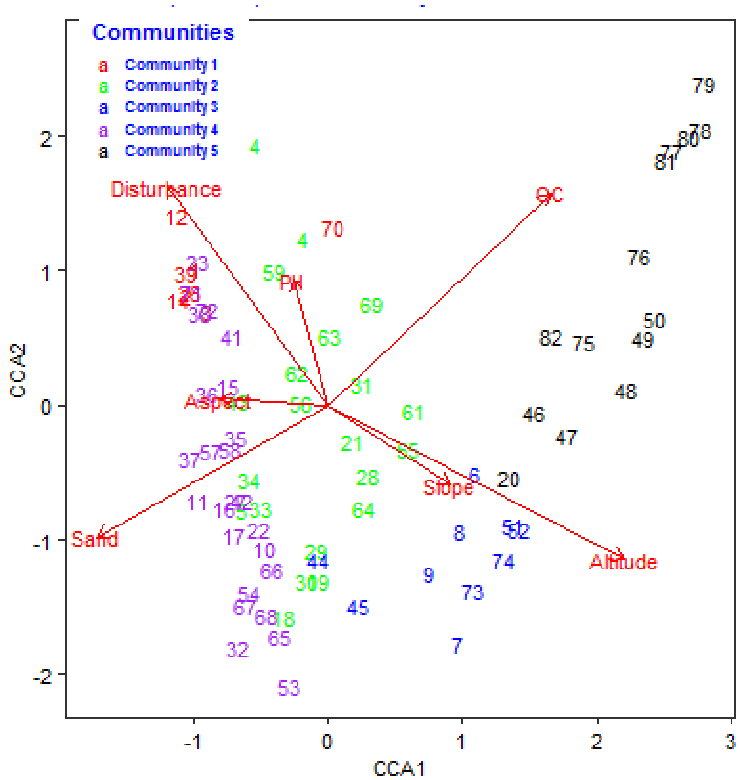


Figure 11. CCA plot of environmental variables and sampling plots (communities)

Species richness, evenness, and diversity of the five plant communities

The Shannon-Wiener diversity index was computed for the five plant community types in the Sida Forest. The result of the Shannon-Wiener diversity index showed that the species diversity, richness, and evenness for each community type were high (Table 7). The species diversity of each plant community type ranged from 3.25 to 4.44. In terms of species richness, community two was found the most species-rich (159 species) followed by community three (145 species) and community one (117 species). While, community five (61 species), and community four (92 species) showed the least species richness. The highest species diversity (H'= 4.44) was found for community two, followed by community three (H'= 4.26) and community one (H'= 4.08), while community five (H' = 3.25) and community four (H'= 3.80) showed relatively the lowest species diversity. In terms of evenness, the highest value was shown for community two (0.88), and the lowest evenness was shown for community five (0.79) when compared with the other community types (Table 7).

Table 7. Descriptive statistics of the environmental variables and the Shannon diversity and evenness indices for the five-plant community types of Sida Forest

Community types(plots)	Statistics	Topographic Variables			Disturbance	Soil variables		Diversity		
		Altitude	Slope	Aspect	Disturbance	Sand	pH	S	H'	E
C1 (12)	Minimum	1505.0	2.00	1.30	0.00	60.00	4.60	117.00	4.08	0.86
	Maximum	1783.0	49.00	4.00	4.00	78.00	6.80			
	Mean	1618.8	13.33	2.67	2.00	69.50	6.23			
	Std.Dev	79.6	11.96	0.85	1.21	6.56	0.61			
C2 (21)	Minimum	1564.0	2.50	1.30	0.00	54.00	5.40	159.00	4.44	0.88
	Maximum	2310.0	54.00	4.00	4.00	76.00	7.10			
	Mean	1964.5	17.60	2.73	0.57	66.19	6.17			
	Std.Dev	211.8	14.99	0.84	1.16	5.86	0.49			
C3 (25)	Minimum	1640.0	4.00	1.00	0.00	56.00	5.20	145.00	4.26	0.86
	Maximum	2309.0	50.00	4.00	4.00	80.00	6.50			
	Mean	1886.6	15.60	3.02	0.92	70.96	5.95			
	Std.Dev	221.7	10.78	0.77	1.12	5.83	0.36			
C4 (10)	Minimum	1950.0	8.00	1.00	0.00	54.00	4.90	92.00	3.80	0.84
	Maximum	2228.0	50.00	3.30	1.00	80.00	6.50			
	Mean	2105.8	30.20	2.02	0.10	66.10	5.92			
	Std.Dev	83.5	17.20	0.99	0.32	8.23	0.57			
C5 (14)	Minimum	2092.0	1.00	1.00	0.00	32.00	4.90	61.00	3.25	0.79
	Maximum	2409.0	51.00	4.00	1.00	70.00	6.50			
	Mean	2304.7	22.36	2.04	0.07	50.93	5.96			
	Std.Dev	92.0	16.05	1.02	0.27	10.22	0.44			

S = species richness, H′ = Shannon diversity index, E = Shannon evenness).

Similarities between plant community types

Sorenson's coefficient of similarity was used to calculate the degree of similarity among the five plant community types. A gradual change in species composition and diversity was observed in the study forest. The number of species shared between C1 and C2, C3, C4, and C5 was 80, 75, 39, and 20 respectively. Community one share more species with communities two (36.7%) and three (36.4%) than with community four (27.2%) and community five (18.3%). The highest similarity was found between community two and three (58.9%), while, relatively less similarity was observed with community four (35.5%) and community five (25.7%). Community three shares more species with community four (32.9%) than with community five (19.5%). Community five shares more species with community four (31.4%) than any other community (Table 8).

Table 8. Sorenson's coefficient of similarity among the five plant community types (C1 - C5) in the study area

Communities	C1	C2	C3	C4	C5
C1	1				
C2	0.367	1			
C3	0.364	0.589	1		
C4	0.272	0.355	0.329	1	
C5	0.183	0.257	0.195	0.314	1

2.3.5. Regeneration status of Sida Forest

The regeneration status of a forest was summarized based on the total density of seedlings, saplings, and mature individuals of each species in all plots. The regeneration status of trees in Sida Forest was characterized by density of seedlings, saplings, and mature individuals of trees. Accordingly, a total of 646 (196.95 individuals h-1) seedlings of 45 species, 339 (103.35 individuals h-1) saplings of 17 species, and 1662 (506.71 individuals h-1) matured trees of 54 species were recorded from all plots (Figure 12).

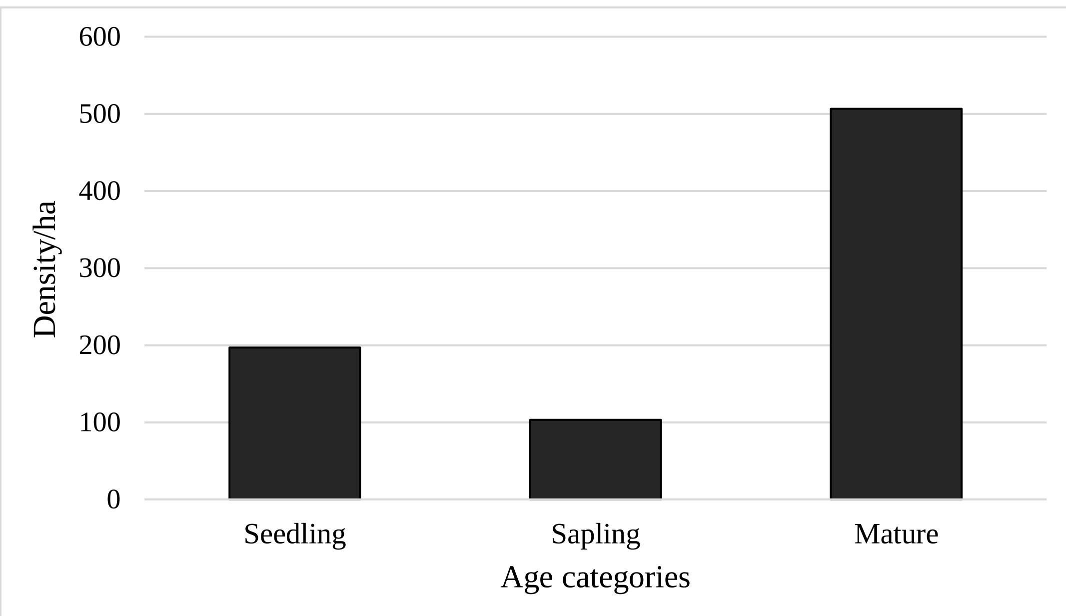


Figure 12. Overall regeneration status of Sida Forest

The density of seedlings for each species ranges from 0.30 individuals ha-1 to 31.71 individuals ha-1. Fourteen tree species contributed 75% of seedlings and 84% of sapling density. Accordingly, tree species with the highest contribution to the seedling and sapling densities were *Podocarpus falcatus*, *Osyris quadripartita*, *Maesa lanceolata*, *Syzygium guineense* subsp. *afromontanum*, *Combretum molle*, *Phoenix reclinata*, *Terminalia brownii*, *Croton macrostachyus*, *Acacia hocki*, *Bersama abyssinica, Juniperus procera, Olea europaea* subsp. *cuspidata*, *Maytenus arbutifolia* and *Eugenia bukobensis*. Whereas the lowest 1(0.15% each) seedling density was contributed by *Vachellia dolichocephala*, *Vachellia tortilis, Albizia schimperiana*, *Balanites rotundifolia*, *Dichrostachys cinerea*, *Diospyros abyssinica*, and *Ficus ovata* (Appendix IV). Nine species were not represented by seedlings, 17 species were not represented by saplings and seven species were without both seedlings and saplings.

Based on the presence or absence of seedlings, saplings, or both, tree species recorded in the Sida Forest were classified as, 1) species without seedlings and saplings, 2) species with seedlings but without saplings, and 3) species with saplings but without seedlings (Table 9).

Table 9. Regeneration status classification of tree species for priority conservation concern

No	Species without saplings	Species without seedlings	Species without saplings and seedlings
1	*Agarista salicifolia*	*Balanites aegyptiaca*	*Balanites aegyptiaca*
2	*Albizia schimperiana*	*Boswellia neglecta*	*Boswellia neglecta*
3	*Balanites aegyptiaca*	*Bridelia micrantha*	*Bridelia micrantha*
4	*Balanites rotundifolia*	*Diospyros mespiliformis*	*Diospyros mespiliformis*
5	*Boswellia neglecta*	*Diospyros scabra*	*Diospyros scabra*
6	*Bridelia micrantha*	*Ficus sycomorus*	*Ficus sycomorus*
7	*Dichrostachys cineral*	*Ficus vasta*	*Ficus vasta*
8	*Diospyros abyssinica*	*Gardenia ternifolia.*	
9	*Diospyros mespiliformis*	*Hagenia abyssinica*	
10	*Diospyros scabra*		
11	*Ficus ovata*		
12	*Ficus sycomorus*		
13	*Ficus vasta*		
14	*Lannea schimperi*		
15	*Mimusops kummel*		
16	*Piliostigma thonningii*		
17	*Vachellia tortilis*		

2.4. Discussion

2.4.1. Floristic composition and species diversity

The floristic composition of the vegetation was described in terms of its species richness, abundance, dominance, and frequency (Lamprecht, 1989). The results of this study showed that the Sida Forest has a significant diversity of plant species in terms of both composition and growth forms. In this study, a total of 254 plant species, belonging to 180 genera and 82 families were recorded, of which 58 (22.83%) of the species were new records to Gamo Gofa Floristic Region of the Flora of Ethiopia and Eritrea. Sebsebe Demissew *et al.* (2021) reported that the vegetation of the southern and southwest parts of Ethiopia has the highest diversity of plant species. The number of species composition in the Sida Forest (82 families, 180 genera, and 254 species) is higher than in other forests of the country such as that of the vegetation in the Dense Forest (75 families, 143 genera, and 158 species) (Ermias Lulekal, 2014), Sire Beggo forest (61 families, 144 genera, and 185 species) (Abyot Dibaba *et al.*, 2014), Gole Forest (57 families, 94 genera, and 114 species) (Mesfin Belete & Demsis, 2020), Majang forest (56 families, 115 genera, and 158 species) (Semegnew Tadesse *et al.*, 2021), and Kibate Forest (52 families, 104 genera, and 125 species) (Misganaw Meragiaw *et al.*, 2021). However species composition in Sida Forest is lower than Bonga Forest (92 families, 207 genera, and 285 species), Berhane-Kontir Forest (95 families, 259 genera, and 374 species), Harenna Forest (86 families, 221genera, and 289 species) (Feyera Senbeta *et al.*, 2014), and Gesha-Sayilem Forest (96 families, 239 genera, and 300 species) (Admassu Addi *et al.*, 2020).

The high species richness of Sida Forest could be associated with environmental factors and its elevation range (ranging from 1500 to 2400 masl.). A study by Vetaas and Grytnes (2002) reported that the maximum species richness for an elevation range between 1500 and 2500 masl. in Ethiopia. Sebsebe Demissew *et al.* (2021) have also reported that the vertical distribution of the flora of Ethiopia has a 'mid-elevation diversity' at an elevation between 1400 and 2400 masl. The possible reasons for the variation in species composition and richness among the different forests may be associated with the differences in environmental factors too (Espinosa *et al.*, 2011; Dong *et al.*, 2019), such as climate, soil characteristics, topography, disturbance, herbivory, forest size, age, and management activities. Climatic variables are also cited for their impact on the distribution of forest species (Li *et al.*, 2017), as temperature increases, species richness increases up to a certain point, beyond that species richness begins to reduce due to water deficits (Gillman & Wright, 2014). Species diversity is known to decrease during the dry season because of the decrease in soil moisture (Song *et al.*, 2021). Elevation and soil characteristics have a significant influence on plant species distribution, richness, and composition (Long *et al.*, 2012; Dong *et al.*, 2019; Song *et al.*, 2021). A positive relationship between tree species richness and soil properties was also reported in another research (Kumar *et al.*, 2010; Rodrigues *et al.*, 2018). In addition to this, the variation in species richness among the different forests might be due to the number of plots sampled and the size of the forest. Increasing the sampling effort would increase the species richness (Kacholi *et al.*, 2015), and forests with a high degree of human interference and disturbances show relatively lower species richness than others.

The result revealed that Fabaceae is the most dominant family with 26 species (10.24%) of the total plants followed by Asteraceae, Lamiaceae, Euphorbiaceae, and Poaceae. Thus, the dominance of Fabaceae in the Sida Forest agrees with the general dominance of the family in the lowland tropical forests. In support of this, Kacholi (2019) reported that Fabaceae is the dominant family in lowland tropical forests. These five plant families were the most frequently occurring families, contributing over 32% of the total number of species in the study forest. In agreement with this, similar results were reported by Motuma Didita *et al.* (2010), Abyot Dibaba *et al.* (2014), Markos Kuma and Simon Shibru (2015), Temesgen Mekonen *et al.* (2015), Mehari Girmay *et al.* (2020), Temesgen Dingamo *et al.* (2022), and Getahun Yemata and Genetu Haregewoien (2022) showing dominance of Fabaceae in different forests of Ethiopia. The dominance of Fabaceae is attributed to its competent and successful dispersal strategies as well as its adaptation potential to the diverse ecologies of the country. According to Ensermu Kelbessa and Sebsebe Demissew (2014) Fabaceae, Asteraceae, Lamiaceaae, Euphorbiaceae, and Poaceae are widely distributed and most species-rich families in the Flora of Ethiopia and Eritrea, ranking in the first, third, seventh, fourth, and second places respectively. They are also the families with the largest number of endemic taxa ranking in the second, first, sixth, third, and fourth places respectively. These families are among the largest families of vascular plants and the most species-rich families comprising 678, 472, 202, 242, and 609 species (Ensermu Kelbessa & Sebsebe Demissew, 2014). Admassu Addi *et al.* (2020) and Getaneh Gebeyehu *et al.* (2019) also reported that these families contributed the highest species richness of their studied forests. The dominance of these families in the study area could also be associated with their successful and efficient pollination, dispersal, and germination mechanisms. In this regard, Bareke and Addi (2018) reported that Fabaceae, Asteraceae, and Lamiaceae are the dominant bee forage families, and hence the diverse pollination and dispersal mechanisms made these families the most widely distributed.

In terms of growth form, shrubs occupied the largest proportion (35%), implying that this forest might be at a higher level of disturbance. In agreement with this, similar results were reported for other forests of Ethiopia including those by Mesfin Woldearegay *et al.* (2018) in the Yegof forest, Getahun Yemata and Genetu Haregewoien (2022) in the Amoro and Zengena forests and Belachew Bogale *et al.* (2022) in Harego forest, indicating that the dominance of shrubs has been evident where habitat fragmentation due to human encroachment is identified as a major threat. Zhang *et al.* (2016) also indicated that anthropogenic disturbances contributed to the increase of shrubs and herbs in the understory. Moreno-Fernández *et al.* (2021) reported that climatic and soil variables have the greatest influence on shrub richness. They revealed that shrub species mainly grow in forests with low rainfall and high temperatures, and nitrogen is the soil variable strongly correlated to shrub richness.

According to Vivero *et al.* (2005), Ethiopia is one of the centers of plant endemism in East Africa. About 9 (3.5%) of the plant species in the study forest are endemic to Ethiopia. Sebsebe Demissew *et al.* (2021) reported that the Floristic Region of the study area (GG) contains vegetation that is rich in endemic species. Geographical isolation and unique climatic conditions made the country rich in endemic species (EBI, 2014; Ensermu Kelbessa & Sebsebe Demissew, 2014). As indicated by Mengesha Asefa *et al.* (2020), endemism is linked to the environmental heterogeneity of the country, which creates complex topography and diverse local habitats that provide micro-habitats for the species. Species endemism increases with elevation, due to topographical isolation and speciation (USAID, 2008; Schmitt *et al.*, 2013). The recorded endemic plant species are not found elsewhere in the world and the presence of these endemic species in the study forest shows the need for immediate conservation measures for this forest. Therefore, identifying and knowing endemic species helps to set conservation priorities and run effective management of the identified species.

2.4.2. Vegetation structure of Sida Forest

Frequency of woody species:

Frequency is an important parameter of vegetation analysis, which shows the pattern of the spread, and distribution of a species in a given area and provides an approximate indication of the homogeneity and heterogeneity of the stand (Lamprecht, 1989; Haileab Zegeye *et al.*, 2006; Kent, 2012). In this study, the majority (80.4%) of the species were recorded in less than 20% of the study plots, whereas some (19.6%) of the species were recorded in more than 20% of the study plots. According to the description of Lamprecht (1989) and Aye *et al.* (2014), more species in lower frequency classes and fewer species in higher frequency classes indicate a high degree of floristic heterogeneity, whereas fewer species in lower frequency classes and more in higher frequency classes indicate floristic homogeneity or similar species composition. Therefore, the high percentage value of species in the lower frequency classes and low value in the higher frequency classes of Sida Forest showed the existence of a high degree of floristic heterogeneity. A high frequency indicates the regular distribution of the species in the forests, while a low frequency indicates that the species is either irregularly distributed or rare in a particular stand.

The frequency class distribution of woody species in the Sida Forest shows a similar pattern to other studies reported by Temesgen Mekonen *et al.* (2015) in Woynwuha Natural Forest, Abyot Dibaba *et al.* (2020) in Agama forest, Getahun Yemata and Genetu Haregewoien (2022) in Bradi Forest, and Belachew Bogale *et al.* (2022) in Harego Forest. Indicating that the number of woody species in the lower frequency classes is higher and gradually decreases towards higher frequency classes. Rey and Alcántara (2000) reported that the presence of a high degree of floristic heterogeneity might be associated with the occurrence of plant species at a wide range of elevations, a wide range of seed dispersal mechanisms, germination potential, resistance to pests and pathogens, habitat preferences, adaptation, degree of exploitation, and availability of suitable environmental conditions for regeneration. On the other hand, the variation in the frequency of species might be attributed to habitat preferences among species, species characteristics for adaptation, degree of disturbance, and availability of suitable conditions (Rey & Alcántara, 2000).

The density of woody species

The density of woody species per hectare in the Sida Forest (682.32 individuals/ha) is higher than the density of woody species documented from other forests in the country by Haile Adamu *et al.* (2012) woodland vegetation in Metema (376.86 individuals per ha), Mehari Girmay *et al.* (2020) Hirmi woodland vegetation (528.4 individuals/ha), Getaneh Gebeyehu *et al.* (2019) dry Afromontane forests of Awi Zone (365 - 664 individuals/ha). However it is lower than those reported by Abreham Assefa *et al.* (2014) at Masha Forest (1681 individuals/ha), Tayachew Birhanu *et al.* (2021) forest in Dangila (2180.6 individuals/ha), Semegnew Tadesse *et al.* (2021) Majang Forest (1478 individuals/ha), and Belachew Bogale *et al.* (2022) Harego Forest (4400.75 individuals/ha). The variations in the density of woody species among the different forest areas might be attributed to the differences in topographic factors, habitat preferences of species, and the degree of anthropogenic disturbances (selective cutting of trees for various purposes). Fikadu Yirga *et al.* (2019) and Goiteom Woldu *et al.* (2020) described the influence of topographic gradients, habitat preferences, and degree of anthropogenic disturbances in the variation of the density of woody species among the forests.

Basal area of woody species

The basal area provides a better measure of the relative importance of the species than simple stem count (Lamprecht, 1989). The total basal area of the Sida Forest was 24.15 m^2/ha, which is within the range of the normal basal area value (23–37 m^2/ha) set for virgin tropical forests in Africa (Lamprecht, 1989). The total basal area of Sida Forest is higher than other forests in the country such as Zengena Forest (22.3 m^2/ha) (Desalegn Tadele *et al.*, 2014), Sire Beggo woodland vegetation (19.3m^2/ha) (Abyot Dibaba *et al.*, 2014), Woynwuha Forest (20.03 m^2/ha) (Temesgen Mekonen *et al.*, 2015), and Harego Forest (9.66m^2 ha−1) (Belachew Bogale *et al.*, 2022), however, it is smaller than other forests Gole Forest (49.2 m^2/ha) (Mesfin Belete & Tamiru Demsis, 2018), Agama Forest (80.8 m^2/ha) (Abyot Dibaba *et al.*, 2020), Majang Forest (139.8m^2/ha) (Semegnew Tadesse *et al.*, 2021), Bradi Forest (91.03 m^2/ ha) (Getahun Yemata & Genetu Haregewoien, 2022), and Shoti forest (77.32 m^2/ha) (Amenu *et al.*, 2022). In the Sida Forest, species with the highest density do not necessarily have the highest basal area, indicating a size difference between the species, such as *Maesa lanceolata*, *Calpurnia aurea,* and *Discopodium penninervium* have the highest density but relatively low basal area, however, *Hagenia abyssinica* and *Ficus sycomorus* have low density but high basal area. The higher basal area was contributed by species with large DBH classes, whereas the lower basal area was contributed by species with lower DBH classes, even though there were many individuals of a species.

About 12.93m^2/ha (53.55%) of the total basal area of the study forest was contributed by ten large-sized species such as *Podocarpus falcatus*, *Ficus sycomorus*, *Syzygium guineense* subsp. *afromontanum*, *Combretum molle*, *Ficus thonningii*, *Hagenia abyssinica*, *Diospyros mespiliformis*, *Juniperus procera*, *Croton macrostachyus* and *Ficus sur*. However, *Senegalia brevispica*, *Allophylus rubifolius*, *Ricinus communis*, *Grewia mollis,* and *Piliostigma thonningii* contributed the least 0.007 m^2/ha (0.03%) to the total basal area. As indicated by Mulugeta Lemenih and Bongers (2011) an area covered with shrub layers and small DBH individuals have a small total basal area contribution in contrast to tree species and large DBH individuals. Otherwise, if we consider density only as a measure, to indicate the overall dominance of the species, shrubs could be the dominant species (Simon Shibru & Girma Balcha, 2004). Thus, the species with the highest contribution to the basal area of the forest is the species with large DBH values and is considered the most important species in the study forest.

Importance Value Index (IVI) of woody species

The important value index is a useful structural parameter in vegetation study used to compare the ecological significance of a species in a given forest (Lamprecht, 1989). It combines data from three parameters, relative density, relative frequency, and relative dominance (Kent, 2012). It reflects the relative ecological importance of a species compared to other associated species in a forest (Kent, 2012), in which species with high IVI values indicate that the species are the most dominant of particular vegetation. In this study, *Podocarpus falcatus*, *Syzygium guineense* subsp. *afromontanum*, *Combretum molle*, *Ficus sycomorus*, *Croton macrostachyus*, and *Ficus thonningii* had higher IVI values than other species; they contributed over 26% of the total importance value indices, suggesting that these species are ecologically the most important and revealed that the species are in a good regeneration pattern in the forest. Whereas, species with a small contribution to the total IVI include *Senegalia brevispica*, *Grewia villosa*, *Gardenia ternifolia*, *Searsia longipes, Dichrostachys cinerea,* and *Piliostigma thonningii* contributed 0.5% to the total IVI. The species with the highest value of IVI (*Podocarpus falcatus, Syzygium guineense* subsp. *afromontanum, Combretum molle*) are the most dominant of Sida Forest and the result of high relative frequency, relative density, and relative dominance, however in others like *Ficus sycomorus* and *Hagenia abyssinica* the highest value of IVI is due to the higher value of relative dominance. The low IVI value of the species could be related to the species being less abundant in the forest, and they require high conservation measures to protect them from decline, which might end in extinction. IVI is also used as a criterion to prioritize species for conservation actions. Species with the highest IVI values need lower conservation efforts than those having the lowest IVI value (Haileab Zegeye *et al.*, 2011). Species with the highest IVI value have to be considered as more resistant to the high pressure of disturbance than the lowest IVI values. As a result, immediate protection and conservation actions are needed for the species with the lowest IVI values of the study forest.

Diameter at breast height (DBH) and height class distribution

The pattern of size-class distribution is used to represent the population structure of a forest. DBH and height of plant species are the two most commonly used size measures in the analysis of plant population structure and provide a good idea for the regeneration of woody species (Getachew Tesfaye *et al.*, 2002). The results of this study revealed that the overall DBH and height class distribution of Sida Forest showed a higher number of individuals in the lower DBH and height classes with a gradual decrease towards the higher DBH and height classes. The lower DBH and height classes, particularly in the first and second classes showed higher density contributing about 73.1% and 76.8% of the DBH and height classes respectively.

The overall DBH and height class distribution pattern of Sida Forest showed an inverted J-shape. This indicates the presence of selective cutting of large-sized individuals, and the dominance of shrub species in Sida Forest or this forest has limited species that grow into larger diameter sizes. A similar pattern of population structure was reported in other forests of the country such as the Gole Forest (Mesfin Belete & Tamiru Demsis, 2018), Majang Forest (Semegnew Tadesse *et al.*, 2021), Bradi Forest (Getahun Yemata & Genetu Haregewoien, 2022), and Harego Forest (Belachew Bogale *et al.*, 2022). This indicates the dominance of small-sized individuals and a progressive decrease in large-sized (matured) trees in the successive higher DBH and height classes. On the other case, the presence of a higher density of species in the lower DBH class is characteristic of secondary forests or it could be related to the selective cutting of matured species for various purposes (Aye *et al.*, 2014). Others reported that the presence of a high density of small-sized individuals in the lowest height classes is an indication of the presence of a high rate of reproduction and good regeneration but low recruitment potential of the vegetation in the forest (Getachew Tesfaye *et al.*, 2002; Kebu Balemie & Fassil Kebebew, 2006). Even if the general pattern of the vegetation structure of Sida Forest is an inverted J-shape, the DBH class distribution of selected woody species showed different patterns of population structures. Thus, the DBH class distribution of individual species was different from the cumulative DBH classes when individual species were analyzed separately. Population structure is an indication of the stability and regeneration status of the forest vegetation (Kent, 2012). In this study, four representative population structure patterns were identified.

The first population structure pattern is an inverted J-shaped, with a relatively high density of individuals in the lower DBH classes than in the higher DBH classes. This pattern indicates a stable population and healthy regeneration potential but low recruitment of the species in the forest, and it might be due to the overexploitation of higher DBH class individuals for various purposes, such as construction, farming, and income generation.

The second population distribution pattern is bell-shaped, where the highest density of individuals is found at the intermediate (middle) DBH classes and decreases toward the lower and higher DBH classes. This pattern indicates a poor reproduction, regeneration, and recruitment of species, which may be associated with the overharvesting of seed-bearing individuals, which affects regeneration. In the other case, this is attributed to overgrazing at young stages and frequent trampling by livestock (Motuma Didita *et al.*, 2010; Abyot Dibaba *et al.*, 2020), or slow seed germination and/or selective removal of mature trees for various purposes (Misganaw Meragiaw *et al.*, 2018).

The third population distribution pattern is J-shaped, where there is the highest density of individuals at the higher DBH classes and the trend decreased towards the lower DBH classes. In this category, the distribution pattern indicates more mature plants than saplings and seedlings. It has a J-shape indicating that recruitment is higher than regeneration. In this pattern, a small number of individuals in the lower DBH classes could be attributed to anthropogenic or environmental disturbances that affect seedling survival such as overgrazing of young seedlings, poor reproduction, and regeneration or it might be because most trees are not producing seeds due to their age or losses due to predators (Misganaw Meragiaw *et al.*, 2018).

The fourth population distribution pattern is a Broken Inverted-J shape. This pattern shows higher density in the lower DBH classes and then decreases up to some limits and again increases up to some points and finally decreases at the higher class. They form a kind of undulating or Zigzag pattern of distribution. This could be due to anthropogenic activities such as firewood collection, grazing, charcoal production, and selective removal of trees for various purposes, which suggest the presence of disturbances in the forest. It might be associated with the presence of disturbance factors, including deforestation by local people in addition to frequent browsing and trampling by livestock (Tesfay Atsbha *et al.*, 2019). Generally, the patterns of population structures of the plant species in Sida Forest showed that only a few species had a good representation of individuals at all size classes. The majority of the species show variations in the population structure of plant species due to the different management practices, and environmental and anthropogenic factors that interrupt the natural regeneration and recruitment of the species in the forests. In the study forest, the communities are semi-pastoral, and they use the plants for their livestock and to construct small temporary huts in/around the forest until they move to the other grazing sites. This suggests the need, to take appropriate forest management and conservation measures by the relevant authorities, in order to facilitate the healthy regeneration of woody species in the forest and to give attention to those species with poor reproduction and recruitment, as well as to reduce human pressure.

Vertical structure

A large proportion (86%) of species was found in the lower storey followed by the middle (12%) and upper storey (2%), indicating the dominance of small-sized individuals in the Sida Forest. The variation in the number of individuals in the lower, middle, and upper height classes could be associated with overgrazing, and/or selective cutting of the usable-sized individuals by local people for various purposes, such as for construction, fuelwood, or any other domestic uses. The presence of a large number of small to medium-sized individuals and the relatively small proportion of large trees indicates that the forest is a secondary/disturbed forest (Aye *et al.*, 2014). As indicated by Friis *et al.* (2010) in disturbed forests, the upper canopy species are usually removed for various purposes, and only short-stature trees in the middle and lower canopy remain in the forest. Some species were found only in the lower storey and upper storey and not in the middle storey; others were only in the upper storey while some were only in the lower storey. Species only in the upper storey are the worst case, as this implies that their regeneration and sustainability are threatened and thus the species requires assisted regeneration or it could face local extinction (Maua *et al.*, 2020). The lower storey was significantly different both in the number of species and the overall density of species.

2.4.3. Plant community types in Sida Forest

Based on the hierarchical cluster analysis, five plant communities were identified in the Sida Forest. Each community type has its distribution range with a specific combination of environmental and disturbance variables. The five plant community types of Sida Forest showed variation in species diversity, richness, and evenness, and were characterized by the difference in floristic composition. The highest species richness were recorded in community types 1 (117), 2 (159), and 3 (145), whereas the lowest species richness were found in community types 4 (92) and 5 (61). The variation in species richness, diversity, and evenness among the plant community types could be related to the variations in environmental factors, such as elevation and slopes (Eilu & Obua, 2005), changes in slope and aspect (Virtanen *et al.*, 2010; Zhang, Xu, *et al.*, 2013), and the variations in temperature and rainfall (Kharkwal *et al.*, 2005). The other possible reason for the variation in species richness and diversity among the plant community types is the differences in the number of sample plots. This means as the sample plots increased, the probability of getting new species increases contributing to higher species richness and diversity, thus the reason for the high species richness diversity and evenness of community 2 and 3 can be associated to the higher number of sample plots, and the elevation range 'mid-elevation' (Sebsebe Demissew *et al.*, 2021). The Shannon–Wiener diversity index is the most popular measure of species diversity because it scores for both species richness and evenness and it is not affected by sample size (Kent, 2012). The value of Shannon-Wiener species diversity and evenness for each community of the study forest ranges from 3.25 to 4.44, which lies within the range for tropical forests. According to Kent (2012), the Shannon-Wiener diversity index of tropical forests usually ranges from 1.5 to 3.5 and rarely exceeds 4.5, and the Shannon diversity index is high when it is above 3.0, medium when it is between 2.0 and 3.0, low when it is between 1.0 and 2.0, and very low when it is smaller than one. In the studied forest, the higher values of the Shannon diversity index (4.44) and evenness (0.88) indicated that the study forest has high species diversity with a more even distribution. In the present study, community two had the highest species diversity (H'= 4.44) and evenness (0.88), followed by community three (H'=4.26, E=0.86) and one (H'= 4.08, E=0.86), whereas, community four (H'= 3.80, E=0.84) and community five (H' = 3.25, E=0.79) had relatively the least in species diversity and evenness. The diversity and evenness follow similar trends, the more diverse community type is also more even. The variations in species diversity and evenness are commonly associated with the interaction of various ecological factors (elevation, topography, aspect, slope and soil nutrients, solar radiation, and disturbances) (Zhang & Dong, 2010; Zhang, Xu, *et al.*, 2013; Redowan, 2015; Kacholi, 2019).

In the present study, significant differences in species diversity and evenness were found between community one (at the lower elevation), where disturbances are higher, and community five (at the higher elevation) with fewer disturbances when compared with communities 2, 3, and 4. In agreement with this, Mengesha Asefa *et al.* (2020) plant species diversity is lower in the Ethiopian highlands than in the lowlands, whereas disturbances from human activities were more frequent in low elevations and decreased above 1600 m (Zhang, Xu, *et al.*, 2013). On the other hand, species richness and diversity could reach to maximum at the intermediate elevation and decline towards the lower and upper elevation (Vetaas & Grytnes, 2002; Zhang, Xu, *et al.*, 2013; Sebsebe Demissew *et al.*, 2021). Thus, the higher species diversity in an area is attributed to appropriate protection, low anthropogenic disturbances, and rich soil nutrients. High Shannon evenness in Sida Forest indicates little dominance by any single species and repeated coexistence of species over all the plots. A high evenness value in a given forest indicates the conservation of the sites might not be of much importance as compared to a low evenness value.

2.4.4. Plant community and environment relationship (Ordination)

The relationship between plant communities and environmental variables is important in understanding the type of plant communities in a given forest ecosystem (McCune & Grace, 2002). Species-environment relationships are among the most important data needed to understand vegetation patterns on forest landscapes (Arekhi *et al.*, 2010)**.** Patterns of plant community formation associated with environmental factors such as climate, soil nutrients, and topographic features as well as anthropogenic and livestock disturbances (Liu *et al.*, 2003; Abella & Covington, 2006), are useful for identifying species sharing similar environments (Arekhi *et al.*, 2010). The CCA analysis result showed that topography, soil factors, and disturbances are the most important factors in determining the abundance and distribution of species among the plant communities. However, all these environmental variables exhibited different effects on the five plant community types. As reported by Arekhi *et al.* (2010) the plant community has its own distribution area with a specific combination of environmental variables. Species diversity and community types depend on a combination of factors, including both disturbances and environmental factors (Getaneh Gebeyehu *et al.*, 2019), as well as topography and soil (Jafari *et al.*, 2004).

In community type one, the composition and distribution pattern of plant species is strongly influenced by disturbances, pH and aspect. This community is found at a lower elevation and close to human settlements, thus, disturbances are the common factors influencing the composition and distribution of species in this community. In this regard, Zhang, Xu, *et al.* (2013), showed that disturbances (selective cutting, grazing by livestock, and expansion of farmlands) occur more frequently and temperature is higher at lower elevations. Thus disturbances are mentioned as the most important factors for the compositional variations of species (Dhar & Sarker, 2021), and species diversity increases with intermediate disturbances (Zhang, Xu, *et al.*, 2013). Species distribution in community type two is influenced by aspect, slope, pH, and sand soil. Slope and pH have a strong influence on the distribution of species in this community. Topographical aspects and slopes may affect environmental conditions, such as light, soil moisture, temperatures, and nutrients besides disturbances, which in turn affect plant diversity (Méndez-Toribio *et al.*, 2016). Exposures to light increase species richness and diversity more than the other part (Getaneh Gebeyehu *et al.*, 2019). Community three was positively correlated with elevation, and slope.

Elevation has a strong influence on the distribution of species in this community, as it occurs in the intermediate elevation. Elevation leads to changes in humidity, temperature, soil type, and other factors influencing the growth and development of plants, which in turn determine the patterns of vegetation distribution (Kreft & Jetz, 2007; Vittoz *et al.*, 2010; Méndez-Toribio *et al.*, 2016). Community four is positively correlated with disturbance, aspect, and sandy soil. The distribution of species in this community was strongly influenced by sandy soil. Community five occurred at higher elevations and positively correlated with elevation, slope, and OC. Consists of the least species diversity. The decrease in species richness with an increasing elevation could be attributed to unfavorable climatic conditions at the higher elevations making difficulties for the survival of various species, and largely in proportion to the available land area (Barry, 2008; Rana *et al.*, 2022).

Similarity among plant community types

The results of the pairwise comparison of Sorensen's similarity coefficient index in species composition among the five plant communities (Community 1, 2, 3, 4, and 5) showed species similarity. The highest similarity between community two and three (58.9%), community one and two (36.7%), community one and three (35.4%), and community two and four (35.5%) could be associated with their elevation similarity. The least similarity between community one and five (18.5%), community three and five (19.5%), and community two and five (25.7%) were also associated with their elevation differences. This is due to the fact that community 5 is located at higher elevations, thus showed a decrease in species richness, and less floristic similarity with other plant communities (such as community 1, 2, and 3). Communities having similar environmental factors (soil and elevation) have more species in common. In this study, communities having nearly similar elevations have more species in common than communities occupying different elevations do. Elevation change determine the patterns of vegetation distribution and composition by regulating the soil type, humidity, temperature, and other factors (Austin *et al.*, 1996; Vittoz *et al.*, 2010). The other possible reason is communities that have adjacent plots to each other have more species in common which shows the availability of nutrients needed by those species and the adaptation of plants to that particular environment. Two sites having similar vegetation have similar environments and two sites with different vegetation have different environments (Oksanen, 2004).

2.4.5. Regeneration status of woody species

The pattern of population dynamics is described by the existence of seedlings, saplings, and mature plant species and determines the regeneration status of the forest. Forest regeneration requires the establishment of seedlings and saplings within the same environment where the parent trees grow. The status of the tree population and the existence of a species in future forest composition is dependent on a sufficient amount of seedlings, saplings, and mature individuals of each species. In this study, the pattern of distribution indicated that the density of matured trees (506.71 individuals h-1) is higher than the density of seedlings (196.95 individuals h-1) and saplings (103.35 individuals h-1). Similar findings were reported by Simon Shibru and Girma Balcha (2004), Mesfin Belete and Tamiru Demsis (2018), and Temesgen Dingamo *et al.* (2022) indicating that seedlings were greater than saplings but less than mature trees. The ratio of mature plant to seedling is 1: 2.57, that of mature to sapling is 1: 4.9, and seedling to sapling is 1: 1.9. The fewer sapling individuals than seedlings suggests the death of most seedlings before reaching the sapling stage due to various factors such as human interferences, browsers, grazers, desiccation, fire and collection of premature plants.

The density of seedlings is greater than that of saplings but less than mature trees and this does not agree with the normal patterns of population structure. This shows poor reproduction and hampered regeneration, which may be due to most trees not producing enough seeds because of their old age or predators might lose seeds after reproduction. Based on the description by Dhaulkhandi *et al.* (2008) and Tiwari *et al.* (2010) the regeneration status of tree species in Sida Forest is at fair regeneration status, as the density of mature trees exceeded the density of seedlings and saplings. Seedling survival is critical for the normal recruitment, however, some factors may disrupt the species recruitment process, and germinated seedlings from the soil seed bank may be killed by frequent livestock trampling and uprooting of seedlings (Mendoza *et al.*, 2009).

According to Dhaulkhandi *et al.* (2008) and Tiwari *et al.* (2010), the regeneration status of the Sida Forest showed different regenerating categories including“good” (7.41%), “fair” (79.63%), and “not regenerate” (12.96%). In addition, some (9) species were without seedlings, without saplings (17 species), and without both seedlings and saplings (7 species) indicating poor reproduction and hindered regeneration. The species without seedlings and saplings could be associated with different factors, such as exposure of the forest for selective tree cutting, free grazing/browsing, forest fires, and soil erosion, seeds in seed banks might be eaten before they germinate, or death of seedlings with frequent livestock trampling, uprooting of seedlings, herbivore attack, and pathogens. On the other hand, environmental conditions of soil moisture, temperature, and light conditions affect the germination and/or survival of seedlings.

Trees in the area affect the germination and growth of seedlings in their neighborhood by causing shades and sun flecks (Wangchuk, 2007). Light affects forest regeneration, shaded sites become safe sites because the shade counteracts the water limitation in low rainfall periods and reduces seed and seedling desiccation, however, the success of early seedling establishment decreases in extreme shading conditions (Vieira & Scariot, 2006). Rich sites support competitive herbaceous vegetation that can shade the forest floor, and tree species may regenerate better on less fertile sites because of reduced competition from the ground vegetation (Wangchuk, 2007; Addo-Fordjour *et al.*, 2009). The litter layer is less suitable in forests for the regeneration of trees because it acts as a barrier so that, the seeds are difficult to touch the soil and inhibit penetration of roots/radicles into the soil (Wang *et al.*, 2008; Yang *et al.*, 2014). Urgent conservation action is required for those species without seedlings and saplings. Woody species that are not regenerating themselves need quick conservation and management action to prevent them from local extinction and understanding the natural regeneration potential of these species is crucial to have detailed information on soil seed banks in the forest. Therefore, all stakeholders at both national and regional levels should participate in the conservation and management of these species, through both in situ and ex-situ conservation.

Conclusions

The assessment of floristic composition in Sida Forest, indicates Sida Forest contains high species diversity, richness and evenness, thus, the forest has high economic & ecological significance. The DBH and height class distribution showed higher density/ha at the lower classes and a gradual decrease in to the higher classes showing an inverted J-shaped vegetation structure of the study forest indicating a healthy population structure and good regeneration status. The vegetation of Sida Forest was classified in to five plant community types indicating the high diversity & heterogeneity of the forest, and the pattern of community formation was mainly determined by environmental factors such as elevation, slope aspect, soil physicochemical properties, and disturbances. The overall regeneration of the forest is at fair regeneration status. Species without seedlings and saplings shows the need of urgent species-specific conservation and management measures to restore the diversity of the forest.

CHAPTER THREE

3. Impact of Elevation Change on the Physicochemical Properties of Soil in Sida Forest, South Omo Zone, Southern Ethiopia

Mesfin Belete Hailemariam, Zerihun Woldu, Zemede Asfaw and Ermias Lulekal

Abstract

*The assessment of the distribution of soil physicochemical properties provides basic information for our understanding of the soils to grow crops and sustain forests and grasslands. Hence, the present study was conducted to assess the distribution of soil physicochemical properties along the elevational gradients and to evaluate the fertility status of the soil. Data on soil physicochemical properties were collected from five points (four from each corner and one from the center) of the main plot. A pit of 20cm × 20 cm was dug at a depth of 30 cm and a kilogram of composite soil samples from each plot was brought to the Wolkite Soil Testing Laboratory for Physicochemical analysis. The data was analyzed using SPSS, ANOVA and Pearson correlation coefficient. The results revealed that some of the physicochemical properties of the collected soil samples showed significant variation and correlation with elevation changes. Sand had a significantly negative correlation with elevation, with the rate of correlation coefficient (r = -0.44**, $P \leq 0.001$). However, silt had a non-significantly positive (r = 0.20, $P < 0.079$) correlation to the elevation, while clay had a significantly positive correlation to elevation (r = 0.40**, $P \leq 0.001$). Soil OC, OM, TN, CEC, and exchangeable Mg^{2+} significant positive correlation to the elevation, with the rate of correlation coefficient (r = 0.42**, $P \leq 0.001$), (r = 0.41**, $P \leq 0.001$), (r = 0.44**, $P \leq 0.001$), (r = 0.34**, P < 0 .002) and (r = 0.27*, $P < 0.014$) respectively. While BD, pH, EC, Av. P, exchangeable Ca^{2+}, and exchangeable K^{+} had a non-significant negative correlation to the elevation, with the rate of correlation (r = -0.70**, $P < 0.134$), (r = -0.20, $P < 0.075$), (r = -0.05, $P < 0.683$), (r = -0.04, $P < 0.701$), (r = -0. 04, $P < 0.693$) and (r = -0.053, $P < 0.693$) respectively. This study attempted to provide information on the impact of elevation on soil's physicochemical properties, indicating that, the soil's physicochemical properties exhibit variation with an elevation changes.*

Keywords/Phrases: Benna-Tsemay; Distribution; Elevation impact; Forest soil; Soil physicochemical properties.

3.1. Introduction

Soil, land, water, and forests are the basics of Ethiopia's economic development, food security, and livelihood sustenance. The diverse topography, climatic conditions, and geology of the country contributed to the diverse soil resources (Abayneh Esayas, 2001; Belete Berhanu *et al.*, 2013). Soil is a collection of natural bodies representing one of the most active and complex natural systems that support plants and have properties due to the integrated effect of climate and biological activities upon parent materials (Gaur, 1997; Brady & Weil, 2002). Soil can influence plant community composition and physiological activities directly, and it is one of the key indexes in the functional recovery and maintenance of ecosystems. It is an essential component of nearly every ecosystem in sustaining the existence of many forms of life on earth, provides a medium for plant growth, supplies the organisms with most of their nutritional requirements, and regulates the environment (Gaur, 1997; Gömöryová *et al.*, 2022). In addition, provides food, fodder, and fuel for meeting basic human and animal needs (Pulakeshi *et al.*, 2014). In forest ecosystems, soil determines species composition, timber productivity, wildlife habitat, species richness, and diversity, maintaining water quality and long-term site productivity (Schoonover & Crim, 2015). The ability of soil to support plant growth depends on its physicochemical and biological properties.

Soil is a heterogeneous unit and shows great variability in its physical and chemical properties. Soil properties varied significantly among soil types and across locations showing differences in parent materials, climate, and land use (Elias, 2019). Knowledge of variation of soil properties is very essential as this determines the productivity and usage of the area. Soil characterization provides information for our understanding of the soils we depend on to grow crops, and sustain forests and grasslands (Ogunkunle, 2004). Forest stands are covered with different tree species and differ in litter quality and root exudates. These differences ultimately create variations in soil properties and may influence the soil microbial community (Chandra *et al.*, 2016). Soil microbes regulate the decomposition rate, organic matter content, and physicochemical properties of forest soil (Noguez *et al.*, 2008; Chandra *et al.*, 2016). All soils have different properties, and working with them requires an understanding of these properties (Mutua *et al.*, 2014), and the assessment of soil quality requires a combination of physical, chemical, and biological factors. The physical and chemical characteristics of soil influence root distribution and the ability to extract water and nutrients (Bronick & Lal, 2005). The physical property of soil plays an important role in soil fertility because the amount and sizes of the soil particles determine the porosity and bulk density, which account for nutrient retention or leaching of nutrients (Chinevu *et al.*, 2013). The knowledge of the physicochemical properties of soil helps in managing resources while working with a particular soil (Brady & Weil, 2002). Before implementing forest conservation or afforestation, it is essential to assess the soil type, soil depth, soil texture, soil structure, pH, and soil nutrient dynamics of each vegetation type (Bronick & Lal, 2005; Quichimbo *et al.*, 2017).

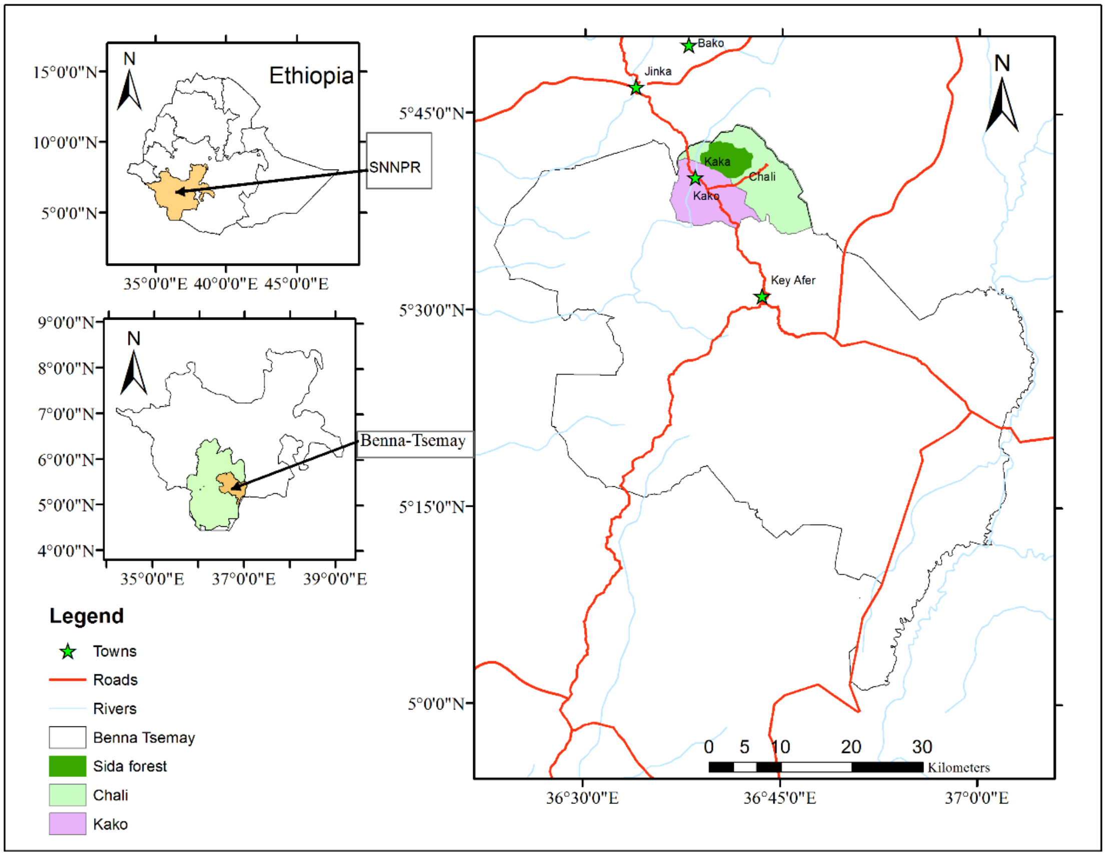
Different factors influence the physicochemical properties of the soil. Climatic variations such as increasing rainfall and decreasing temperature along the elevation gradient are the most important factors that have significant effects on soil properties (Pourbabaei *et al.*, 2020; Li *et al.*, 2021). As reported by Ambade *et al.* (2022), and Tekleweini Gereslassie *et al.* (2018) the physicochemical qualities of the soil are affected by soil contamination such as by polycyclic aromatic hydrocarbons (PAHs). Various studies addressed the impact of elevation on soil physicochemical properties (Saeed *et al.*, 2014; He *et al.*, 2016; Sierra *et al.*, 2017; Pourbabaei *et al.*, 2020; Li *et al.*, 2021; Gömöryová *et al.*, 2022; Han *et al.*, 2022), but there are limited data from forest ecosystems. Soil degradation associated with the past use of fire to clear vegetation, charcoal production, and over-cultivation/overgrazing is the main factors in the loss of soil, causing billions of tons of soil to remove every year (Engdawork Assefa, 2015; Weldemariam Seifu *et al.*, 2020). In addition to this, slope steepness, deforestation, and unwise utilization of land are the factors in the loss of soil (Siraj Beshir *et al.*, 2015; Hailu Addis *et al.*, 2016). Food insecurity and rural poverty in the African smallholder farming system are due to soil nutrient depletion (Weldemariam Seifu *et al.*, 2020). Most previous studies carried out on the Ethiopia soils focused on potential agriculture areas, for master plan preparation and small-scale soil map preparation (Abayneh Esayas, 2005). Thus, the soil in Ethiopia needs high attention on soil-specific management, which in turn requires a major investigation across the country. Knowledge of the geographical distribution of the soils and their physicochemical properties is necessary for policymakers to improve forestland management and increase the well-being of the population.

Information on soil characteristics obtained through soil surveys and soil fertility evaluation, which can be carried out using field and laboratory diagnostic techniques (Singh & Singh, 2015). To understand the relationships between soils and vegetation in forest ecosystems, it is necessary to identify and determine the factors that characterize their relationships. Thus, consistent monitoring of soil quality and the up-to-date status of soil properties is a very important tool for the management of forest ecosystems on a sustainable basis (Paul, 2018; Opeyemi *et al.*, 2020). The Sida Natural Forest is a less accessible forest, which comprises four vegetation types in Ethiopia, the *Acacia-Commiphora* woodland and bushland, *Combretum-Terminalia* woodland and wooded grassland, Dry Evergreen Afromontane Forest and grassland complex, and the Riverine vegetation. The local communities depend on this natural forest for medicine, wild food, fuel wood, timber, water, honey, livestock fodder, and other biodiversity-related benefits. However, there is no studies have been done so far on the soil physicochemical properties that control the distribution and productivity of plant species in Sida Forest. Thus, this study attempted to provide information on the soil's physicochemical properties of Sida Forest along its elevation gradients. These results are helpful to determine the soil's fertility status and the distribution of soil physicochemical properties along the forest's elevational gradients.

3.2. Materials and methods

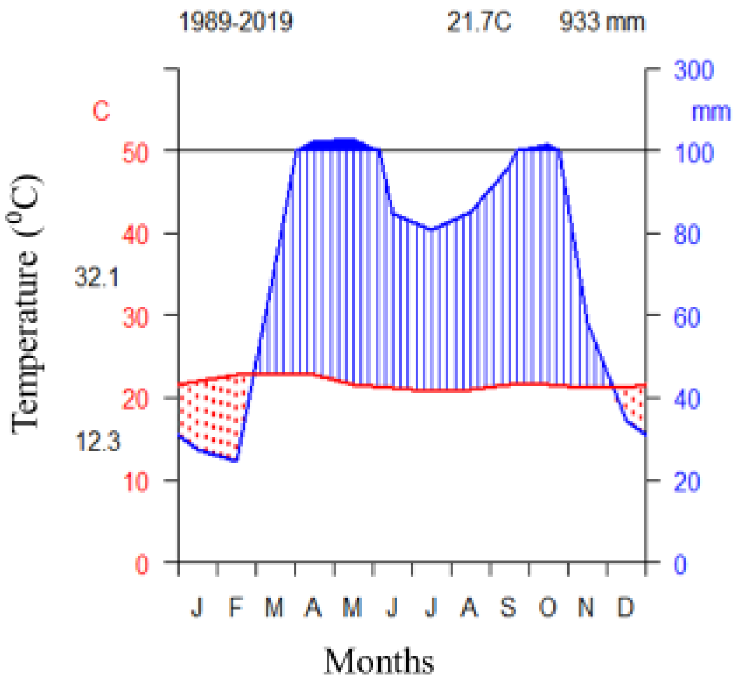
3.2.1. Descriptions of the study area

This study was conducted in Benna-Tsemay District, South Omo Zone, southern, Ethiopia. The Benna-Tsemay District is located about 739 km south away from the capital city of Ethiopia, Addis Ababa. The study District is located at $5^{0}03' – 5^{0}34'$ N latitude and $36^{0}33' – 37^{0}03'$ E longitude with elevations ranging from 500 to 2400 masl. The majority of the communities in the Benna-Tsemay District belong to the Benna and Tsemay ethnic groups. Pastoralism and agropastoralism are the two main livelihood options in the study area. The livelihoods of these pastoralist communities are mainly the rearing of livestock, goats, and sheep and the use of their products and the agropastoralists are dependent on both livestock products and crop cultivation. The greater proportion of the study area is characterized by arid and semi-arid climatic conditions. The major vegetation type of the study area belongs to *Acacia-Commiphora* woodland and *Combretum-Terminalia* woodland and wooded grassland (Friis *et al.*, 2010).



Map of Ethiopia showing the location of the study area, Benna-Tsemay Districts in South Omo Zone, southern Ethiopia

The rainfall pattern of the study area is bimodal. The average annual precipitation of the District was 933 mm and the average annual temperature was 20.7^{o}C. The dry season occurred from the beginning of December to the end of February. The long rainy period occurs from the end of March to the beginning of June and the short rainy season occurs between October and November. The average monthly maximum temperature of the warmest month is 32.1 ^{o}C and the average monthly minimum temperature of the coldest month is 12.3 ^{o}C.



The climate diagram of the study district shows rainfall distribution and temperature variation from 1989 to 2019.

3.2.2. Soil data collection and Preparation for physicochemical analysis

Soil sample collection

A total of eighty-two composite soil samples were collected from the Sida Forest having different elevation ranges (1500 to 2400 masl.). Plots of 20m×20m were laid systematically to collect the soil sample. Then soil samples were collected from five places, four from each corner of 20m×20m plot and one from the center of the main plot. A pit of 20 cm x 20 cm was dug at a depth of 30 cm, and soil samples were collected. Then the samples were mixed well to form a composite, and about a kilogram of soil samples from each plot was brought to Wolkite Soil Testing Laboratory using sterile polythene bags.

3.2.3. Soil Laboratory Analysis

The laboratory analyses (physical and chemical properties) were done following standard procedures. Accordingly, soil samples were air dried in a properly ventilated room on a plastic tray, and ground in a Wiley mill, to pass through a 2 mm sieve for all the soil parameters except for TN and OC passed through a 0.5 mm sieve to remove the coarser materials (root particles, rocks, and large organic materials). Then the air-dried, ground and sieved samples were labeled and stored in semi-open plastic bags to maintain a low air exchange until the physicochemical analysis. The laboratory analysis was carried out for both physical (particle size distribution) and chemical properties (pH-H_2O, electrical conductivity (EC), organic carbon (OC), organic matter (OM), total nitrogen (N), available phosphorus (P), cation exchange capacity (CEC) and exchangeable cations (Ca^{2+}; Mg^{2+} and K^{+})) of the soil.

For the analysis of soil texture classes, the Bouyoucos hydrometer method was used as suggested by Bouyoucos (1962) and Kalra and Maynard(1991), after destroying OM using hydrogen peroxide (H_2O_2). Soil color (dry) was determined using the Munsell soil color chart (Color, 1994). Bulk density (BD) was determined using the core-sample method as described by Blake and Hartge (1986). The soils from core samples were oven-dried at 105 °C for 24 hours and the bulk density was calculated by dividing the masses of the oven-dry soils (g) by the respective volumes (cm3) of the soil.

$BD = \frac{M2-M1}{V}$, Where: BD: dry soil bulk density (gm/cm3), M1: the weight of core (g), M2: the weight of core + oven-dried soil (g), and V: volume of the core (cm3).

The soil pH (pH-H2O) was determined in a 1: 2.5 soil-to-water ratio using a pH meter as described by Webster (2008). The electrical conductivity (EC) of soils was determined in a soil: water ratio of 1:2.5 extract with the aid conductivity meter as described by Okalebo *et al.* (2002). The soil organic carbon (SOC) content was determined using the wet oxidation method with potassium dichromate (K2Cr2O7) in a sulfuric acid medium Walkley and Black (1934) and the percent soil organic matter was obtained by multiplying the percent SOC by Van Bemmelen factor (1.724). Total Nitrogen (TN) was determined following the Kjeldahl distillation method as described by Bremner (1982). The carbon-to-nitrogen ratio (C/N) was calculated from the ratio of soil organic carbon to total nitrogen. Available phosphorus was determined calorimetrically using a spectrophotometer after the extraction of the soil samples with 0.5 M sodium bicarbonate ($NaHCO_3$) at pH 8.5 following the Olsen method (Olsen, 1954). Cation exchange capacity (CEC) was determined titrimetric by repeated saturation using 1M ammonium acetate (NH_4OAC) followed by washing, distilling, and titrating (Chapman, 1965). The exchangeable base cations were also extracted by saturating the soil sample using neutral 1M NH_4OAC. Exchangeable Ca and Mg were determined from the extract using an atomic absorption spectrophotometer (AAS), while exchangeable K was determined from the same extract using a flame photometer (FP) (Chapman, 1965).

3.2.4. Quality Control

Quality control is a method to minimize errors and raise accuracy and precision in all aspects of laboratory work. In this study, all the chemicals and reagents meet the purity standards set by the American Chemical Society (ACS), which is a high-quality chemical for laboratory use. All laboratory equipment (instruments) meet the standards for soil chemical and physical laboratory analysis. The equipment has been calibrated periodically, tested before use, maintained properly, and verified depending on their proposed use. The data were generated under statistical control by trained staff in the laboratory and each laboratory activity was done using standard procedures, following proper laboratory management. During soil testing standard operating procedures (SOPs), standardized methods, and standard solutions at specific (optimum) temperatures and pH ranges were used. Before taking the soil samples to the laboratories, the samples were checked for homogeneity, placed on a plastic tray, dried, and ground using mortar and pestle to pass through a 2 mm sieve. The duplicated samples were analyzed within one to five days after they were received at the laboratory, the soil test results were released immediately after sample analysis, and the remaining soil samples were stored for reference.

3.2.5. Statistical Data Analysis

The elevation of the study area varied from 1500 to 2410 meters above sea level and was classified into three different elevation classes. The three elevation classes are lower (1505–1800 m), middle (1800–2100 m), and higher (2100–2410 m). A global positioning system (GPS) was used to identify the site's elevation, longitude, and latitude. The data obtained from the laboratory analysis result were statistically analyzed and summarized as mean ± SE (standard error). The analyses were conducted using the computer program SPSS statistical software (version 26.0) package for Windows. Statistical differences between soil parameters and the three elevational ranges were tested using a one-way analysis of variance (ANOVA). Pearson correlation coefficient was carried out to assess the relationship between soil parameters and elevation ranges. A P-value less than 0.05 ($P < 0.05$) was considered statistically significant.

3.3. Results

3.3.1. Physicochemical properties of the soils

Soil colours of the study area

All soil colours were determined under wet conditions and Hue 7.5YR was used for soil colour determination. The lower and middle elevations have colours ranging from 7.5YR 4/2 (Greyish brown) to 7.5YR 2/2-3/1 (Brownish black), while at higher elevations the soil colours were ranging from 7.5YR 4/1-6/1 (Brownish grey) to 7.5YR3/3-3/4 (Dark brown). The majority (56.10%) of the soil in the study area was Brownish black followed by Brownish grey (31.71%) (Table 10). The colour of the soil is usually a reflection of the amount of organic matter present in the soil hence darker soils with brown/black colour indicate the presence of high amounts of organic matter as compared to those with greyish brown coloured soils.

Table 10. Soil colour types of the study area

Soil colors (Hue 7.5 YR)	Lower	Middle	Higher	Total	%
Brownish grey (4/1-6/1)	9	10	7	26	31.71
Brownish black (2/2-3/2)	15	10	21	46	56.10
Greyish brown (4/2-6/2)	5	2	0	7	8.54
Dark brown (3/3-3/4)	0	2	1	3	3.66

Soil texture (Sand, Silt, and Clay proportions (%))

In this study, the physical properties were determined from the particle size distribution. Particle size distribution was determined based on the relative proportion of sand, silt, and clay within the soil sample. The particle size distribution of the soil showed clear differences in that sand content was higher in all plots. The sand content ranged from 32% to 80%, the highest percentage (80%) was obtained at the lower elevation, while the lowest percentage (32%) was recorded at the higher elevation. The silt content of the soil sample ranged from 6% to 30%, the highest percentage (30%) was recorded at the higher elevation, while the lowest percentage (6%) was obtained from the lower and middle elevations. The clay content of the soil sample ranged from 2% to 43%, the highest percentage (43%) was recorded from the higher elevation, while the lowest percentage (2%) was recorded from the middle elevation.

The analysis of variance showed that there is no significant ($P < 0.05$) difference in the percentage of sand, silt, and clay concerning elevation. The correlation analysis revealed that there is a statistically significant negative correlation between sand and elevation ($r = -0.44^{**}$, $P \leq 0.001$), however, a non-significant positive ($r = 0.20$, $P < 0.079$) correlation exists between silt and elevation. While, the content of clay showed a statistically significant positive ($r = 0.40^{**}$, $P \leq 0.001$) correlation with elevation. Considering the three elevation gradients, the highest (69.17±1.07) mean value of sand was recorded at the lower elevation and the least (60.38±2.31) sand value was recorded at the higher elevation. Indicating that the concentration of sand decreased along the elevational gradient. The highest (21.10±1.95) mean value of clay was recorded at the higher elevation and the least (14.76±0.94) value of clay was recorded at the lower elevation. Showing that, the clay concentration increased along the elevational gradient.

From the soil textural triangle, the texture class distribution of the soil varied from sandy loam to clay. The majority of the textural classes of the soils are sandy loam 48 (58.54%) followed by sandy clay loam 27 (32.93%) and clay loam 3 (3.66%), as indicated in Figure 13. The result indicated that sandy loam is the dominant texture class in the upper (0 - 30 cm) layer of the soil of the study area.

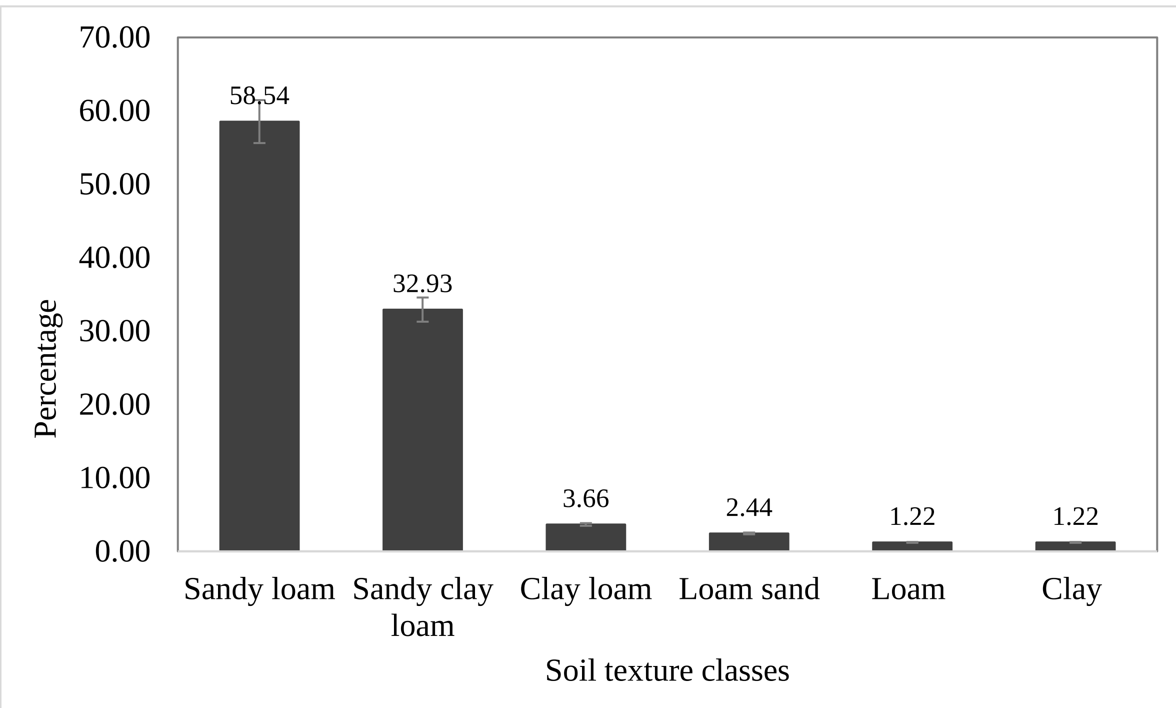


Figure 13. Soil textural class size distribution in the study area

Bulk density (BD) (gm/cm3)

The bulk density value of the soils varied from 0.13 gm/cm^3 at the higher elevation to 0.54 gm/cm^3 at the lower elevation. The highest BD value was recorded at the lower elevation, while the lowest BD value was recorded at the higher elevation. The correlation analysis result revealed that BD showed a non-significant negative (r = -0.70**, P < 0.134) correlation with elevation. The results of the analysis of variance also indicated that there is no significant (P < 0.05) difference in BD along with an increase in elevation. The highest (0.46±0.02) mean value of BD was recorded at the lower elevation, while the least BD was recorded at the middle (0.21±0.01) and higher (00.15±0.01) elevation. Indicating a decreasing trend in BD along with an increase in elevation (Table 11).

Table 11. The physical properties of the soil across the three elevation classes show the mean (mean ± SE), correlation coefficient (r), and significant level of the soil texture and bulk density

Soil parameters	Elevation			Correlation coefficient (r)	Sig.(2 tailed)	P< 0.05
	Lower	Middle	Higher			
Sand	69.17±1.07	67.29±1.58	60.38±2.31	-0.444**	0.001	0.206
Silt	16.34±0.85	16.67±1.10	18.52±1.00	0.195	0.079	0.808
Clay	14.76±0.94	16.04±1.29	21.10±1.95	0.395**	0.001	0.217
BD	0.46±0.02	0.21±0.01	0.15±0.01	-0.697**	0.001	0.134

** Significant at 0.01 level (2-tailed), * Significant at 0.05 level (2-tailed).

3.3.2. Chemical Properties of Soil

PH of the soil

The pH (1:2.5- H_2O) values throughout all the plots of the soils varied from 4.6 to 7.1 in the lower elevation (Table 12). The pH values had shown a tendency to decrease with an increase in elevation. The analysis of variance showed that there is no significant (P < 0.05) difference in pH value along with an increase in elevation. The Pearson correlation analysis revealed that soil pH was found to be non-significantly negative (r = -0.20, P < 0.075) correlation with elevation, however, there were slight numerical variations in the soil pH along with an increase in elevation. The lowest (5.98±0.09) mean value of pH was recorded at the higher elevation, whereas the highest (6.13±0.10) mean value was recorded at the lower elevation. This trend indicated that acidity increased along with an increase in elevation.

Electrical conductivity (Milisimese/centimeter (mScm-1)) of the soil

The electric conductivity (EC) of the soil is used to estimate the soluble salts of aqueous soil extract. In this study, the EC of the soils ranged from 14 $mScm^{-1}$ at the lower elevation to 630 $mScm^{-1}$ at the higher elevation. The ANOVA result showed a non-significant (P < 0.05) difference in EC value along with an increase in elevation. The correlation analysis revealed that EC content was found to be non-significant negatively (r = -0.05, P < 0.683) correlated with elevation. EC did not show any significant variation along elevation gradients, even though relatively higher mean values were recorded at the lower (158.24±16.2) and higher (145.06±20.45) elevations than at the middle (107.21±13.20) elevation (Table 12). There was no regular variation of EC along with elevational gradients except for a slight decrease at the middle elevation.

Organic carbon, organic matter, total N, C/N ratio, and available phosphorus

The organic carbon (OC) content of the soil differs among the three elevation ranges, showing an increasing trend with increasing elevation. The SOC of the study area varied from 0.78% in the lower elevation to 1.24% in the higher elevation. The correlation analysis result revealed that SOC showed a significant positive ($r = 0.42^{**}$, $P \leq 0.001$) correlation with elevation. The analysis of variance also showed that there is a significant ($P < 0.05$) difference in SOC along with an increase in elevation. Indicating that elevation had a significant impact on soil organic carbon, as elevation increases SOC also increase. Considering the three elevation classes, the highest (5.55±0.7) mean value of SOC was recorded at the higher elevation, while the least (3.41±0.42 and 2.75±0.30) mean values were recorded at the lower and middle elevations respectively (Table 12).

The organic matter (OM) content varied from 1.31% at the lower elevation to 25.1% at the higher elevation indicating an increase along with the elevation gradient. The correlation analysis revealed that SOM showed a significant positive ($r = 0.41^{**}$, $P \leq 0.001$) correlation with elevation. The ANOVA result also showed that there is a significant ($P < 0.05$) difference in the content of SOM along with an increase in elevation. The highest (9.46±1.25) mean value of SOM was recorded at the higher elevation, while the least (5.81±0.71 and 4.68±0.51) mean value of SOM was recorded at the lower and middle elevations respectively (Table 12).

The total nitrogen (TN) content of the soils ranged from 0.06% at the lower elevation to 1.25% at the higher elevation. The correlation analysis result showed a significant positive ($r = 0.44^{**}$, $P \leq 0.001$) correlation of TN with elevation. In addition, the ANOVA result revealed that there is a significant ($P < 0.05$) difference in TN content with an increase in elevation. Indicating that the total nitrogen content increased along with an increase in elevation. Based on the effect of elevation on soil TN across the different elevational ranges, the highest (0.49±0.06) mean value of TN was recorded from the higher elevation, while the least was recorded from the lower (0.29±0.04) and middle (0.23±0.03) elevation (Table 12). The distribution pattern of TN with an elevational gradient was similar to that of OC and OM, showing an increasing trend along the elevation gradients.

Carbon to nitrogen ratio (C/N): The carbon to nitrogen ratio varied from 3.06 to 19.38 at the higher elevation. The correlation analysis revealed that the C/N ratio was found to be non-significant negatively (r = -0.05, $P < 0.671$) correlated with elevation. However, the ANOVA result showed that there is a significant ($P < 0.05$) difference in the C/N ratio with an increase in elevation. The highest (11.82±0.10) mean value of the C/N ratio was recorded at the lower elevation, followed by the middle (11.79±0.06) and higher (11.78±0.41) elevation (Table 12). Indicating a decrease in the C/N ratio along with an increase in elevation.

Available phosphorus (Av. P): The available phosphorus values varied from 1.43 mg/kg at the middle elevation to 3.88 mg/kg at the lower elevation. The correlation analysis revealed that Av. P was found to be non-significant negatively (r = -0.04, $P < 0.701$) correlated with elevation. The ANOVA result also revealed that there is no significant ($P < 0.05$) difference in Av. P content along with an increase in elevation. However, there was a minor numerical variation in available phosphorus content along with an increase in elevation. Accordingly, the maximum (12.10±2.10) mean value of Av. P was recorded at the middle elevation, followed by the lower (10.71±1.05) and higher (9.98±1.68) elevations (Table 12). The Av. P values had shown a general tendency to decrease with an increase in elevation.

Table 12. The chemical properties (pH, electrical conductivity, organic carbon, total nitrogen, C/N ratio, and available phosphorus (Av. P)) of the soil across the three elevation ranges

Soil parameters	Elevation			Correlation coefficient (r)	Sig.(2 tailed)	P < 0.05
	Lower	Middle	Top			
PH	6.13±0.10	6.02±0.09	5.98±0.09	-0.198	0.075	0.845
E.C	158.24±16.25	107.21±13.20	145.06±20.45	-0.046	0.683	0.241
OC	3.41±0.42	2.75±0.30	5.55±0.71	0.416**	0.001	0.036
OM	5.81±0.71	4.68±0.51	9.46±1.25	0.411**	0.001	0.037
TN	0.29±0.04	0.23±0.03	0.49±0.06	0.436**	0.001	0.030
C/N	11.82±0.10	11.79±0.06	11.78±0.41	-0.048	0.671	0.001
AV.P	10.71±1.05	12.10±2.100	9.98±1.68	-0.043	0.701	0.297

** Significant at 0.01 level (2-tailed), * Significant at 0.05 level (2-tailed).

Cation exchange capacity (CEC) (Milli equivalent/100g soil (meq/100 g))

Cation exchange capacity is the capacity of the soil to hold cation nutrients and exchange cations. CEC content of the soil of the study area varied from 1.4 meq/100g soil at the lower elevation to 49 meq/100g soil at the higher elevation. The correlation analysis result revealed a significant positive (r = 0.34**, $P < 0.002$) correlation between CEC and elevation. However, the ANOVA result indicated that there is no significant ($P < 0.05$) difference in CEC with an increasing elevation. However, there is a slight numerical variation among CEC content along with an elevational gradient. Accordingly, the highest (23.55±2.06) mean value of CEC was recorded at the higher elevation, followed by the lower (17.96±1.60) and middle (16.67±1.14) elevation (Table 13). These showed that CEC content was changed in response to a change in elevation, an increase in elevation leads to an increase in CEC.

Exchangeable base cations (Milli equivalent/100g soil (meq/100 g))

The Exchangeable calcium (Ca^{2+}) contents of the soil varied from 0 meq /100g of soil to 38 meq /100g of soil at the lower elevation. The correlation analysis revealed that Ca^{2+} showed a non-significant negative ($r = -0.04$, $P < 0.693$) correlation with elevation. The ANOVA result also showed that there is no significant ($P < 0.05$) difference in Ca^{2+} concentration along with an increase in elevation. However, there is a slight numerical variation in exchangeable Ca^{2+} content along with the elevational gradients. The least mean value (7.67±0.81) of Ca^{2+} was recorded at the middle elevation, whereas the maximum mean value was recorded at the lower (10.86±1.45) and higher (9.76±0.88) elevations (Table 13).

The exchangeable magnesium (Mg^{2+}) content of the soil varied from 0 meq /100g of soil to 16 meq /100g of soil at the higher elevation. The correlation analysis revealed that exchangeable Mg^{2+} showed a significant positive ($r = 0.27^*$, $P < 0.014$) correlation with elevation. However, the ANOVA result exhibited that there is no significant ($P < 0.05$) difference in Mg^{2+} content along with an increase in elevation. There was no regular variation of exchangeable Mg^{2+} content with an increase in elevation, the highest (8.52±0.77) mean value of Mg^{2+} was recorded at the higher elevation, followed by the lower (6.55±0.67) and middle (5.92±0.71) elevation (Table 13).

The exchangeable potassium (K^+) content of the soil varied from 0.04 meq/100g of soil to 2.3 meq/100g of soil at the lower elevation. The correlation analysis revealed that exchangeable K^+ was a non-significantly negative ($r = -0.053$, $P < 0.693$) correlation with elevation. The ANOVA result also showed that there is no significant ($P < 0.05$) difference in exchangeable K^+ content along with an increase in elevation. However, there was a slight numerical variation in K^+ along with an increase in elevation. The exchangeable K^+ values had shown a tendency to decrease with an increase in elevation. Relatively, a higher (0.49±0.09) mean value was recorded at the lower elevation, and the least mean value was recorded at the highest (0.47±0.06) and middle (0.42±0.097) elevation (Table 13). There was no regular variation of K^+ along with the elevational gradients.

Table 13.Cation exchange capacity (CEC) and Exchangeable cations across the three elevation classes

Soil parameters	Elevation			Correlation coefficient (r)	Sig.(2 tailed)	P < 0.05
	Lower	Middle	Higher			
CEC	17.96±1.60	16.67±1.14	23.55±2.06	0.337**	0.002	0.471
Ca^{2+}	10.86±1.45	7.67±0.81	9.76±0.88	-0.044	0.693	0.387
Mg^{2+}	6.55±0.67	5.92±0.71	8.52±0.77	0.271*	0.014	0.755
K^{+}	0.49±0.09	0.42±0.097	0.47±0.06	-0.053	0.635	0.607

** Significant at 0.01 level (2-tailed), * Significant at 0.05 level (2-tailed).

3.4. Discussion

3.4.1. The Physical Properties of the Soil

Soil colours

The colours of the soil varied from greyish-brown to brownish-black. There was not much variation in soil colour along with an increase in elevation. The colours of the soil are usually a reflection of the amount of organic matter present in the soil hence darker soils with brown/black colours indicate the presence of high amounts of organic matter as compared to those with greyish-red coloured soils. The variations in soil colour might be due to variations in organic matter and soil texture (Noshadi *et al.*, 2013). On the other hand, a study report by Walia and Rao (1997) indicated that soil colours look to be the function of chemical and mineralogical composition as well as textural makeup of the soils and are conditioned by topographic position and moisture regime. According to Mangalassery *et al.* (2005), the variations in soil colours might be due to the differences in the content and hydration of iron oxide and variation in mineral suites coupled with other dominant pedological features.

Soil texture (Sand, Silt, and Clay proportions (%))

The results of the study revealed that sand has the highest percentage (80%) followed by clay (43%) and silt (30%), indicating the dominance of sand-forming minerals in parent materials. The variations in soil texture may be due to differences in parent material, physiography, in situ weathering, and translocation of clay (Basavaraju *et al.*, 2005; Sireesha & Naidu, 2013). The size class distribution directly influences the porosity and sand is the most porous and cannot retain water, however, clay has a good water retention capacity, which is an important factor in soil fertility and makes it more stable than other soil particles. Thus, clay particle is referred to as the nutrient storehouse, and hold nutrient cations for nutrient exchange in the soil for plant uptake. In this study, there is no significant variation in silt content along the elevation gradient. However, sand content decreases along with an increase in elevation, whereas clay content increases with an increase in elevation. Yang *et al.* (2008) and Charan *et al.* (2013), indicated that climate, parent material, vegetation type, and pedogenic processes influence the textural class of the soil along with elevation changes. Hence, the soils of the study area have more proportion of coarse-grained soil particles, which indicates the slow process of soil formation.

The textural class of the soils varied from sandy loam to clay. About 58.54% of the sample tested soil texture classes were sandy loam. A study report by Defera *et al*. (2019) showed that sandy loam is a dominant soil texture class in forest land. The differences in textural classes along an elevation gradient in the study area might be due to the difference in parent material, vegetation type, and pedogenic processes. As indicated by Sireesha and Naidu (2013) the variation in soil texture classes might be due to the differences in topography, in-situ weathering, and translocation of clay by eluviation and age of soils. This texture class (sandy loam) has a very rapid infiltration rate and permeability (>120 mm/h) (Hazelton & Murphy, 2016). A study report by Charan *et al.* (2013) indicates a similar result for soil texture classes.

Bulk density (BD)

Bulk density (BD) has a strong effect on porosity at field capacity and soil strength. In this study, BD has a significant correlation and variation with elevation, indicating that the value of BD decreased along with an increase in elevation, ranging from 0.13 gm/cm^3 to 0.542 gm/cm^3. Following the BD rating suggested by Hazelton and Murphy (2016), the BD of the soils was within the range of very low (< 1.0) in all elevations. The higher BD at the lower elevation than at the middle and higher elevation is associated with the high content of soil organic carbon, organic matter, and clay content at higher elevations. The possible reason for the low BD at the higher elevation was associated with high organic carbon, organic matter, and higher clay content (Sakin, 2012;Saeed *et al*., 2014; Obasi *et al.*, 2015). According to Shiferaw Addis *et al.* (2019), the low BD at a higher elevation associated with fewer disturbances, higher litterfall, and organic matter accumulation, while the highest BD at the lower elevations was due to high sand content and compaction of soil by grazing (Habtamu *et al.*, 2014; Muche *et al.*, 2015; Obasi *et al.*, 2015; Weldemariam Seifu *et al.*, 2020). Organic matter increased soil porosity and lowered bulk density (Ping *et al.*, 2013; Weldemariam Seifu *et al.*, 2020). Thus, as BD increases the pore space of the soil decrease, and the soil particles compact together hampering the air and water circulation between soil pore spaces. However, in the study area, the value of BD was lower, indicating that the soil has better conditions for plant root growth and provides good aeration for microorganisms and good water retention capacity of the soil is an important factor in soil fertility.

3.4.2. The chemical properties of soil

Soil pH and electrical conductivity

In this study, the results showed a decreasing trend of soil pH along with an increased elevation. The pH values varied from 4.6 to 7.1. According to the pH rating suggested by Hazelton and Murphy (2016), the pH of the soils was within the range of very strongly acid (4.5-5.0) to neutral (6.6-7.3). Evaluation of pH along elevational classes showed a tendency to decrease with an increase in elevation, indicating acidity increases with an increase in elevation. A similar study reported by Fantaw Yimer *et al.* (2006), indicated that the negative relationships of pH with elevation could be because increasing elevation increases rainfall and thus causes increased leaching and a reduction in soluble base cations leading to higher H^+ activity and registered as decreased pH levels. The difference in soil pH along with an increase in elevation is associated with changes in species composition (Russell, 2002) and leaching of base cations (Tsui *et al.*, 2004; Rezaei & Gilkes, 2005). Other similar studies also reported that soil pH decreased significantly along with an increase in elevation (Wang *et al.*, 2018; Zebire *et al.*, 2019; Ratier Backes *et al.*, 2021).

Electrical conductivity (EC): Salinity levels are usually determined by measuring the electric conductivity of soil/water suspensions. In this study, the EC value of the soils ranged from 14 $mScm^{-1}$ to 630 $mScm^{-1}$. Following the soil EC rating suggested byWeldemariam Seifu *et al.* (2020), the EC content of the soils in the study area was within the range of moderately saline (8–16) to strongly saline (> 16). The result indicated that there is no significant ($P < 0.683$) difference in salt accumulation along with increasing elevation. However, there is higher EC in the higher elevation followed by lower and middle elevations. The highest clay content in higher elevations holding nutrient cations for nutrient exchange in the soil for plant uptake contributes to higher EC. In agreement with this, Charan *et al.* (2013) reported that the higher EC content of the soil in the higher elevation is linked with higher clay content that contains a higher accumulation of base-forming cations. The higher EC in the lower elevation might be due to the highest amount of basic cations (base-forming cations) like Ca^{2+}, Mg^{+2}, and K^+. In this regard, Charan *et al.* (2013), describe lower elevations have more salt accumulation due to the highest amount of basic cations.

In contrast to this, the lower EC value in the middle elevation might be due to the lowest amount of basic cations, which is removed by washing away basic cations by erosion and leaching. This result is in agreement with the result reported by Berhanu Seyoum (2016) who stated that the lowest EC of middle elevation could be associated with the loss of exchangeable bases by erosion and leaching.

Organic carbon, organic matter, total N, C/N ratio, and available phosphorus

The soil organic carbon content showed a wide variation along the elevational gradient, varying from 0.78% to 1.24%. Following the soil OC rating suggested by Hazelton and Murphy (2016), the OC content of the soils in the study area was within the range of low (0.60–1.00) to moderate (1.00–1.80). The distribution of organic carbon exhibited that the content was lower at lower elevations and increased with an increase in elevation. The variation in organic carbon content is directly dependent on carbon input through plant residue decomposition and the amount of litter accumulated on the soil surface under different tree species. The reduction in organic carbon content could be related to the levels of disturbances, livestock grazing, vegetation cover change, increase in soil erosion rate, removal of woody species, and dominance of invasive species (Terefe Tolessa & Feyera Senbeta, 2018; Pourbabaei *et al.*, 2020). Different vegetation and tree species with different characteristics have different litter decomposition processes leading to differences in organic carbon and nitrogen in the soil. This variation can be attributed to a different rate of organic matter decomposition, the activity of soil microorganisms, litter volume, root system, soil texture, and environmental factors such as temperature and species composition along the elevational gradient (Tsui *et al.*, 2004; Pollierer *et al.*, 2007; Saljnikov *et al.*, 2013; Terefe Tolessa & Feyera Senbeta, 2018).

Soil texture class influences OC storage, the high OC at the higher elevation is associated with an increase in clay and silt content than at the lower elevation. Similar results were reported in other studies by Charan *et al.* (2013), Bhattacharyya *et al*. (2008), and Saiz *et al.* (2012) indicated that increasing clay and silt content suppresses microbial activity, reduces carbon leaching, and stimulates plant production via increasing water holding capacity and thus increases carbon inputs to the soil thus leads to an accumulation of OC. Sandy soils had the lowest SOC stocks regardless of climate because of the low nutrient and water retention capacity as well as the poor structural characteristics of these soils (Saiz *et al.*, 2012).

The greater OC content in the higher elevation was linked to less solar radiation, higher soil moisture, and lower temperature (Moser *et al.*, 2008; Salinas *et al.*, 2011; Vieira *et al.*, 2011; Shedayi *et al.*, 2016), which inhibited soil respiration and promoted the mineralization of organic matter. Higher amounts of precipitation lead to higher plant biomass production and OC inputs. Soil moisture positively mediates litter decomposition and litter biomass influences OC and TN (Zhang, Liu, *et al.*, 2013; Castanha *et al.*, 2018). Moreover, this increase in organic carbon at a higher elevation is associated with a shorter period of plant growth (Pourbabaei *et al.*, 2020). These results agree with previously reported studies where OC was higher in colder and wetter areas as compared to hotter and drier areas (Jenkinson, 1990; Charan *et al.*, 2013; Muche *et al.*, 2015; Hazelton & Murphy, 2016). On the other hand, Bangroo *et al.* (2017) indicated that soil in shady areas has higher SOC than in sunny areas, due to higher soil moisture and lower temperature, and Xiang *et al.* (2021), stated that OC stocks were higher under the middle and high canopy density than those under low canopy density. According to Durán Zuazo *et al.* (2013), the lower density of vegetation cover at the lower elevation could lead to a decrease in soil organic matter, increased runoff, erosion, and decreased organic carbon content. A significant increase in soil organic carbon with increasing elevation was also shown in other studies (Shedayi *et al.*, 2016; Sierra *et al.*, 2017; Hou *et al.*, 2019; Pourbabaei *et al.*, 2020; Xiang *et al.*, 2021). However, there is no clear pattern in the distribution of soil organic carbon along an elevational gradient.

Soil organic matter (OM) is the most reactive and powerful factor in the formation of soil and its fertility. Soil organic matter provides energy for biological processes, improves soil structural stability, influences water retention capacity, alters thermal properties, and contributes to the cation exchange capacity (Saljnikov *et al.*, 2013; Mutua *et al.*, 2014; Jones *et al.*, 2017). In this study, the SOM content increased with an increase in elevation, ranging from 1.31% to 25.1%. According to Hazelton and Murphy (2016), the OM content of the soils in the study area was within the range of low (1.00–1.70) to very high (> 5.15). The highest soil OM content was recorded at the higher elevation and the least was recorded at the lower and middle elevations. The high OM content at higher elevations is associated with soil texture (Charan *et al.*, 2013), and clay soils contain more OM than sandy soils (Jenkinson, 1990). Poorly drained soils accumulate higher SOM than well-drained soils, due to poor aeration causing a decline in soil oxygen concentrations. Many soil microorganisms involved in decomposition are aerobic and will not function well under anaerobic conditions. In this study, the high OM content was associated with more clay content at the higher elevation (Jenkinson, 1990). In agreement with this a study report by Bhattacharyya *et al.* (2008), Gupta and Germida (1988), Walker *et al.* (2001), and Karbozova–Saljnikov *et al.* (2004) revealed that lack of water in the dry area, higher precipitation and lower temperatures of higher elevation resulted in retarded mineralization of plant residues and limit the decomposition of OM resulting in accumulation of OM.

Total Nitrogen (TN) measures the total amount of nitrogen present in the soil, much of which is held in organic matter and is not immediately available to plants. The total nitrogen content of the study area ranged from 0.06% to 1.25%. According to the TN rating suggested by Hazelton and Murphy (2016), the TN content of the soils of the study area was within the range of low (0.05–0.15) to very high (> 0.5). In this study, the total nitrogen content is higher at high elevations than at middle and lower elevations, showing a significant increase with an increase in elevation. These results agree with previously reported studies by Han *et al.* (2022) and Shedayi *et al.* (2016) revealed that there is a significant increase in total nitrogen content with an increase in elevation. The higher nitrogen contents are attributed to the large supply of plant residue and the low temperature at a higher elevation. These results agree with the report by Saljnikov *et al.* (2013) where TN was significantly higher in colder and wetter as compared to hotter and drier climates. The reduction in soil TN content in the lower and middle elevations could be related to the level of disturbances, such as overgrazing, logging, firewood collection, and deforestation. In agreement with this, the studies reported by Terefe Tolessa and Feyera Senbeta (2018), Ambachew Demessie *et al.* (2011), Peng *et al.* (2013), and Biyensa Gurmessa *et al.* (2016) revealed that disturbances reduce the content of TN in the soil. On the other hand, Chinevu *et al.* (2013) reported that reduction in aeration, higher compaction of soil, and conversion of nitrate to gaseous nitrogen by anaerobic soil microorganisms cause nitrogen losses. According to Yihenew Gebreselassie (2002), the low TN content recorded might be due to the rapid mineralization of OC and reduced input of plant residues. The increase in temperature will accelerate the decomposition of nitrogen in soil organic matter, which will affect soil availability of nitrogen. Similar study by Han *et al.* (2022) revealed that climate warming enhances the mineralization of soil organic matter, which contains most of the soil nitrogen.

The carbon-to-nitrogen ratio of the soil decreases along with an increase in elevation. The C/N ratio ranged from 3.06% to 19.38%. According to the C/N ratio rating suggested by Hazelton and Murphy (2016), the C/N ratio of the soils in the study area was within the range of very low (<10) to medium (5–25). The carbon-to-nitrogen ratio measures the relative nitrogen content of organic materials. It can be measured for soil carbon or organic materials. The carbon-to-nitrogen ratio (C/N) is commonly used as an indicator of organic matter quality.

The available phosphorus (Av. P)

The concentrations of Av. P ranged from 1.43 mg/kg to 3.88 mg/kg. According to Hazelton and Murphy (2016), the Av. P of the study area was within the range of very low (< 5). In agreement with these Fantaw Yimer *et al.* (2006), reported that the lower levels of available phosphorus are due to increased phosphorus fixation, and more than half of the phosphorus content is stored in the tree biomass, hence the quantity and quality of litterfall are important factors on phosphorus content. There are variations in the Av. P content among the three elevation ranges, indicating a decrease in Av. P content with an increase in elevation. as indicated by Mulugeta Lemenih and Fisseha Itanna (2004) an increase in organic carbon content at higher elevations resulted in low available phosphorus. A similar result reported by Pourbabaei *et al.* (2020) indicated that variations of phosphorus at different elevations with differences in the nutrient content could be related to geological changes and the density of tree species.

Cation Exchange Capacity (CEC) and Exchangeable Cations (Ca^{2+}, Mg^{2+}, and K^{+})

The cation exchange capacity (CEC) refers to the exchange of positively charged ions at the surface of negatively charged colloids. The higher the CEC, the more capable the soil can retain mineral elements (Zebire *et al.*, 2019). The CEC status in the soil of the study area ranged from 1.4 meq/100g of soil to 49 meq/100g of soil. According to the CEC rating suggested by Hazelton and Murphy (2016), the CEC of the soils was within the range of very low (< 6) in the lower elevation to very high (> 40) in the higher elevation. Indicating an increase in CEC with an increase in elevation. According to Chinevu *et al.* (2013), the higher the clay content of the soil, the higher the cation exchange capacity and the higher the fertility of the soil. The concentration of CEC is determined by the amounts of clay and humus present in the soil (Chinevu *et al.*, 2013; Ping *et al.*, 2013). Clay and humus substances are essential cation reservoirs of the soil, therefore the high clay content with high content of organic matter in the higher elevation of the study area is associated with the high CEC, and the low CEC in the lower elevation is due to high sand soils with little organic matter. This result is in agreement with the findings of Brady and Weil (2002), Chinevu *et al.* (2013), and Ping *et al.* (2013).

Exchangeable base cations

The decreases and losses of base cations from forest soils are primarily linked with downward leaching (Schroth *et al.*, 2007; Richardson *et al.*, 2017), increased soil acidity, increased soil OM mobilization, soil compaction, and decreased cation exchange capacity associated with greater losses of base cations (Wilhelm *et al.*, 2013; Eroğlu *et al.*, 2016).

Exchangeable potassium (K^+) contents were varied from 0.04 meq/100g of soil to 2.3 meq/100g of soil. According to the K^+ rating suggested by Hazelton and Murphy (2016), the K^+ of the soils in the study area was within the range of very low (0–0.2) to very high (> 2). The K^+ values show a tendency to decrease with an increase in elevation. Similar studies reported by Pourbabaei *et al.* (2020) and Sapkota (2017) revealed that potassium decreases with an increase in elevation. The reduction in K^+ content with an increase in elevation is associated with its high leaching. Potassium does not combine with organic compounds of the soil and the increased base saturation (calcium and magnesium) along with elevation leads to easy leaching of K^+ from the soil (Seibert *et al.*, 2009). A study reported by Tsui *et al.* (2004), revealed that less leaching of soil at lower elevations can be a source of accumulation of soluble ions, including potassium.

Exchangeable Calcium (Ca^{2+}) contents were varied from 0 meq /100g of soil to 38 meq /100g of soil. Following Hazelton and Murphy (2016), the Ca^{2+} of the soils was within the range of very low (0–2) to very high (> 20). There were variations among the Ca^{2+} content along with the elevational gradient. The higher Ca^{2+} content was recorded in the lower elevation and the least was recorded in the higher and middle elevations. Similar studies by Wang *et al.* (2018) and Sapkota (2017) indicated that the content of exchangeable Ca^{2+} decreased with an increase in elevation.

Exchangeable magnesium (Mg^{2+}) contents varied from 0 meq /100g of soil to 16 meq /100g of soil at the higher elevation. According to Hazelton and Murphy (2016), the Mg^{2+} content of the soils was within the range of very low (0–0.3) to very high (> 8). It was found that exchangeable magnesium contents of soils showed a significant difference with elevation. A similar study reported by Sapkota (2017), revealed that Mg^{2+} showed a significant difference with elevation. The concentration of exchangeable Mg^{2+} showed a significant increase along with an increase in elevation.

3.4.3. Pearson's correlation analysis for soil physicochemical parameters with elevation

A diverse range of correlations was recorded among different soil variables with elevation. The result of Pearson's correlation revealed that different soil variables were significantly correlated with elevation and with each other. Elevation was positively correlated with soil OC, OM, TN, CEC, exchangeable Mg^{2+}, clay, and silt. However, pH, EC, C/N ratio, Av P, exchangeable Ca^{2+}, exchangeable K^{+}, BD, and sand were negatively correlated with elevation. The pH had a positive and non-significant correlation with the EC ($r = 0.201$, $P < 0.070$), OC ($r = 0.002$, $P < 0.983$), C/N ($r = 0.078$, $P < 0.488$), Av. P ($r = 0.043$, $P < 0.701$), CEC ($r = 0.004$, $P < 0.972$), BD ($r = 0.002$, $P < 0.988$), and ($r = 0.170$, $P < 0.128$). While exchangeable Ca^{2+} and K^{+} had a positive and highly significant relationship ($r = 0.412^{**}$, $P \leq 0.001$) ($r = 0.389^{**}$, $P \leq 0.001$) with pH respectively. However, OM ($r = -0.001$, $P < 0.993$), TN ($r = -0.014$, $P < 0.898$), exchangeable Mg^{2+} ($r = -0.093$, $P < 0.406$), clay ($r = -0.060$, $P < 0.594$) and silt ($r = -0.200$, $P < 0.072$), had negative and non-significant correlation with pH. Organic carbon had a positive significant correlation with OM ($r = 1.000^{**}$, $P \leq 0.001$), TN ($r = 0.978^{**}$, $P \leq 0.001$), CEC ($r = 0.711^{**}$, $P \leq 0.001$), exchangeable Ca^{2+} ($r = 0.531^{**}$, $P \leq 0.001$), exchangeable Mg^{2+} ($r = 0.391^{**}$, $P \leq 0.001$) and clay ($r = 0.683^{**}$, $P \leq 0.001$). While positive and non-significant correlation with pH ($r = 0.002$, $P < 0.983$), EC ($r = 0.168$, $P < 0.132$), and silt ($r = 0.061$, $P < 0.586$). However Organic carbon had a negative significant correlation with Av. P ($r = -0.313^{**}$, $P < 0.004$) and sand ($r = -0.597^{**}$, $P < 0.001$), but a negative non-significant correlation with C/N ($r = -0.041$, $P < 0.714$), exchangeable K^{+} ($r = -0.051$, $P < 0.649$), BD ($r = -0.119$, $P < 0.287$) (Table 5). The significant relationship of soil physicochemical parameters with elevation can be seen in Table 14 and for their P-value refer to Table 15.

Table 14. Pearson's correlation coefficient (r) for selected soil physicochemical parameters and elevation

Correlations																
	Elevation	pH	EC	OC	O.M	TN	C/N	Av. P	CEC	Ca^{2+}	Mg^{2+}	K^{+}	BD	Sand	Clay	Silt
Elv.	1															
pH	0.198	1														
E.C	-0.046	0.201	1													
OC	0.416**	0.002	0.168	1												
O.M	0.411**	-0.001	0.154	1.000**	1											
TN	0.436**	-0.014	0.156	0.978**	.978**	1										
C/N	-0.048	0.078	.349**	-0.041	-0.06	-0.21	1									
Av. P	-0.043	0.043	-0.02	-0.313**	0.311**	0.316**	0.017	1								
CEC	0.337**	0.004	.238*	0.711**	0.708**	0.706**	0.021	0.295**	1							
Ca^{2+}	-0.044	0.412**	.345**	0.531**	0.528**	0.519**	-0.092	-0.18	0.638**	1						
Mg^{2+}	0.271*	-0.093	.236*	0.391**	0.389**	0.386**	0.078	-0.241*	0.537**	0.168	1					
K^{+}	-0.063	0.389**	.379**	-0.051	-0.06	-0.07	0.241*	0.274*	-0.04	0.041	-0.1	1				
B.D	-0.697**	0.002	0.119	-0.119	-0.11	-0.13	-0.019	-0.03	-0.14	0.142	-0.1	-0.064	1			
Sand	0.444**	0.17	0.015	-0.597**	0.597**	0.627**	0.145	0.280*	0.610**	-0.187	-0.278*	-0.031	.219*	1		
Clay	0.395**	-0.06	-0.05	0.683**	0.684**	0.684**	-0.075	0.375**	0.607**	0.257*	0.280*	-0.124	0.185	-.851**	1	
Silt	0.195	-0.2	0.056	0.061	0.06	0.118	-0.157	0.051	0.215	-0.024	0.09	0.251*	0.096	-.560**	0.05	1

Elv. = Elevation, EC= Electric conductivity, OC = organic carbon, OM= organic matter, TN= total nitrogen, C/N= carbon to nitrogen ratio, Av. P= available phosphorus, CEC= cation exchange capacity, K^{+}= exchangeable potassium, Ca^{2+}= exchangeable Calcium, Mg^{2+}= exchangeable magnesium, BD. – bulk density, **- significant at $p < 0.01$, *- significant at $p < 0.05$ between soil properties and elevation.

Table 15. Pearson's correlation coefficient (r) for soil physicochemical parameters and elevation

Correlations

		Elevation	PH	E.C	OC	O.M	TN	C/N	Av. P	CEC	Ca^{2+}	Mg^{2+}	K^{+}	B.D	Sand	Clay	Silt
Elv.	Pearson Correlation	1	-.198	-.046	.416**	.411**	.436**	-.048	-.043	.337**	-.044	.271*	-.063	-.697**	-.444**	.395**	.195
	Sig. (2-tailed)		.075	.683	.001	.001	.001	.671	.701	.002	.693	.014	.574	.001	.001	.001	.079
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
PH	Pearson Correlation	-.198	1	.201	.002	-.001	-.014	.078	.043	.004	.412**	-.093	.389**	.002	.170	-.060	-.200
	Sig. (2-tailed)	.075		.070	.983	.993	.898	.488	.701	.972	.001	.406	.001	.988	.128	.594	.072
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
E.C	Pearson Correlation	-.046	.201	1	.168	.154	.156	.349**	-.024	.238*	.345**	.236*	.379**	.119	.015	-.052	.056
	Sig. (2-tailed)	.683	.070		.132	.167	.161	.001	.834	.031	.002	.033	.001	.289	.892	.644	.620
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
OC	Pearson Correlation	.416**	.002	.168	1	1.000**	.978**	-.041	-.313**	.711**	.531**	.391**	-.051	-.119	-.597**	.683**	.061
	Sig. (2-tailed)	.001	.983	.132		.001	.001	.714	.004	.001	.001	.001	.649	.287	.001	.001	.586
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
O.M	Pearson Correlation	.411**	-.001	.154	1.000**	1	.978**	-.056	-.311**	.708**	.528**	.389**	-.055	-.114	-.597**	.684**	.060
	Sig. (2-tailed)	.001	.993	.167	.001		.001	.618	.004	.001	.001	.001	.625	.309	.001	.001	.592
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
TN	Pearson Correlation	.436**	-.014	.156	.978**	.978**	1	-.214	-.316**	.706**	.519**	.386**	-.065	-.130	-.627**	.684**	.118
	Sig. (2-tailed)	.001	.898	.161	.001	.001		.054	.004	.001	.001	.001	.564	.245	.001	.001	.292
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
C/N	Pearson Correlation	-.048	.078	.349**	-.041	-.056	-.214	1	.017	-.021	-.092	.078	.241*	-.019	.145	-.075	-.157
	Sig. (2-tailed)	.671	.488	.001	.714	.618	.054		.882	.849	.411	.484	.029	.865	.195	.502	.159
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
Av. P	Pearson Correlation	-.043	.043	-.024	-.313**	-.311**	-.316**	.017	1	-.295**	-.182	-.241*	.274*	-.026	.280*	-.375**	.051
	Sig. (2-tailed)	.701	.701	.834	.004	.004	.004	.882		.007	.102	.029	.013	.816	.011	.001	.647
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
CEC	Pearson Correlation	.337**	.004	.238*	.711**	.708**	.706**	-.021	-.295**	1	.638**	.537**	-.039	-.135	-.610**	.607**	.215
	Sig. (2-tailed)	.002	.972	.031	.001	.001	.001	.849	.007		.001	.001	.726	.227	.001	.001	.052
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
Ca^{2+}	Pearson Correlation	-.044	.412**	.345**	.531**	.528**	.519**	-.092	-.182	.638**	1	.168	-.041	.142	-.187	.257*	-.024
	Sig. (2-tailed)	.693	.001	.002	.001	.001	.001	.411	.102	.001		.130	.711	.203	.092	.020	.830
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82

Mg^{2+}	Pearson Correlation	.271*	-.093	.236*	.391**	.389**	.386**	.078	-.241*	.537**	.168	1	-.103	-.095	-.278*	.280*	.090
	Sig. (2-tailed)	.014	.406	.033	.001	.001	.001	.484	.029	.001	.130		.358	.393	.011	.011	.422
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
K^{+}	Pearson Correlation	-.063	.389**	.379**	-.051	-.055	-.065	.241*	.274*	-.039	-.041	-.103	1	-.064	-.031	-.124	.251*
	Sig. (2-tailed)	.574	.001	.001	.649	.625	.564	.029	.013	.726	.711	.358		.566	.780	.267	.023
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
B.D	Pearson Correlation	-.697**	.002	.119	-.119	-.114	-.130	-.019	-.026	-.135	.142	-.095	-.064	1	.219*	-.185	-.096
	Sig. (2-tailed)	.001	.988	.289	.287	.309	.245	.865	.816	.227	.203	.393	.566		.048	.097	.390
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
Sand	Pearson Correlation	-.444**	.170	.015	-.597**	-.597**	-.627**	.145	.280*	-.610**	-.187	-.278*	-.031	.219*	1	-.851**	-.560**
	Sig. (2-tailed)	.001	.128	.892	.001	.001	.001	.195	.011	.001	.092	.011	.780	.048		.001	.001
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
Clay	Pearson Correlation	.395**	-.060	-.052	.683**	.684**	.684**	-.075	-.375**	.607**	.257*	.280*	-.124	-.185	-.851**	1	.051
	Sig. (2-tailed)	.001	.594	.644	.001	.001	.001	.502	.001	.001	.020	.011	.267	.097	.001		.647
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
Silt	Pearson Correlation	.195	-.200	.056	.061	.060	.118	-.157	.051	.215	-.024	.090	.251*	-.096	-.560**	.051	1
	Sig. (2-tailed)	.079	.072	.620	.586	.592	.292	.159	.647	.052	.830	.422	.023	.390	.001	.647	
	N	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82

**. Correlation is significant at the 0.01 level (2-tailed), *. Correlation is significant at the 0.05 level (2-tailed).

Conclusions

The soil's physicochemical properties exhibit variations in relation to changes in elevation. In this study, the effect of elevation variation on the physicochemical properties/qualities of the soil was analyzed and the results revealed that the elevation changes had an impact on the physicochemical properties of the soil. The highest percentage of sand was recorded at the lower elevation, while the highest percentage of clay and silt was recorded at the higher elevation. The evaluation of soil properties indicated that the values of some soil physicochemical properties were increased with increasing elevation. The concentration of soil organic carbon, organic matter, total nitrogen, and cation exchange capacity increases along with an increase in elevation. This is due to the different rates of organic matter decomposition, the activity of soil microorganisms, litter volume, root system, soil texture, and environmental factors such as temperature and plant species composition. Whereas, the highest bulk density, pH, and electric conductivity values were recorded at the lower elevation, indicating a decrease with an increase in elevation. This is due to high sand content and livestock trampling causing an increased bulk density, and increased rainfall in higher elevations causes leaching of base cations and decreased pH levels. However, there was no regular variation in the content of available phosphorus and exchangeable bases (Ca^{2+}, Mg^{2+}, and K^{+}) along the elevational gradients. The result of Pearson's correlation revealed that the different soil variables were significantly correlated with each other and with elevation. Elevation was positively correlated with soil OC, OM, TN, CEC, exchangeable Mg^{2+}, clay, and silt, while, pH, EC, C/N ratio, Av P, exchangeable Ca^{2+}, exchangeable K^{+}, BD, and sand were negatively correlated with elevation. Finally, this study provides information on the impact of elevation on soil's physicochemical properties along the elevation gradients.

CHAPTER FOUR

4. Ethnobotanical study of *Piliostigma thonningii* (Schumach.) Milne-Redh. (Fabaceae) in the South Omo Zone, southern Ethiopia

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Abstract

Trees are important components of terrestrial ecosystems; they provide ecological, economic, and cultural services to humans. There is an urgent need for undertaking ethnobotanical investigations and documentation on the indigenous botanical knowledge of the local communities of a given area. This study was conducted to assess and document the ethnobotany of Piliostigma thonningii and the associated indigenous knowledge of the local people related to the use, management practices, and the threatening factors in the South Omo Zone of southwestern Ethiopia. Six Kebeles were purposively selected from two districts of the zone and a total of 84 respondents were sampled, with the consideration of gender, age, and wealth status. Data were collected using structured and semi-structured interviews, field observations, and focus group discussions. Relevant descriptive statistical methods were used to analyze the data. Ethnobotanical knowledge held by informants was computed using Pearson's chi-square test and direct matrix ranking and pair-wise ranking was used to prioritize the uses according to community preferences and the level of the destructiveness of the reported threats. The results showed that P. thonningii provides different functions to people's livelihoods as shade, food, fodder, soil fertility, fuelwood, medicine, rope, multipurpose materials (e.g., Borketa for sitting and head support), huts, beehives, farm implements, chairs, fences, and timber. The indigenous knowledge of local people on the uses of P. thonningii has shown a significant ($P < 0.05$) relationship to age groups (being higher for elderly people). The consumption practice of respondents has a significant ($P < 0.05$) association with the Kebeles, age, and income, with a higher value for Hamer, lower-aged groups, and low-income families. It provides nutritious animal feed to improve browse intake, survival, and productivity of domestic animals and also improve the productivity of farms through amelioration of soil fertility. The status of P. thonningii has been decreasing due to agricultural expansion, collection of the species for firewood, dry fencing, and due to browsing. Respondents' attitude and interest in maintaining and conserving the species has shown a significant ($P< 0.05$) association with gender, wealth, and level of education. Higher interest was observed in men than women, mid-high wealth class households than low income, and people with education than uneducated. This study attempted to provide information on the multiple uses of P. thonningii. Given the key roles of P. thonningii for the people and the environment to improve household food security, agricultural productivity, and income sources and the threats to it, the need to protect it in natural forests and woodlands and optimize its uses in agroforestry systems is high. Serious consideration of this species will ultimately allow households to reap the benefits expected to accrue from it in the arid and semi-arid areas of Ethiopia where plants of this nature are usually rare.

Keywords/Phrases: Benna-Tsemay, Ethnic group, Ethnobotany; Hamer, Indigenous knowledge, Informants.

4.1. Introduction

Piliostigma thonningii (Schumach.) Milne-Redh. is a multipurpose tree species, common in open woodland and wooded grasslands of sub-humid Africa at medium to low altitudes. It is widely distributed and found throughout tropical Africa except in Somalia (Orwa *et al.*, 2009). In Ethiopia, it occurs in deciduous woodlands and wooded grasslands in most parts of the country(Thulin *et al.*, 1989). *P. thonningii* is one of the most important indigenous multipurpose trees used for various purposes (Azene Bekele & Tengnäs, 2007). It is used as a source of food for humans in the Benna-Tsemay and Hamer Districts of the South Omo Zone, locally known as Olofoo (Benna and Hamer) (Assegid Assefa & Tesfaye Abebe, 2011). Its occurrence and uses have been studied in the Quara area of north Gonder (Mekuanent Tebkew *et al.*, 2018), and the Benishangul Gumuz region (Dessalegn Ayele, 2017). *P. thonningii* is known as Monkey bread or Camel's foot in English and Kameel Spoor in Africans (Dasofunjo *et al.*, 2013). Reports by Wubalem Tadesse *et al.* (2012), Dessalegn Ayele (2017), Mekuanent Tebkew *et al.* (2018), and Almaz Ayenew (2019) showed that *P. thonningii* is also consumed by animals as fodder. However, in other African countries, *P. thonningii* is used for various purposes other than food. Sources show that the different parts of the tree (leaves, pods, and seeds) which are nutritious are browsed by animals including elephants, livestock, and antelopes (Jimoh & Oladiji, 2005; Orwa *et al.*, 2009; Egharevba & Kunle, 2010; Chidumayo, 2018; Jemiseye *et al.*, 2019). The leaves of *P. thonningii* are eaten and chewed by the Masai people to relieve thirst (Jemiseye *et al.*, 2019).

The wood is suitable for poles, firewood, charcoal, carpentry, construction, household utensils, and farm implements (Thulin *et al.*, 1989; Orwa *et al.*, 2009; Chidumayo, 2018). The bark is used to make strings, ropes, and clothes (Thulin *et al.*, 1989; Orwa *et al.*, 2009; Egharevba & Kunle, 2010). Different phytochemicals (such as flavonoids, tannins, alkaloids, saponins, terpenoids, anthraquinones, steroids, and volatile oils) are extracted from the parts of *P. thonningii* and used to treat various diseases, such as fever, toothache, wound healing, dysentery, respiratory ailments (bronchitis, cough, and chest complaints), snake bites, hookworm, skin infections, stomach ache, and chronic ulcers (Jimoh & Oladiji, 2005; Orwa *et al.*, 2009; Ukwuani *et al.*, 2012; Deshi *et al.*, 2014; Baldé *et al.*, 2016; Dluya & Dahiru, 2018; Jemiseye *et al.*, 2019; Musah, 2019). In Tanzania, the tender leaves are chewed and the juice is swallowed to treat stomachache, coughs, and snakebite. The roots are also used to treat prolonged menstruation, hemorrhage, and miscarriage in women and also for the treatment of coughs, colds, body pain, and STDs (Ruffo *et al.*, 2002).

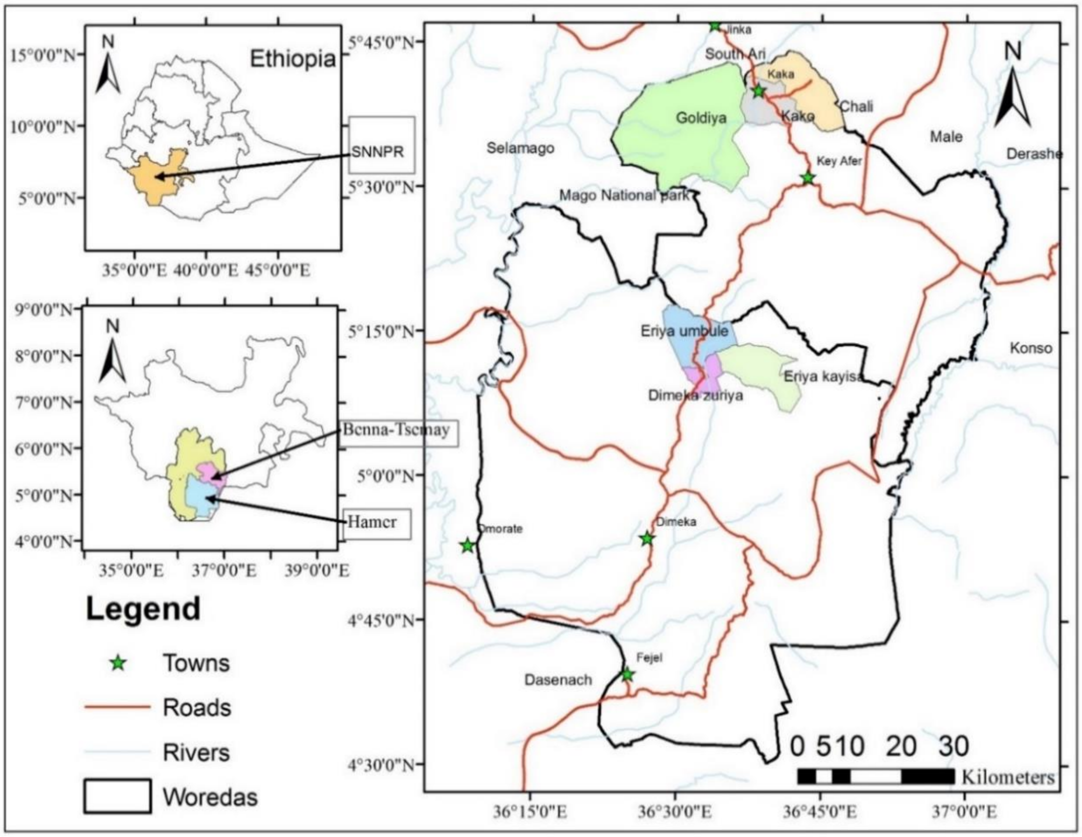
Ethnobotanical knowledge of *P. thonningii* in Ethiopia in general and the South Omo Zone in particular is not adequately documented. Therefore the present study was conducted to document the different ethnobotanical uses of *P. thonningii* and the associated indigenous botanical knowledge of the local community, to identify the influence of demographic factors on the indigenous knowledge of the local community on the use of *P. thonningii*, to assess the management practices, and threats to its sustainability in the South Omo Zone.

4.2. Materials and methods

4.2.1. Descriptions of the study area

This study was conducted in the arid and semi-arid areas of the South Omo Zone, southern, Ethiopia. In the zone, there are eight districts, and the zone town is Jinka. The study districts, Benna-Tsemay (Key Afer) and Hamer (Dimeka) are located about 739 and 839 km from the capital city of Ethiopia, Addis Ababa, respectively. Benna-Tsemay District is located at 5° 03′ to 5° 34′ N latitude and 36° 33′ to 37° 03′ E longitude with altitude ranging from 500 to 2000 masl. and Hamer District is located between 4° 31′ to 5° 28′ N latitude and 36° 09′ to 36° 53′ E longitude with altitude ranging from 381 (Kizo-Baze plain) to 2084 masl (Buska-Ale mountain). The study Districts cover a total land area of 9496 km^2 (Hamer = 5742 km^2 and Benna-Tsemay = 3754 km^2).

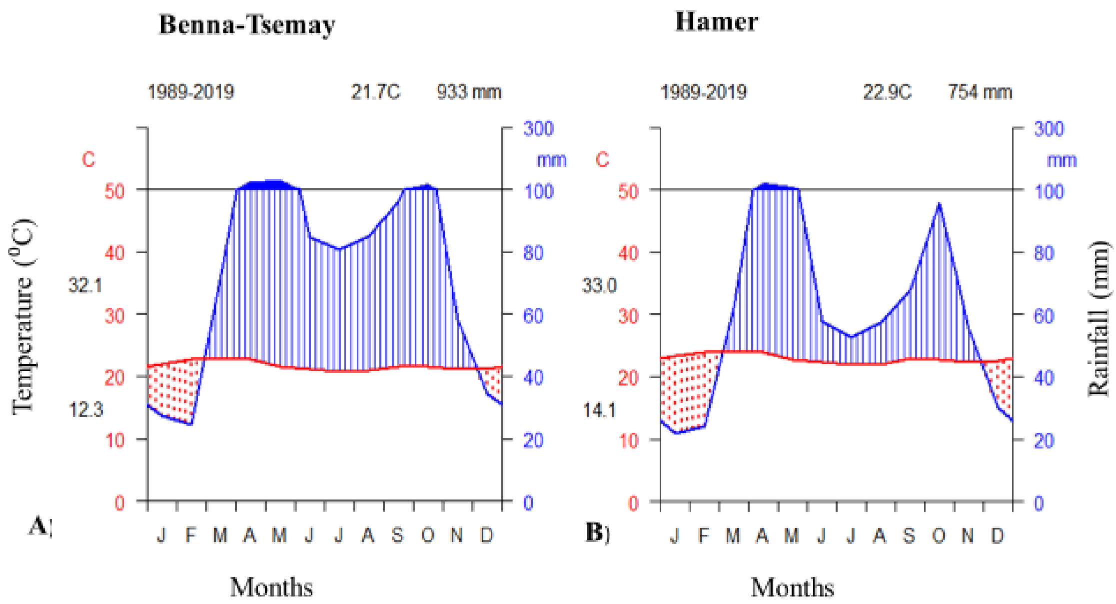
The greater proportion of the study area is characterized by arid and semi-arid climatic conditions. According to the agroecological map of the Ethiopian Institute of Agricultural Research (EIAR, 2011), the agroecology of the study Kebeles (subdistricts) of Benna-Tsemay District is categorized as warm humid lowlands (H_2) and the study Kebeles of Hamer District is categorized as warm semi-arid lowlands (SA_2).



Map of Ethiopia showing the location of the study area, Hammer and Benna-Tsemay Districts in South Omo Zone, southern Ethiopia

The rainfall pattern of both districts is bimodal. The average annual precipitation of the Benna-Tsemay district was 933 mm and the average annual temperature was 20.7 °C. The dry season occurred from the beginning of December to the end of February. The long rainy period which is the cropping season occurs from the end of March to the beginning of June and the short rainy season, which is important only for pasture, occurs between October and November. The average monthly maximum temperature of the warmest month is 30.2 °C and the average monthly minimum temperature of the coldest month is 12.3 °C.

The average annual precipitation of the Hamer District was 754 mm and the average annual temperature was 22.9 °C. The dry season occurred from mid-November to the beginning of March. The long rainy season occurs from the end of March to May and the short rainy season is from the end of September to the end of October. The average monthly maximum temperature of the warmest month is 33 °C and the average monthly minimum temperature of the coldest month is 14.1 °C. The climate of Hamer is relatively drier than Benna-Tsemay.



Climate diagram of the study district showing rainfall distribution and temperature variation from 1989 to 2019 [Data source: Centre for Environmental Data Analysis (Harris & Jones, 2019).

The vegetation of the study area belongs to the types known as *Acacia-Commiphora* woodland and *Combretum-Terminalia* woodland and wooded grassland (Friis *et al.*, 2010). Most of the pastoral and agro-pastoral communities of the study area rely mainly on dry forest resources for livestock fodder, income, food, and medicine. The maj ority of the communities in the Benna-Tsemay District belong to the Benna and Tsemay ethnic groups. The human population of the District was 55,590 (CSA, 2007). However, the current (2018) report from the Benna-Tsemay district agricultural bureau shows 72,749 (36,262 male and 36,487 female) (Key-Afer, Agriculture Bureau, unpublished report). The majority of the communities in the Hamer District belong to the Hamer ethnic group. The population of the District was 46,129 (CSA, 2007). However, the current (2018) report from the Hamer District Agricultural Bureau shows 78,545 (40,122 male and 38,423 female) (Dimeka, Agriculture Bureau, unpublished report). Pastoralism and agropastoralism are the two main livelihood options in the study area. The livelihoods of these pastoralist communities are mainly the rearing of livestock, goats, and sheep and the use of their products and the agropastoralists are dependent on both livestock products and crop cultivation. There is limited cereal crop production in Hamer and the people collect and use some wild edible plants (Getachew Addis *et al.*, 2013). Their main source of income was from the sale of livestock, which was followed by the sale of honey (Admasu Terefe *et al.*, 2010). Food insecurity is a common problem in the study area caused by complex factors such as frequent and extended drought, degradation of natural resources, lack of appropriate technologies, and unpredictable climatic conditions which reduce livestock and plant productivity; this threatens the livelihoods of the pastoral and agro-pastoral communities (Admasu Terefe *et al.*, 2010; Muhamed Adem *et al.*, 2014). Mobility and collection of wild foods are the coping mechanisms for climate variability and food insecurity in the study area (Admasu Terefe *et al.*, 2010; Ermias Lulekal *et al.*, 2011; Getachew Addis *et al.*, 2013; Leul Kidane & Alemu Kejela, 2021).

4.2.2. Sampling and informant selection

A reconnaissance survey was first conducted in May 2018 to gain an overview of the availability, distribution, and consumption practice of *P. thonningii*. From the eight districts of the South Omo Zone, two districts (Benna-Tsemay and Hamer) were selected considering their difference in agroecology and the presence of at least two major ethnic groups (Benna and Hamer ethnolinguistic communities) and the occurrence of *P. thonningi* was taken as criteria for inclusion of kebeles in the study. A discussion was made with both Benna-Tsemay and Hamer district administrators, environment protection, forest, and climate change officers, agricultural development agents, and community elders. Following this, field observation was made jointly with field assistants and agricultural development agents to select Kebeles and to check the availability, distribution, and accessibility of *P. thonningii* within the study area. The data collected through this activity helped to purposively select six sample Kebeles (three from Hamer-speaking and three from Benna-speaking Districts).

The sample size was determined following the standard procedure of Cochran's sample size formula indicated in Kotrlik and Higgins (2001). Consequently, the sample sizes for the two Districts were determined separately based on the total number of households in each district (11,118 Benna and 9,225 Hamer), and finally, the proportionally calculated manageable sample size for Benna-Tsemay (34 households) and Hamer (33) was used. To make the number of households involved in the interview equal in the two Districts and in each Kebele, a total of 36 households from each district and 12 households from each Kebele were selected to make an overall total of 72 households. Informants were stratified by gender and relative socio-economic status as low-wealth and medium-high-wealth status households based on the information obtained from local authorities (agricultural development agents and Kebeles administrators). The wealth status of households in each Kebele was assessed by the district food security desk following the criteria set by the Ministry-of-Agriculture (MOA, 2014), and the list of poor households who benefit from the Productive Safety Net program was given to the Kebele food security task force. The 72 general informants were identified by taking one household informant from each stratified randomly identified household and two key informants from each kebele were purposively selected making a total of 84 informants. The informant sampling approach was followed by Martin (1995). Thus, out of the 84 informants, 72 (12 informants × 3 Kebeles × 2 ethnic groups) were general informants selected randomly by a lottery method from the stratified households to give equal chances. The other 12 informants (from 2 ethnic groups × 3 Kebeles × 2 key informants) were key informants selected purposively based on the recommendations from local authorities and elders, confirmed to be knowledgeable about *P. thonningii* , and volunteered to participate in the study.

4.2.3. Data collection

The ethnobotanical data were collected using a structured interview, semi-structured interview, direct field observation, and focus group discussions (Martin, 1995; Cotton & Wilkie, 1996). The structured interview was based on fixed questions and was mainly used for the collection of local knowledge. The structured questionnaire was also documented by interviewing informants using the Open Data Kit (ODK collect version 1.15.1), an application loaded on a smartphone. Each interviewee was asked the same questions independently without contacts or sharing information with the other informants or with the target population. The semi-structured interview was conducted based on a checklist of questions and both the structured and semi-structured interviews were prepared in English and translated to the local languages (Benna and Hamer) by a proficient local translator. The structured questionnaire is composed of closed questions while the semi-structured questionnaire has open-ended questions (Appendix 5). Informants were allowed to raise their own points during the interview, not necessarily as responses to questions. The interviewer probed deeper by asking additional questions whenever interesting information was sensed.

A guided field walk procedure was followed to collect and record voucher specimens of plants found near/under *P. thonningii* in the selected Kebeles jointly with a field assistant and a translator. Field assistants were selected based on their willingness, ability to walk long distances, general plant knowledge in local names, and capability of translating both ways. The field observation created an opportunity to make a note of the relationship of *P. thonningii* with other species and other features of the study area.

Six focus group discussions (FGDs) were conducted for crosschecking and verification of the information. Accordingly, the FGDs were undertaken in groups of six in each of the selected Kebeles. The discussion was conducted with key informants, farmers, Kebele administrators, and agricultural development agents, mediated by the researcher. Information collected through focus group discussion is important to triangulate the ethnobotanical data collected through the structured and semi-structured interviews.

4.2.4. Data analyses

Statistical Package for Social Sciences (SPSS) Version 26.0 was used to analyze ethnobotanical data. A Pearson's chi-square test was used to detect (at $P < 0.05$) the relationship of the ethnobotanical knowledge held by respondents between different ethnic backgrounds, gender, wealth status, age groups, educational levels, and Kebeles, regarding the use categories, consumption practice, and attitude of the respondents to conserve the species, and also used to detect the relationship between the different age groups of low- and mid-high wealth status respondents who were involved in the collection and consumption of the fruit. Ethnobotanical ranking methods were employed to analyze the most preferred use of *P. thonningii* and the most destructive threats to it. Direct matrix ranking was carried out to rank the most preferred use of *P. thonningii* in the study area. The 12 key informants were requested to compare the uses of *P. thonningii* based on their preferences and importance to the community. Each key informant arranged the uses according to personal preference, and perceived importance to the community on a 0 to 5 scale, with 0-no value, and 5-the highest value. The 12 key informants were requested to rank the uses of *P. thonningii*. The pair-wise ranking was employed to determine the degree of destructive activities or threats to *P. thonningii* on a scale of 0 to 5, with 0-not destructive, and 5-the most destructive. Finally, the given numbers were summed up for all key informants, giving an overall rank in the manner shown by Martin (1995). Then, the highest scores for use diversity ranking were considered as the most preferred use of *P. thonningii* to the local people, and the highest scores for threats were considered the most destructive threats to *P. thonningii*.

4.3. Results

4.3.1. Demographic Characteristics of Informants

A total of 84 (72 general and 12 key) informants were involved in the ethnobotanical study of *P. thonningii* and 6 individuals in each kebele participated in the focus group discussions for triangulation of the collected information. The proportions of male and female informants were equal in number (42, 50% each). All the interviewed informants were aged 18–78 years and classified into four age groups based on the perception/cognition of informants (Zeigler, 1978), demographic structure, and motivation of households (Pashardes, 2011; Mettler *et al.*, 2020). Fourteen percent were 18–30 years old, 35% were 31–45 years old, 45% were from 46 to 60 years old, and the remaining 6% were 61–78 years old. Respondents were from different educational backgrounds and classified following the Ethiopian education system 4-4-2-2 (grades 1 to 4, grades 5 to 8, grades 9 to 10, and grades 11 to 12). Eighty percent of the respondents were illiterate, 1% able to read and write, and the remaining 8% and 11% were from grades 1 to 4 and 5 to 8, respectively (Table16).

Table 16. Demographic characteristics of informants

Age groups	Gender				Educational status	Gender			
	Male	Female	Total	%		Male	Female	Total	%
18–30	7	5	12	14	Illiterate	30	37	67	80
31–45	16	13	29	35	Read and write	0	1	1	1
46–60	14	24	38	45	Grade 1 to 4	4	3	7	8
61–78	5	0	5	6	Grade 5 to 8	8	1	9	11
Total	42	42	84	100		42	42	84	100

4.3.2. The multiple uses of *P. thonningii*

The results of the study show that *P. thonningii* is a multipurpose tree used by local communities for various purposes. Based on the consensus points of the focus group discussions, *P. thonningii* is recognized for its contribution to people's livelihoods in many different ways. Both the Benna and Hamer ethnic groups use *P. thonningii* for multiple purposes. It provides various functions including economic and ecological functions such as the provision of shade, food, fodder, soil fertility, provision of firewood, medicine, rope (cordage), *Borketa* (traditional multipurpose material used as a stool and head support), construction of huts, beehives, fences, and preparation of farm implements. Almost all respondents of both districts widely expressed that they use *P. thonningii* for firewood and shade. About 92% of the respondents confirmed that they eat the seeds, 69% verified its use as fodder for livestock and 49% for making *Borketa* and other uses as indicated in Figure 15. The Hamer people predominantly use this species as a source of food (98%), fodder (83%), fence (36%), and for building huts (24%) as compared to the Benna ethnic group who reported using it predominantly for making *Borketa* (52%), rope (55%), chair (50%), timber (24%), beehives (26%), and farm implements (40%). All the uses of the species reported in the two districts are given in Figure 14. However, the use of *P. thonningii* for fuelwood (100%), shade (100/98%), soil fertility (29/26%), and axe handle (19/17%) were comparable between the two ethnic groups. Twenty-four percent of Benna respondents indicated that they use *P. thonningii* for timber while it is not known as a timber tree in Hamer. Two percent of Hamer respondents indicated that they use it to treat ailments, while the Benna respondents did not indicate any use of it for medicinal purposes.

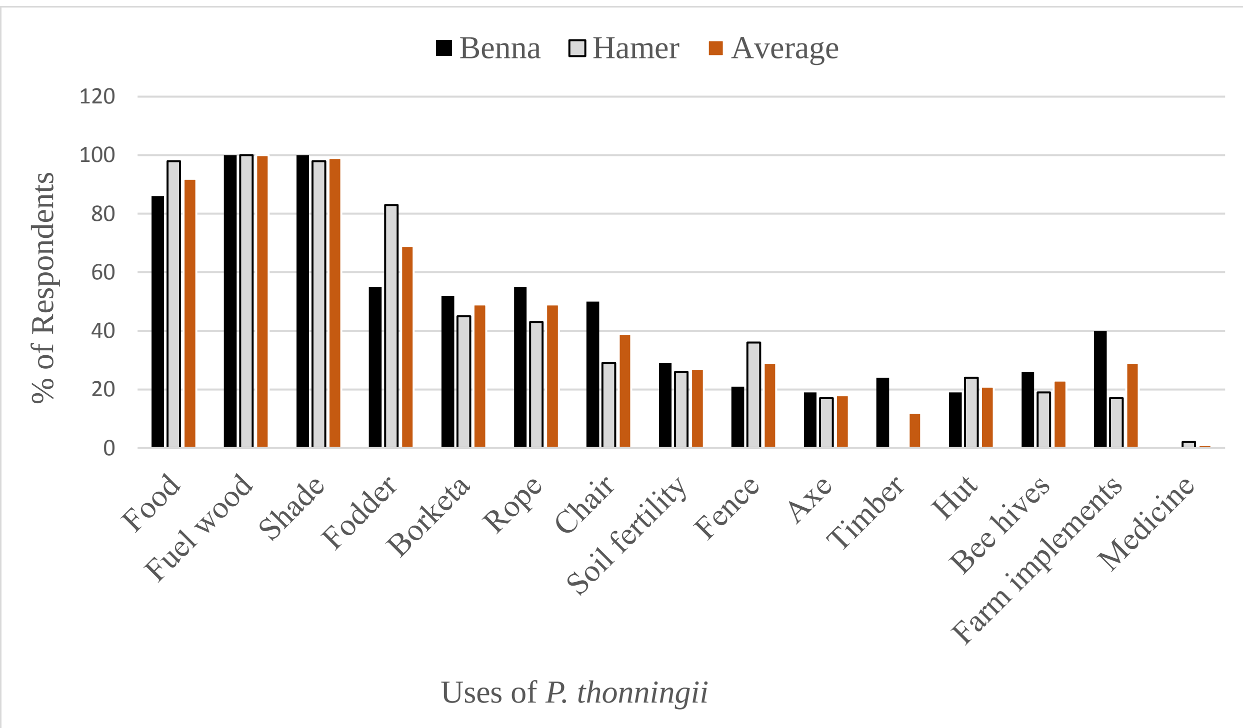


Figure 14. Percentage of informants' responses on the ethnobotanical uses of *P. thonningii* (n=84)

There is a significant relationship between the age of respondents and their ethnobotanical knowledge of *P. thonningii* (X^2 = 273.6, df = 42, $P < 0.0001$). Older age respondents know more about the uses of *P. thonningii* than younger age respondents. There is no significant (*P*

< 0.05) relationship between the ethnic groups, gender, wealth status, and educational level of the respondents regarding their knowledge of the uses of *P. thonningii*. The different use categories in each Kebele (Table 17) were analyzed using Pearson's chi-square test and the result shows that there is a significant association (P <0.05) between Kebeles in the ethnobotanical knowledge of use categories (X^2 = 107.4, df = 70, P < 0.003).

Table 17. The different use categories of *P. thonningii* in each Kebele

Kebele	Use categories														
	F	Fw	Sh	Fd	B	R	Ch	Sf	Fn	A	T	H	Bh	Fi	M
Kako	12	12	12	11	1	6	0	2	0	0	0	1	0	0	0
Goldiya	12	12	12	12	10	9	6	4	2	1	0	0	1	2	0
Cali	6	12	12	4	5	4	8	0	1	1	3	1	3	3	0
Dimeka zuriya	11	12	12	5	3	0	2	0	3	1	0	4	2	1	1
Eriya Umbule	12	12	12	12	9	6	2	3	1	0	0	0	0	0	0
Eriya Kayisa	12	12	11	12	4	5	2	2	5	0	0	0	0	0	0

NB: *F*= food, *Fw* =fuelwood, *Sh* =shade, *Fd* =fodder, *B* =Borketa, *R* =rope, *Ch* =chair, *Sf* =soil fertility, *Fn* =fence, *A* =axe, *T* =timber, *H* =hut, *Bh* =beehives, *Fi* =farm implement, *M* =medicine

The contribution of *P. thonningii* as a source of food

The majority of the respondents (98% of Hamer and 86% of Benna) indicated that they use *P. thonningii* as a source of food and consume the fruit during normal times and during periods of famine to ensure food security. The communities of the study area consum wild food plants as a coping mechanism for surviving during a famine period. Recurrent drought and shortage of food are serious problems for the agropastoral communities of the study area. In addition to household consumption, wild food plant provides an opportunity to supplement household incomes by selling edible fruits when there is a shortage of food. The fruit ripens from December to February depending on the availability of rainfall. When the brown pod cracks and the seeds shatter away, the pulp surrounding the seeds is eaten raw mainly by children as a snack or as emergency food (Figure 15).

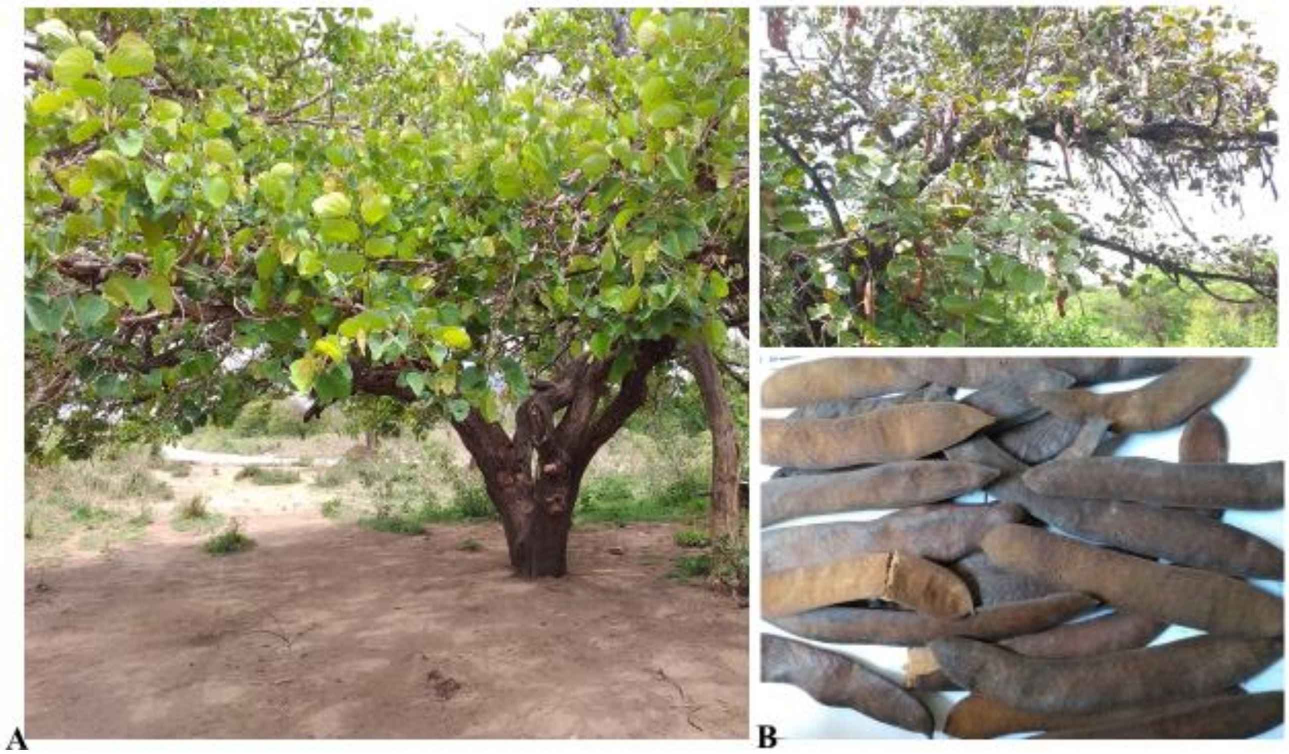


Figure 15. The whole tree of *P. thonningii* (A) and its ripened fruits (B)

Genders and age groups that collect/consume the fruits of *P. thonningii*

The edible part (fruit) is collected from the grazing lands and farmlands and consumed raw by all community members (children, adults, and elders) during normal times and times of famine. However, 89% of the respondents reported that children were involved in the collection and consumption of the fruit while only 67% of adults and 6% of elders collect and consume *P. thonningii* fruits. There is no difference in the collection/consumption of the fruit between gender of the same age groups.

Respondents from mid-high wealth status households replied that children were involved more in the collection and consumption of fruit than adults and elders. However, the low-wealth status households replied that there is no difference in the collection and consumption of the fruit among the different age groups of poor families. The chi-square test results of the different age groups and wealth classes of informants who were involved in the collection and consumption of the fruit shows that there is a significant ($X^2 = 5.063$, df = 1, $P < 0.024$) relationship among the respondents of low wealth status and mid-high wealth status respondents, indicating the former group consumes more. On the other hand, households in both wealth categories reported that there is no difference in the collection and consumption of fruit between adults and elders of both low and mid-high-wealth status households.

The Pearson's chi-square test results regarding the frequency of consumption practices of respondents showed that there is a significant ($P < 0.05$) association between ethnic groups ($X^2 = 8.87$, df = 2, $P < 0.012$), age ($X^2 = 13.67$, df = 6, $P < 0.034$), and wealth status ($X^2 = 11.33$, df = 2, $P < 0.003$), whereas gender and educational levels did not show significant association at $P < 0.05$. Members of the Hamer ethnic group have a strong attachment and hence consume the fruits of *P. thonningii* more than the Benna ethnic group and poor households consume more than rich households. However, there is no significant difference between the Kebeles in the frequency of the consumption of the fruit. The consumption of the fruits does not have a complex negative side effect, though 17% of the respondents reported that they experienced side effects, such as stomach aches, loss of appetite, and constipation, while 83% of the respondents did not complain of any side effect as a result of consumption of *P. thonningii* fruits.

The role of *P. thonningii* as a source of livestock feed

The use of *P. thonningii* as livestock feed is common in both (Benna-Tsemay and Hamer) communities. The majority of the respondents (83%) reported that they use *P. thonningii* as a source of feed for their livestock. However, some (17%) of the respondents replied that they do not use it as livestock feed. All of the respondents of both study areas reported that *P. thonningii* is used as a preferred livestock feed both during times of feed availability and during the dry season. The browsed parts of *P. thonningii* are mainly seeds, fruits (pod), and leaves, especially the shoot and young leaves are copiously consumed by animals. The majority of the respondents (83%) indicated that seeds and fruits (pods) are the most consumed parts than any other parts. However, 69% of the respondents replied that leaves are also consumed by livestock (cattle, goats, and sheep). Small branches are also lopped as dry-season fodder for goats and the branches are used to reinforce fences.

Respondents of both districts reported that different livestock types (cattle, goats, and sheep) consume the parts of *P. thonningii*. The consumption of *P. thonningii* by cattle, goats, and sheep depends on the availability of feeds. The majority of respondents reported that it is preferred and consumed by cattle (83%) and goats (80%), and few respondents replied that it is consumed by sheep (15%).

Agricultural Uses of *P. thonningii*

Piliostigma thonningii is used as an agroforestry tree to improve agricultural productivity. Almost all of the respondents (100% of Benna and 97% of Hamer) reported that they use the species as a shade tree for their crops and animals and 17% of Benna and 14% of Hamer respondents reported that soil under and near *P. thonningii* is moist and fertile. They also use the tree for making farm implements; 40% of Benna and 17% of Hamer ethnic groups reported that they use the species to make different farm materials. Respondents explained why they prefer to cultivate crops under *P. thonningii* where 88% of the respondents reported that they cultivate crops near/under *P. thonningii* by saying that it controls the temperature and keeps the soil moist, 74% of the respondents reported that it provides good shade for their crops and animals, and the other 29% of the respondents reported that it makes the soil fertile.

During the field survey, the researcher observed and recorded different herbaceous and woody plant species growing under/near (up to 1 m radius outside the tree canopy) *P. thonningii* trees that added to 29 species distributed in 18 families. The woody species constituted 69% (45% shrub, 24% tree species), herbs constituted about 20%, and climbers constituted 10%. Further analysis of the data showed that 7 (25%) species belong to the family Fabaceae, two species each to Anacardiaceae, Euphorbiaceae, Rubiaceae, Rutaceae, and Tiliaceae, and a single species each in the remaining 12 families (Appendix 6). Many of the characteristics of *P. thonningii* showed that it is an ideal agroforestry tree.

The results of the study further showed that members of the local community cultivated different crops near/under *P. thonnongii* including maize (*Zea mays*), sorghum (*Sorghum bicolor*), cowpea (*Vigna unguiculata*), Teff (*Eragrostis tef*), pigeon pea (*Cajanus cajan*), finger millet (*Eluesine coracana*), cabbage (*Brassica* spp.), groundnut (*Arachys hypogea*), potato (*Solanum tuberosum*), tomato (*Lycopersicon esculenta*), pepper (*Capsicum annuum*), and onion (*Allium cepa*). The responses of the majority of the respondents showed that the crops most abundantly and commonly cultivated under/near *P. thonningii* are maize (95%), sorghum (94%), and cowpea (45%) (Figure 16).

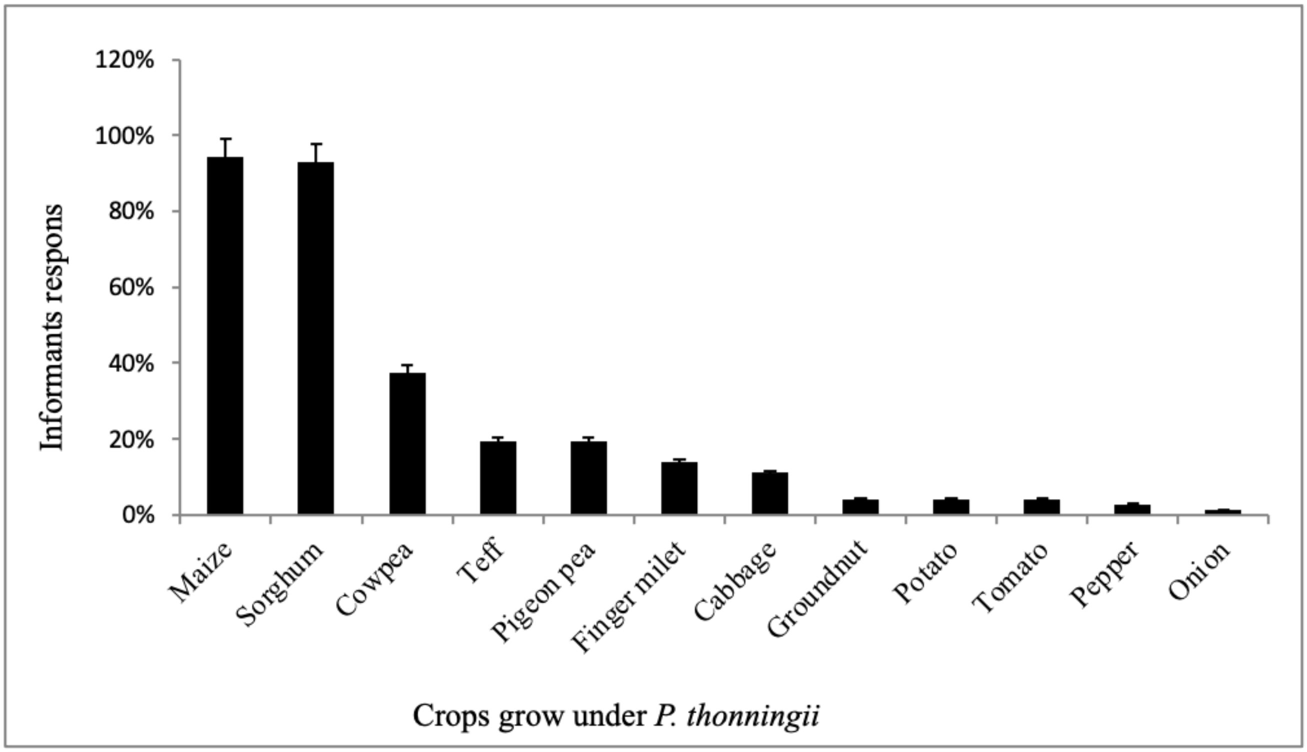


Figure 16. Percentage of farmers' response on the type of crops grown under/near *P. thonningii* in Benna-Tsemay and Hamer districts.

The role of *P. thonningii* as a source of fuel and other uses

The results of the study show that *P. thonningii* is used as a source of fuel, household materials, and other uses. The woody part of the plant is used as a source of firewood, for making *Borketa*, huts, beehives, chairs, fences, axe handles, and timber. Regarding firewood collection, all (100%) of the respondents from both districts agreed that they use wood as a source of fuel, 49% of the respondents reported that wood is used for making household materials such as *Borketa*, a traditional multipurpose material used as a stool and head support (the structure of *Borketa* is found in dryad data repository); 39% for chair; 29% for fencing; 23% for making beehives; 21% for making huts; 29% for farm materials; 18% for axe; and 12% for timber. About 49% of the respondents reported that the inner layer of the bark is used to make rope and 1% of the respondents reported that the bark is used as traditional medicine for the treatment of liver disease through fumigation.

The results of direct matrix ranking, which was carried out to evaluate the multipurpose uses of *P. thonningii* and their relative importance to the local people, showed that fodder, food, and firewood ranked in the 1st, 2nd, and 3rd places respectively. The remaining uses of *P.*

thonningii as a shade tree, agricultural value, fencing, making household and farm materials, beehives, and medicine take the ranks from 4 to 9 respectively (Table 18). This shows that the local people use *P. thonningii* mainly for fodder, food, and fuelwood; however, they also use it for different purposes, indicating that it is a multipurpose tree.

Table 18. Direct matrix ranking of the use preferences of *P. thonningii* by 12 key informants

Uses	Key informants													
	K1	K2	C1	C2	G1	G2	D1	D2	U1	U2	Ky1	Ky2	Total	Rank
Food	4	3	3	3	4	4	3	3	4	3	4	4	42	2
Shade	3	3	2	2	3	3	2	3	3	3	3	2	35	4
Fodder	4	4	4	4	5	4	4	3	5	4	5	4	50	1
Firewood	3	3	2	4	3	4	3	3	3	4	3	4	39	3
Agriculture	2	2	3	3	2	3	3	1	2	2	2	0	25	5
Beehives	1	0	2	0	2	1	0	0	2	0	2	0	10	8
Fencing	3	2	0	2	1	2	1	2	2	3	3	2	23	6
Medicine	0	0	3	0	0	0	0	0	0	2	0	0	5	9
Household and farm materials	1	2	2	1	0	1	2	1	2	1	2	2	17	7
Total score	21	19	21	19	20	22	18	16	23	22	24	18	246	
Kebele average		20		20		21		17		22.5		21		

NB: *K* =Kako, *C* =Cali, *G* =Goldiya, *D* =Dimeka zuriya, *U* =Eriya Umbule, *Ky* =Eriya Kayisa

4.3.3. The status of *P. thonningii* in the study area

All respondents from Benna and 45% of the respondents from the Hamer District reported that the abundance of *P. thonningii* has decreased while the other 45% of respondents from the Hamer District replied there is no difference in abundance as observed over time and while a minority (10%) of the respondents from Hamer District felt that the abundance of *P. thonningii* has increased in the past 10 years (Figure 17).

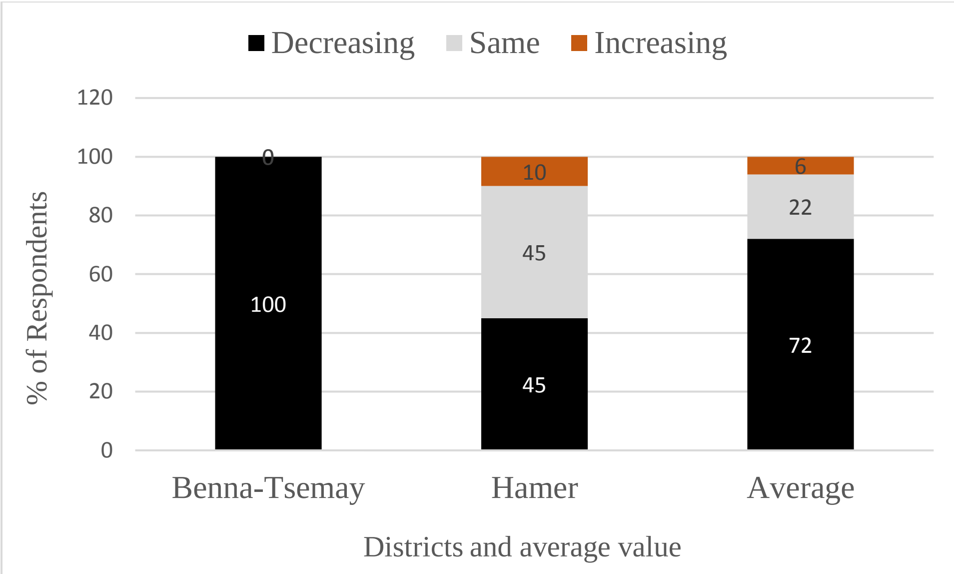


Figure 17. Informant's response on the status of *P. thonningii* in the study area

4.3.4. Threats to the sustainability of *P. thonningii*

All respondents of Benna and the slight majority (55%) in Hamer reported that the sustainability of *P. thonningii is* threatened by some unfavorable factors. However, 45% of Hamer respondents replied that there are no threats to the sustainability of *P. thonningii*. According to the information from respondents and participants of the focus group discussion, the main threatening factors to *P. thonningii* are agricultural expansion, firewood collection, overgrazing, harvesting for construction of fences, use for farm and household materials, and charcoal production. Based on this information, the degree of destructive effects of these threats was analyzed using pair-wise ranking. The results suggested that agricultural expansion, firewood collection, fencing, overgrazing, making household and farm materials, and charcoal production are the major factors threatening the continuity of *P. thonningii* in the two districts. Agricultural expansion and firewood collection ranked in the 1st and 2nd places, respectively, indicating that they are the most proximate threatening factors (Table 19).

Table 19. Results of a pair-wise ranking of factors considered threats to *P. thonningii* and their degrees of destructive effects

Threatening factors	Respondents of each Kebele													
	K1	K2	C1	C2	G1	G2	D1	D2	U1	U2	Ky1	Ky2	Total	Rank
Firewood	4	4	4	4	5	4	4	4	5	5	4	5	52	2
Agricultural expansion	5	5	5	5	4	5	4	5	4	4	5	4	55	1
Overgrazing	2	2	3	1	3	2	1	2	2	2	2	3	25	4
Fencing	3	2	2	3	2	3	2	3	3	1	3	2	29	3
Household and Farm materials	1	1	1	2	2	1	0	1	1	2	2	1	15	5
Charcoal	0	0	1	0	1	1	1	0	0	0	0	0	4	6

NB: K = Kako, *C* = Cali, *G* = Goldiya, *D* = Dimeka zuriya, *U* = Eriya Umbule, *Ky* = Eriya Kayisa

4.3.5. Traditional management practices and the attitudes of respondents to maintain and conserve *P. thonningii*

Respondents' perceptions about the management and conservation practices of *P. thonningii* showed that 89% of the low-wealth status and 25% of those mid-high-wealth status responded that they do not have awareness and interest in managing and conserving *P. thonningii*. However, 11% of the low-wealth status and 75% of mid-high-wealth status respondents expressed that they are interested and willing to maintain and conserve the species. Over half of the male respondents (58%) and 28% of female respondents replied that they are interested in maintaining a good cover of *P. thonningii* but 72% of female and 42% of male respondents were not interested and lacked the willingness to manage and conserve. The educational level also affects the perception and willingness to manage and conserve. Most of the respondents had formal education, grades 5 to 8 (89%), and 36% of the illiterate respondents expressed their interest in maintaining and conserving *P. thonningii* but 64% of the illiterates, all of those who can only read and write, and 11% of those who had a formal education level of grades 5 to 8 do not show an interest to maintain and conserve *P. thonningii* (Fig. 18).

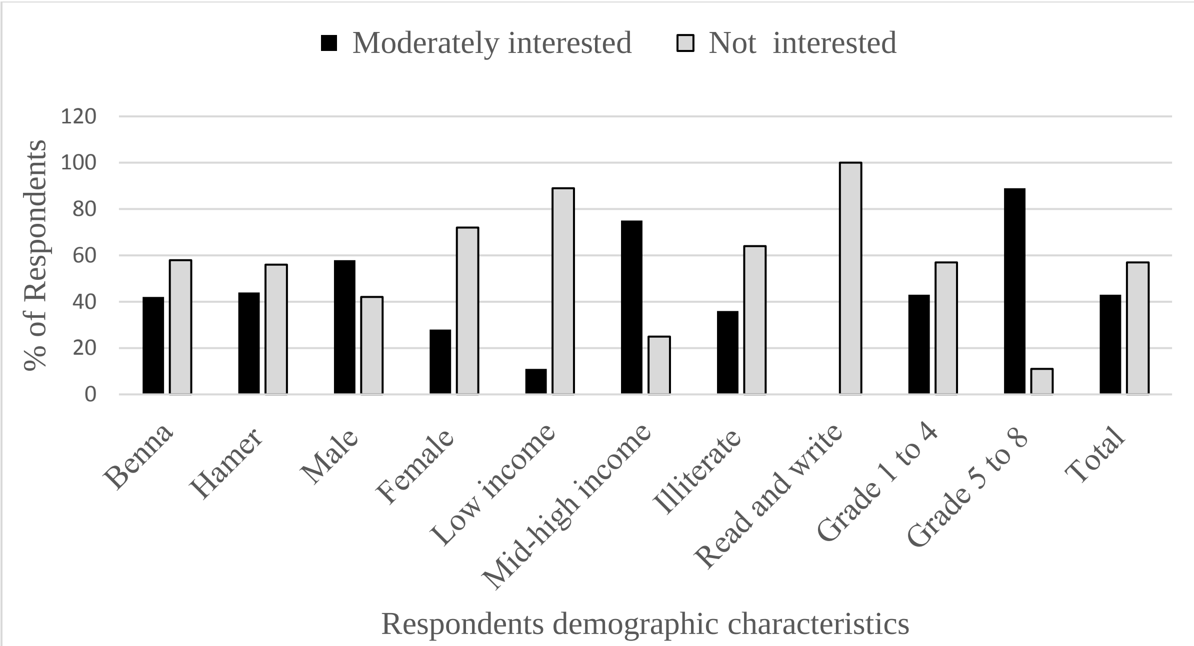


Figure 18. The attitude of respondent's to maintain and conserve *P. thonningii*

The Pearson's chi-square test results on the perception and attitude of respondents to maintain and conserve *P. thonningii* shows that there is a significant association between gender (X^2 = 18.36, df = 1, $P < 0.0001$), wealth status (X^2 = 83.56, df = 1, $P < 0.0001$), and educational level (X^2 = 71.17, df = 3, $P < 0.0002$) of respondents. However, there is no statistically significant ($P < 0.05$) association between the different age and ethnic groups regarding their perception and attitude towards the maintaining and conserving of *P. thonningii*. This indicates that men, mid-high wealth status households, and educated people are more knowledgeable and have the willingness to maintain and conserve *P. thonningii* than women, low wealth status households, and uneducated community members. The statistical analysis result shows that there is no significant difference between kebeles towards the maintenance and conservation of *P. thonningii*. They manage and conserve the species in their farms and homesteads by avoiding cutting and protecting them from livestock damage.

4.4. Discussion

4.4.1. The multiple uses of *P. thonningii*

The results indicated a strong relationship between the local communities and *P. thonningii* in that the species provides several economic and ecosystem functions in the study area so much that it has become an integral part of the local culture. This shows that there is an intrinsic relationship between humans and their environment and between knowledge about plants and their uses. In this regard, Martin (1995), Kacholi (2014), and Amjad and Arshad (2014) describe the relationship between plants, people, and the environment and the knowledge of local communities about the uses of plants as a source of food, medicine, fuelwood, timber, fodder, shade, poles, and habitats for other organisms. Similarly, Demel Teketay *et al.* (2010) describe the indirect benefits of wild edible plants such as sources of genetic diversity; encouragement of agroforestry practice in dryland areas; habitat for different organisms; rehabilitation of degraded lands; and soil and water conservation as well as mitigation and adaptation to climate change.

The ethnobotanical knowledge of respondents about *P. thonningii* among the two ethnic groups within and between the different wealth statuses, gender, and educational levels is similar. This indicated that the transfer of indigenous knowledge on the uses of *P. thonningii* within the community is not differentiated by wealth status, gender, and level of education because of the co-existence and similarity of their cultural practices and the pastoralist mode of life. This finding is in line with that of Tesfaye Awas *et al.* (2010) the ethnobotanical knowledge of Berta and Gumuz people of western Ethiopia equated with the age and educational level. The relationship in the knowledge of respondents on the uses of *P. thonningii* among the different age groups showed that older members of the communities were more knowledgeable on the uses of *P. thonningii* as compared to the younger members of the communities. The relationship in the ethnobotanical use of *P. thonningii* between Kebeles is associated with the lifestyle of the households, food insecurity, availability of infrastructure, and distance of the Kebeles from the town. For example, concerning food and timber, Cali Kebele was different from others because the majority of the people of Cali were involved in crop cultivation other than using wild plants. In the use as fodder, Cali and Dimeka Zuriya Kebeles were different from other Kebeles because these Kebeles are relatively near the town and involved in agriculture crop production and use crop residue for their livestock feed. In agreement with this, Bortolotto *et al.* (2015) describe that proximity to urban centers reduces the use of wild plants for various purposes. The Kebeles Goldiya and Eriya Umbule use the tree for making *Borketa* more than the other Kebeles because the majority of the communities were pastoralists, they move from place to place to find animal feed during drought and use the material as a stool and head support.

Contribution of *P. thonningii* as a source of food

A study by Tilahun Teklehaymanot (2017) shows that people in semi-arid and arid areas rely more on wild edible plants as compared to people in humid and highland regions. This study was conducted in the arid and semi-arid areas of southern Ethiopia where there are harsh environmental conditions. In arid and semi-arid environments drought has a dominant effect on agricultural food production and livestock productivity. In most arid environments, the role of wild edible plants as food security agents has been reported by different authors (Guinand & Lemessa Dechassa, 2001; Gemedo Dalle *et al.*, 2005; Tilahun Teklehaymanot & Mirutse Giday, 2010; Assegid Assefa & Tesfaye Abebe, 2011; Getu Alemayehu *et al.*, 2015). The results of the present study showed that the communities of the South Omo Zone consume *P. thonnngii* as a supplement to staple foods and to fill a variety of food gaps besides fighting food insecurity during the period of drought. Similar studies byGuinand and Lemessa Dechassa (2001), Admasu Terefe *et al.* (2010), Getachew Addis *et al.* (2013), and Leul Kidane and Alemu Kejela (2021) indicated that the collection of wild foods is used as coping mechanisms to climate variability and food insecurity. A higher use of wild foods has been linked with greater food security (Pawera *et al.*, 2020). Thus, wild edible plants served as "buffer food" as they had rescued people during floods, drought, and major famines. In agreement with this, the findings of Denbela Hidosa *et al.* (2015) and Tilahun Teklehaymanot (2017) indicated that people in semi-arid and arid regions of the Oromia and Afar regions survive times of severe hunger by consuming wild edible plants. The fact that the fruit is the edible part of *P. thonningii* and consumed raw has an added advantage as an emergency quick-fix facility at critical moments in the daily and annual cycles. This also goes along with the general finding in Ethiopia that the fruit is the dominant part of wild edible plants (Zemede Asfaw & Mesfin Tadesse, 2001; Kebu Balemie & Fassil Kebebew, 2006; Tilahun Teklehaymanot & Mirutse Giday, 2010; Ermias Lulekal *et al.*, 2011; Getachew Addis *et al.*, 2013).

Piliostigma thonningii is relevant to household food security to supplement the staple food in normal times, to fill seasonal food shortages, and to fight poor micronutrient intake or otherwise called hidden hanger (Reta Regassa, 2013). Similar studies in Africa show that the fruit and seeds of *P. thonningii* are nutritious and contain the primary metabolites like protein, starch, fat, and lignin (Jimoh & Oladiji, 2005; Egharevba & Kunle, 2010; Deshi *et al.*, 2014;

Jemiseye *et al.*, 2019). As reported by Poulton and Poole (2001), and Adhikari *et al.* (2016), wild edible plants are nutritionally rich and supply vitamins and micronutrients. In addition to improving food security, the consumption of fruits from trees improves blood circulation, prevents diabetes, and reduces obesity, cancer, and chances of being affected by heart diseases (Jeambey *et al.*, 2009). The finding on raw consumption of the fruits of *P. thonningii* equates to the work of Guinand and Lemessa Dechassa (2001), Kebu Balemie and Fassil Kebebew (2006), Tilahun Teklehaymanot (2017) and Tatek Dejene *et al.* (2020), indicating fruits of most wild edible trees are consumed raw, not cooked or preserved, suggesting that the fruit is not toxic.

The difference in ethnic background, age, and wealth status of the community has affected the pattern of collection and consumption of the fruit. The mid-high wealth status families tend to see the consumption of the fruit of *P. thonningii* as a sign of poverty, but poor families collect and consume the fruit to mitigate the risks of hunger and make it an important part of their daily dietary intake. In agreement with this, Poulton and Poole (2001) reported that wild edible plants make many contributions to poor people's livelihoods and most of the disadvantaged and vulnerable peoples of the society mitigate risks using wild food plants. However, in the study area when there is a serious shortage of food affecting both the poor and rich families, all are involved in the collection and consumption of the fruit as explained by informants.

According to mid-high wealth status respondents, children are the main participants in the collection and consumption of the fruit than adults and elders. This is because children can climb up to a tree, collect fruit while tending cattle in the grazing fields, fetch water, collect firewood, or walk to the fields. On the other hand, adult members of the community mostly spent their time on other daily activities like farming, the market, and other social activities. Moreover, elder members of the communities spend most of their time at home and do not have a chance to get and collect the fruit. However, during food shortages adults and even elder members of the community are involved in the collection and consumption of the fruit. In agreement with this, the findings of Guinand and Lemessa Dechassa (2001) and Tilahun Teklehaymanot and Mirutse Giday (2010) indicated that adults and elders collect and consume the fruit from the wild and over 70% of the wild edible plants were consumed during times of food scarcity and starvation. In normal times, mainly children and poor families were involved in the collection and consumption of the fruit. This goes in line with the response of low-wealth status households who stated that there is no difference in the collection and consumption of the fruit among the different age groups of poor families.

The consumption of the fruit is sometimes accompanied by some complaints. A few respondents (17%) reported that excessive consumption of the fruit causes stomach aches, loss of appetite, and constipation and induces thirst. Other than minor complaints and discomforts, *P. thonningii* seeds or other parts of the plant did not cause serious side effects to the majority of the respondents (83%) even when consumed uncooked. This may be related to the assertion by Nwosu *et al.* (2016) that the level of dietary fiber of *P. thonningii* is quite high when compared with that of most legumes and seeds. Dietary fiber plays an important role in reducing the risk and lowering the incidence of numerous diseases (Maćkowiak *et al.*, 2016). It prevents constipation and provides other health benefits, such as maintaining a healthy weight and lowering the risk of diabetes, heart disease, and some types of cancer. This indicates fiber-rich food is suitable for health and the local people know the importance and contribution of wild fruits to their daily dietary ratio as well as alleviating possible health problems such as stomach irritation, stomach aches, and constipation.

The role of *P. thonningii* as a source of animal feed

The majority of the respondents (81% of Hamer and 75% of Benna-Tsemay Districts) replied that the seeds, fruit (pod), and leaves of *P. thonningii are* consumed by different livestock types. It is an important fodder tree in the study area with the leaves, pods, and seeds being nutritious and preferred by cattle, goats, and sheep. It is browsed directly from the tree or lopped/cut fresh during feeding. The edible parts provide valuable livestock feed under open grazing conditions. This is especially important during the dry season when grazing resources are limited. The use of the parts of *P. thonningii* as livestock feed has been reported in different studies such as Guinand and Lemessa Dechassa (2001), Takele Geta *et al.* (2014), and Almaz Ayenew (2019). In agreement with this study, the findings of Jimoh and Oladiji (2005), Azene Bekele & Tengnäs (2007), Orwa *et al.* (2009), Egharevba & Kunle (2010), Chidumayo (2018) and Jemiseye *et al.* (2019) revealed that the pods are nutritious and preferred by domestic animals such as cattle and browser wild animal species such as the African elephant and antelopes.

The *P. thonningii* leaf meal has a high crude protein content (20.5%) (Nwosu *et al.*, 2016), as compared to other browse trees (like finger millet straw) indicating the potential of this tree leaf to be used as a supplement to improve poor quality feed. In the study area, livestock prefers the young leaf over the matured one in agreement with Nwosu *et al.* (2016) who reported that higher crude protein content of *P. thonningii* at the early stage of the leaf than the mature leaf. A similar study on the use of multipurpose fodder trees by Takele Geta *et al.* (2014) indicated that *P. thonningii* leaves are nutritious and improve poor-quality roughage, and are important for livestock production in promoting health, growth, and milk production. The proper use and management of *P. thonningii* is, therefore, essential to realize these potentials.

Agricultural uses of *P. thonningii*

Integrating *P. thonningii* into the agricultural field and grazing land plays an important role in achieving household food security and in the conservation of other plants. *P. thonningii* allows good production of crops and creates a suitable microclimate for other plants growing under or near the canopy. The findings of Chidumayo (2018) indicated that it is a promising agroforestry tree in sub-Saharan Africa. It is a deciduous tree that undergoes a physiological dormancy and sheds its nitrogen-rich leaves during the dry season, to cope with moisture deficiency. The litter from the shed leaves improves the soil structure and permeability while the retained leaves in the dry season provide shade to conserve the available soil moisture by reducing the evapotranspiration under the tree. The findings of Wood and Burley (1991) and, Chidumayo (2018), which are in agreement with this study, show the role of *P. thonningii* as an excellent shade tree that helps in retaining soil moisture and nutrients. Thus, plants under *P. thonningii* remain green for a longer period in the dry season providing grazing material for both wild and domestic animals. A study by Zerihun Woldu *et al.* (1999) shows the role of canopy trees like *Acacia tortilis* and *Acacia senegal* in promoting better growth and productivity of agricultural crops and herbaceous species growing under their canopy by creating favorable conditions for the soil nutrients and moisture.

The role of *P. thonningii* as a source of fuel and other uses

The use of *P. thonningii* as a source of fuelwood, for construction (making huts), for making household equipment (*Borketa*, chair, and axe handles), fences, beehives, and timber are widely experienced. In agreement with this, Thulin *et al.* (1989), Azene Bekele and Tengnäs (2007), Orwa *et al.* (2009), and Chidumayo (2018) reported the suitability of *P. thonningii* as a source of fuelwood, poles, charcoal, carpentry, construction, to make a household material and farm implements. The utilization of this tree is linked with the daily life activities of the local communities of the study area. In the study area, firewood is the most preferred and affordable domestic fuel for cooking and heating for both rural and urban communities. In agreement with this study, the findings of Zenebe Gebreegziabher (2007) and Eastaugh *et al.* (2010), showed the importance of multi-purpose woody species to increase the supply of fuelwood for rural household consumption and 80% of rural households use fuelwood as their primary energy source. Similarly in southwestern Ethiopia, fuelwood is the main energy source for the majority of the people (Berhanu Niguse *et al.*, 2017). Zenebe Gebreegziabher (2007), and Alemu Mekonnen and Köhlin (2009) reported that more than 90% of households in Ethiopia use biomass fuels (fuelwood, animal dung, and agricultural residues) especially fuelwood as their primary energy source to meet their cooking and heating needs and more (99.9%) rural households rely on biomass fuels than those in urban areas.

The results of the study showed that 49% of the respondents reported that the inner part of the stem bark is suitable for making ropes. In the study area, ropes are used for tying the roof of the huts and to make whips for herding goats and cattle. Similarly, Thulin *et al.* (1989), and Egharevba and Kunle (2010) confirmed the use of the inner bark to make ropes/cordage. Unsustainable use for making ropes and some other functions becomes destructive to the species. Therefore, it is necessary to use it sustainably without killing the parent tree.

Few respondents (1%) reported the use of *P. thonningii* for traditional medicinal uses for the treatment of liver disease through fumigation; similarly, a study by Berhane Kidane *et al.* (2014) shows that the leaf of *P. thonningii* is used for the treatment of similar diseases. Inversely, a study by Awhin *et al.* (2013) shows that chronic/habitual/recurring consumption of *P. thonningii* may cause liver injury thereby increasing liver enzyme activity. There is no information regarding its medicinal use in other parts of Ethiopia; therefore, there is a need for more research on the medicinal uses of *P. thonningii*. The plant is not extensively used for medicinal purposes presumably because there are other medicinal plants more potent than *P. thonningii* preferred by the people of the study area. However, in different African countries (such as Nigeria, and Kenya), it is used as a traditional medicine. The different parts (flowers, bark, fruits, roots, leaves, and stems) are used elsewhere to treat various diseases (Jimoh & Oladiji, 2005; Orwa *et al.*, 2009; Egharevba & Kunle, 2010; Ukwuani *et al.*, 2012; Baldé *et al.*, 2016; Nwosu *et al.*, 2016; Dluya & Dahiru, 2018; Jemiseye *et al.*, 2019; Usman, 2019). It is important to document and share the experience with other people elsewhere about the medicinal uses of *P. thonningii* in case they are not aware of it.

4.4.2. The status of *P. thonningii* in the study area

The abundance of *P. thonningii* is decreasing (72.6%) mainly due to the expansion of agricultural land, firewood collection, overgrazing, and harvesting wood for the construction of fences and charcoal production, while the others (22.6%) reported that there is no change in the status because before 10 years the local community used to set bushfire to enhance the re-sprouting of pasture grasses and to control animal exo-parasites (tsetse fly and ticks). Currently, setting bushfires intentionally or inadvertently is prohibited which promotes the reestablishment of woody species while the expansion of agricultural land decimates the tree cover. The effects of the two opposite processes cancel each other and the status of *P. thoningii* appears to remain unchanged. However, 4.76% of the respondents indicated that the status is increasing due to the prohibition of fire setting. After fire setting, there is an increase in the species richness of all plants (Reilly *et al.*, 2006). Burkle *et al.* (2015) reported that local species richness of forbs was higher in burned landscapes compared to unburned landscapes at the low-productivity site, but lower in burned landscapes at the high-productivity site. The researcher field observation from 2018 to 2020 confirmed that there is a decrease in the status of *P. thonningii* because of the destruction of the habitats. Many of the woodland and grazing lands were converted to agricultural land; in some areas, there is still illegal bushfire to acquire more agricultural land and the awareness of the local community to the conservation of natural resources is limited.

4.4.3. Threatening factors to *P. thonningii*

Piliostigma thonningii faces different threats to its continued existence from various human activities. Agricultural expansion, firewood collection, and harvesting for fencing were found to be the most threatening factors. Agricultural expansion is a major threat because nowadays the community of the study area is changing from a pastoral to an agropastoral way of life and the population is increasing. The suitable habitats for the growth of *P. thonningii* are increasingly threatened by the continued conversion of woodland and grazing land into farmlands. A study by Assegid Assefa and Tesfaye Abebe (2011) showed that the community of the South Omo Zone is changing from a pastoral to an agropastoral way of life. In agreement with this study, FAO (2017) showed the major cause of deforestation in Ethiopia resulted from the conversion of forested land into agricultural land and other land-use systems. During the field observation and group discussion, it was observed that the agricultural development workers and local administrators pushed the pastoral community to be involved in agriculture without selecting appropriate land suitable for agriculture and without consideration of the agroforestry system. In addition, both rural and urban households use firewood predominantly as a domestic fuel including *P. thonningii*. Multi-purpose woody species increase the supply of fuelwood for rural household families (Zenebe Gebreegziabher, 2007).

4.4.4. Traditional management practices and attitude of respondents to maintain and conserve *P. thonningii*

The attitude and interest of respondents to maintain and conserve *P. thonningii* are different among gender, wealth status, and educational levels. Respondents from mid-high wealth status, men, and educated members of the community practice some activities to manage and conserve *P. thonningii* that grow in their farms and homesteads by avoiding cutting and protecting it from livestock damage but there is no direct planting and protection of *P. thonningii* found in their communal land (grazing and woodland). Personal observation also confirmed that *P. thonningii* grows in farmlands, farm boundaries, watershed areas, and homesteads as live fence and shade. This tradition is a good implication of indigenous management strategies for the conservation and management of this species. A study by Cao *et al.* (2020) and Mulugeta Kebebew and Gemechu Leta (2016) describes the importance of introducing the preferred wild plants into farmlands and home gardens for the conservation of biodiversity and mitigation of climate change. However, respondents from low-wealth status have limited or are not interested in maintaining and conserving the species, because most of the low-wealth status respondents do not have their own land or have a parcel of their own land. They are using borrowed land, and in such borrowed land, they are not allowed by the owner of the land to plant perennial plants. Therefore, low-wealth status households do not have planting experiences at all, but not only that they lack the willingness to manage and conserve. Similarly to this, Almaz Ayenew (2019) indicates the very low farmers practice in planting and managing the tree. They are constrained by the priority to ensure basic food self-sufficiency in their allocated land and give prior satisfaction to their needs to produce staple food. A similar finding by Poulton and Poole (2001) shows poor households lack lands for the cultivation of wild edible fruits and they focus on the cultivation of crops that help them to ensure their basic food requirement on their lands. The other difficulty is the low market values of wild fruits when compared to cultivated fruits, which discourages the growth of fruit by poor households. This information shows that, as the wealth status increases the attitude of respondents to manage and conserve also increases.

The level of education affects the attitude and interest of respondents to maintain and conserve *P. thonningii*. As the education level increases, the knowledge and attitude to manage and conserve also increases, indicating that educated communities have more knowledge and willingness to maintain, conserve, and plant trees. On the other side, men have more interest in maintaining, conserving, and planting *P. thonningii* than women. In this regard, in the study area, men control and manage the land and participate in tree planting than women; this restricts female participation in planting. As indicated by Gandile *et al.* (2017), the most notable biodiversity conservation practice was the protection of forests using indigenous knowledge. Therefore, it is necessary to incorporate economic and cultural importance in biodiversity assessments and conservation measures, involving local resource users and all stakeholders from different sectors to maintain and conserve the species. The ecological knowledge held by local and indigenous users must be recognized and fully incorporated into management and conservation plans. In agreement with this, Carvalho and Frazão-Moreira (2011) describe the importance of local knowledge in plant resources management and conservation.

Conclusion and recommendations

This study attempted to provide information on the multiple uses of *P. thonningii* besides documenting the traditional knowledge of the local community. In the study area, the pastoral and agropastoral communities use *P. thonningii* for various purposes. There is a good transfer of local traditional knowledge between the communities on the uses of *P. thonningii*. However, it was observed that there is knowledge gap through generations indicating that the youth are less knowledgeable about the uses of *P. thonningii*. Therefore, documentation of the traditional knowledge of the local communities on the uses of *P. thonningii* in the present study area and other parts of the country is very valuable and needs to be scaled-up.

P. thonningii contributes to the nutritional intake of the local communities and helps to ensure food security during times of seasonal food shortage. Therefore, consideration should be given to *P. thonningii* when strategies are developed to fight food insecurity and to improve rural livelihood systems. It is an excellent fodder tree, used by the pastoral and agro-pastoral communities of the study area to feed their livestock under open grazing conditions. It improves the nutritional content of poor feed quality and the survival and productivity of livestock. It is also used as an excellent agroforestry tree to improve soil fertility, moisture retention capacity, and maintain soil structure in addition to provision of human food, livestock feed, and other related uses. The local communities also use it for different purposes, such as the source of fuelwood, for the construction of huts, making beehives, and household utensils (*Borketas*, chairs, and axe handles). Therefore, it is necessary to integrate it into the agroforestry systems and home-garden practices. *P. thonningii* is less known for its medicinal use as compared to other African countries. Therefore, it is necessary to undergo more research on its traditional medicinal value.

The results also showed that the status of *P. thonningii* is decreasing because of the pressures from various anthropogenic factors. The main threatening factors are agricultural expansion, firewood collection, harvesting for fencing, and overgrazing. Thus, there is a need to create public awareness and community-based management. Therefore, it is important to promote *P. thonningii* as a valuable tree to improve household food security, agricultural productivity, and income source of the local communities.

CHAPTER Fve

5. GENERAL DISCUSSION, CONCLUSION AND RECOMMENDATIONS

5.1. Floristic Composition

The floristic composition of the vegetation of Sida Forest has a high diversity of plant species, with the presence of 254 plant species and endemism 9 (3.5%). New (58 species) species to the Gamo Gofa Floristic Region of the Flora of Ethiopia and Eritrea was recorded. This finding follow the facts that the flora of Ethiopia is highly diverse, ranking the country the fifth floral-rich country in tropical Africa (EBI, 2014; Ensermu Kelbessa & Sebsebe Demissew, 2014).

The topographic heterogeneity and elevation range account for species distribution patterns and variations in species composition (Zerihun Woldu *et al.*, 1999; Husen *et al.*, 2012; Abyot Dibaba *et al.*, 2014). Thus, the topographic heterogeneity and differences in elevation range (1505-2410 masl.) of the study forest create microhabitats within a short distance, and intermediate level of disturbance may promote an increase in species richness and endemism. Endemism is linked to environmental heterogeneity, which creates complex topography and diverse local habitats that provide micro-habitats for the species (Mengesha Asefa *et al.*, 2020). As reported by Sebsebe Demissew *et al.* (2021) the vegetation of the study area (southern and south-west Ethiopia) has the highest diversity of plant species and is rich in endemics. The maximum species richness in Ethiopia was found in the elevation between 1400 and 2500 masl., which is a 'mid-elevation diversity' (Vetaas and Grytnes, 2002; Sebsebe Demissew *et al.*, 2021).

The species diversity of the Sida Forest is more associated with the richness of shrub species. Studies in other forests of Ethiopia showed that the dominance of shrubs has been evident where habitat fragmentation due to human encroachment is identified as a major threat (Belachew Bogale *et al.*, 2022). Anthropogenic disturbances contributed to the increase of shrubs and herbs in the understory (Zhang *et al.*, 2016), low rainfall and high temperature correlated to high shrub richness in a forest (Moreno-Fernández *et al.*, 2021).

The family Fabaceae is found to be the dominant family in Sida Forest, which is commonly true for tropical lowland forests. Studies by Ensermu Kelbessa and Sebsebe Demissew (2014) and Kacholi (2019) indicated that Fabaceae is the dominant family in lowland tropical forests. Similar studies in other forests of Ethiopia showed that Fabaceae is the dominant family (Bhattacharyya *et al.* (2008); Motuma Didita *et al.*, 2010; Abyot Dibaba *et al.*, 2014; Temesgen Mekonen *et al.*, 2015; Abiyot Tadesse *et al.*, 2018; Mehari Girmay *et al.*, 2020; Getahun Yemata & Genetu

Haregewoien, 2022; Temesgen Dingamo *et al.*, 2022). The diverse pollination and dispersal mechanisms, regeneration capacity, as well as its adaptation potential to the diverse ecologies of the country made the Fabaceae the most widely distributed family.

The frequency class distribution of plant species in Sida Forest showed a higher number of woody species in the lower frequency class and a small number of species in the higher frequency classes. According to the description of Lamprecht (1989) and Aye *et al.* (2014), presence of more species in lower frequency classes and fewer species in higher frequency classes is an indication of a high degree of floristic heterogeneity, whereas fewer species in lower frequency classes and more in higher frequency classes indicate floristic homogeneity or similar species composition. Therefore, the high percentage value of species in the lower frequency classes and low value in the higher frequency classes of Sida Forest showed the existence of a high degree of floristic heterogeneity. A high frequency indicates the regular distribution of the species in the study forest, while a low frequency indicates that the species is either irregularly distributed or rare in a particular stand. The bimodal rainfall patterns of the study area might contribute to the high floristic heterogeneity of the study forest. Rey and Alcántara (2000), reported that the presence of a high degree of floristic heterogeneity might be associated with the occurrence of plant species at a wide range of elevations, a wide range of seed dispersal mechanisms, germination potential, resistance to pests and pathogens, habitat preferences, adaptation, degree of exploitation, and availability of suitable environmental conditions for regeneration.

The basal area provides a better measure of the relative importance of the species than simple stem count. The basal area of woody species in Sida Forest is within the range of virgin tropical forests. In this forest, the higher basal area was contributed by species with large DBH classes such as *Podocarpus falcatus*, *Ficus sycomorus*, *Ficus thonningii*, *Hagenia abyssinica*, and *Ficus sur*, and is considered the most important species in the forest. Shrubs and small DBH individuals have a smaller total basal area contribution, by contrast, tree species with large DBH class have a larger total basal area contribution (Mulugeta Lemenih & Bongers, 2011). The importance value Index reflects the relative ecological importance of a species compared to other associated species in a forest (Kent, 2012). A species with higher IVI values, suggests that those species are ecologically the most important and the species are in a good regeneration pattern in the forest. Whereas, species with a small IVI value indicate the species is less abundant in the forest, and they require high conservation measures to protect them from extinction. IVI values are used as a criterion to prioritize species for conservation actions. Species with the highest IVI value are considered more resistant to the high pressure of disturbance and need lower conservation efforts than those having the lowest IVI value (Haileab Zegeye *et al.*, 2011).

5.2. Plant population structure and regeneration status

Vegetation structure is the organization of individuals and the spatial pattern of growth forms in a plant community, especially in relation to their height, abundance, or coverage within the individual layer (Mueller-Dombois & Ellenberg, 1974). Population structure is an indication of the stability and regeneration status of the forest (Kent, 2012). Plant population structure and density of major canopy trees help to understand the status of the regeneration of a species and the ecology of the forest. Individuals of a species form a species population within a given area and the pattern of size-class distribution is used to represent the population structure of a forest. DBH and height are the two most commonly used size measures in the analysis of plant population structure and provide a good idea for the regeneration of woody species (Getachew Tesfaye *et al.*, 2002). The overall DBH and height class distribution of Sida Forest showed a higher number of individuals in the lower DBH and height classes with a gradual decrease towards the higher DBH and height classes. The overall DBH and height class distribution pattern of Sida Forest showed an inverted J-shape**.** This pattern is an indication of a stable population and healthy regeneration potential and low recruitment potential of the forest. However, any population pattern other than an inverted J-shape indicates a disturbed forest (Motuma Didita *et al.*, 2010; Abyot Dibaba *et al.*, 2020), and the characteristic of secondary forests or it is due to the selective cutting of mature individuals of the species for various purposes (Aye *et al.*, 2014).

Size class distribution as DBH and height are used to evaluate the structure and regeneration of a species. Four representative population structures (inverted J-shaped, bell-shaped, J-shaped, and Broken inverted-J-shaped) were identified in Sida Forest when the DBH class of selected woody species was analyzed separately. This could be due to the difference in management practices, and environmental and anthropogenic factors that interrupt the natural regeneration and recruitment of the species in the forests. The variation is also associated with overgrazing, and/or selective cutting of the usable-sized individuals by local people for various purposes, such as for construction, fuelwood, or any other domestic uses. The presence of a large number of small to medium-sized individuals and the relatively small number of large trees indicates that the forest is a secondary/disturbed forest (Aye *et al.*, 2014). Similarly, Friis *et al.* (2010) showed that in disturbed forests only short-stature trees are found in the middle and lower canopy, as the upper canopy species are removed for various purposes. Species only in the upper storey are the worst case because their natural regeneration and sustainability are threatened and thus the species requires assisted regeneration or it could face local extinction (Maua *et al.*, 2020).

The pattern of population dynamics is described by the presence of a sufficient number of seedlings, saplings, and mature plants, which determine the regeneration status of the forest. Forests can be restored with natural regeneration through seedling establishment and resprouting or coppicing from cut stumps, which results in high-quality forests with high biodiversity (Vieira & Scariot, 2006; Wang *et al.*, 2008). The seedling bank is fundamental to the dynamics of the forest, and regeneration contributes both to the maintenance of species composition and allows species to invade new regions (Girma Amente *et al.*, 2006; Wangchuk, 2007). In Sida Forest, the density of matured trees is higher than the density of seedlings and saplings. Based on the description by Dhaulkhandi *et al.* (2008) and Tiwari *et al.* (2010), the regeneration status of Sida Forest showed different regenerating categories including "fair" (79.63%) regeneration capacity, "not regenerating" (12.96%) and "good" (7.41%) regeneration status. However, the overall regeneration status of the forest was not satisfactory, most of the woody plant species were under the fair" (79.63%) regeneration category. The fewer saplings than seedlings suggests the death of seedlings before reaching the sapling stage due to the death of seedlings from the soil seed bank by frequent livestock trampling, desiccation, fire, and uprooting of seedlings (Vieira & Scariot, 2006; Mendoza *et al.*, 2009). The species without seedlings and saplings show poor reproduction and hindered regeneration. This could be associated to selective tree cutting, free grazing, forest fires, soil erosion, and seeds in seed banks might be eaten before they germinate, or death of seedlings, uprooting of seedlings, herbivore attack, environmental conditions of soil moisture, temperature, and light conditions. Resprouting is common and more important for forest regeneration (Murphy & Lugo, 1986; Vieira & Scariot, 2006). Rich sites support competitive herbaceous vegetation that can shade the forest floor, and tree species may regenerate better on less fertile sites because of reduced competition from the ground vegetation (Wangchuk, 2007; Addo-Fordjour *et al.*, 2009). The litters layer is less suitable in forests for the regeneration of trees because it acts as a barrier so that, the seeds are difficult to touch the soil and inhibit penetration of roots/radicles into the soil, this barrier effect increases with the thickness of the litter layer (Wang *et al.*, 2008; Yang *et al.*, 2014).

5.3. Plant community types in forest ecosystem

A plant community is a collection or assemblage of plants growing together in a particular location sharing a common environment that shows a definite association with each other, with the physical environment (Kent, 2012). Five plant communities were identified in Sida Forest, and each community has its own distribution range with a specific combination of environmental and disturbance variables. The five plant community types of Sida Forest showed variation in their species diversity, richness, and evenness, and were characterized by differences in floristic composition. The highest species richness (159), diversity (4.44), and evenness (0.88) were recorded in community two (*Albizia gummifera-Croton macrostachyus* community type) whereas the least species richness (61), diversity (3.25), and evenness (0.79) were recorded in community five (*Ficus thonningii-Phoenix reclinata-Syzygium guineense* subsp. *afromontanum*).

The variation in species richness, diversity, and evenness among the plant communities is due to the variations in environmental factors, such as climate, elevation, aspect, soil content, moisture, human influence, and grazing intensity. This finding is aligned with various research reports by Luan *et al.* (2012), Li *et al.* (2017), Kacholi (2019), and Kassaw Awoke *et al.* (2023). The other possible reason for the variation in species richness and diversity among the plant community types is related to the differences in the number of sample plots, i.e. community one (12 sample plots), community two (21 sample plots), community three (25 sample plots), community four (10 sample plots) and community five (14 sample plots). As the sampling effort increased such as sample size, plot size, and the number of plots, the probability of getting new species increased contributing to higher species richness and diversity (Zhang *et al.*, 2014). The species diversity and evenness of each community in the study forest is within the range documented for tropical forests by Kent and Coker (1992), i.e 1.5 to 3.5 and rarely exceeds 4.5, and the Shannon diversity index is high when it is above 3.0, medium when it is between 2.0 and 3.0, low when it is between 1.0 and 2.0, and very low when it is smaller than one. Sida Forest had high species diversity with an even distribution, diversity index of 4.44, and evenness of 0.88. A community with a high evenness index is more stable than the lesser ones. High evenness in Sida Forest indicates little dominance by any single species and repeated coexistence of species over all the plots. Higher heterogeneity of species in the communities promotes higher stability and resilience than the monotypic and pure communities (Rana *et al.*, 2022). Species richness and diversity reach maximum at the intermediate elevation and decline towards the lower and upper elevation (Zhang, Xu, *et al.*, 2013; Sebsebe Demissew *et al*., 2021).

The distribution of plant species among the plant communities indicates differences in species composition. One plant community (community 5) located at the higher elevations showed a decrease in species richness, exhibiting less floristic similarity with other plant community types located in the lower elevation (communities 1, 2, and 3). Rana *et al.* (2022) showed that species richness decreases with increasing elevation, largely in proportion to the available land area, but species endemism increases with elevation, due to topographical isolation and speciation (Zerihun Woldu *et al.*, 1999; USAID, 2008; Schmitt *et al.*, 2013). In this study, communities having nearly similar elevations have more species in common than communities occupying different elevations. The other possible reason is the communities that have adjacent plots to each other have more species in common (Oksanen, 2004), which shows the availability of nutrients needed by those species and the adaptation of plants to that particular environment.

5.4. The Effects of Environment and Disturbance Factors on Plant Species Distribution

The relationship between plant communities and environmental variables is important in understanding plant community formation in a forest (McCune & Grace, 2002). The environmental factors such as temperature, rainfall, light, elevation, slope, aspects, soil nutrients and disturbances determine the patterns of plant community formation and species distribution (Liu *et al.*, 2003; Abella & Covington, 2006). Ordination integrates both species and environment data and identifies compositional gradients in a community as a response to measured environmental variables. CCA is best suited to the community data sets where species response to the environment is unimodal and the underlying environmental variables have been measured (McCune & Grace, 2002). The result of the ordination diagram expresses patterns of vegetation in floristic composition and demonstrates the relationship between the species and each of the environmental variables. The CCA result suggested that topographical variables (elevation, slope, and slope aspect), soil variables (sand, and pH), and disturbances had a significant effect on the floristic composition, species diversity, and distribution among the plant communities in Sida Forest. The CCA ordination graph showed topography, soil factors, and disturbances are the most important factors in determining the distribution of species among the plant communities identified in Sida Forest. However, all these environmental variables exhibited different effects on the five plant community types. In the present study, elevation is found the main controlling factor governing the distribution and diversity of plant species in the forest.

In this study, community one is found at a lower elevation, where species diversity and distributions were influenced by disturbances, soil pH, and aspect. Indicating that disturbances are the most influencing factor. Studies by Getaneh Gebeyehu *et al.* (2019), Admassu Addi *et al.* (2020) and Dhar and Sarker (2021) indicated that species diversity increases with intermediate disturbances and the compositional variation of species among plant communities were based on the level of disturbances. Topographical aspects, slope, pH, and sandy soil influence species diversity and distribution in community two. Méndez-Toribio *et al.* (2016) indicated that topographical aspects and slopes affect the environmental conditions such as light, soil moisture, temperatures, and nutrients that determine plant species diversity. The diversity and distribution of plant species in community three is influenced by elevation and slope. Studies by Zerihun Woldu *et al.* (1989), Friis *et al.* (2010), Eiserhardt *et al.* (2011), and Méndez-Toribio *et al.* (2016) indicated that the changes in elevation determine the patterns of plant species distribution. In community four of the study forest species diversity and distribution was determined by disturbance, aspect, and sandy soil. Species composition, diversity, and distribution in plant communities are influenced by disturbance (Ermias Aynekulu *et al.*, 2016; Admassu Addi *et al.*, 2020), and soil texture (Maharjan *et al.*, 2022). While community five, which is located at a higher elevation with relatively low species richness (61) is influenced by elevation and slope. The decrease in species diversity in community five is attributed to unfavorable climatic conditions at the higher elevations making difficulties for the survival of various species (Barry, 2008; Rana *et al.*, 2022).

5.5. Impact of elevation on the physicochemical properties of forest soil

Elevation and soil characteristics have a significant influence on plant community formation, species distribution, richness, and composition (Long *et al.*, 2012; Dong *et al.*, 2019; Bulenga, 2021; Song *et al.*, 2021). Elevation determines the physicochemical properties of soil (Mulugeta Lemenih & Fisseha Itanna, 2004; Charan *et al.*, 2013; Saeed *et al.*, 2014; He *et al.*, 2016; Sierra *et al.*, 2017; Pourbabaei *et al.*, 2020; Li *et al.*, 2021; Weldemariam Seifu *et al.*, 2021; Gömöryová *et al.*, 2022; Han *et al.*, 2022). The physicochemical properties of the soil in the study forest, vary along elevation gradients, indicating sandy soil has the highest percentage (80%) followed by clay (43%) and silt (30%). This shows the dominance of sand, though the content of sand decreases with increasing elevation, whereas clay increases. Climate, parent material, vegetation type, and pedogenic processes influence the textural class of the soil along with elevation changes (Basavaraju *et al.*, 2005; Yang *et al.*, 2008; Charan *et al.*, 2013; Sireesha & Naidu, 2013).

The textural class of the soils in the study forest varies from sandy loam to clay. About 58.54% of the sample soil is sandy loam. Sandy loam is a dominant soil texture class in forestland (Defera *et al.*, 2019), and has a very rapid infiltration rate and permeability (Hazelton & Murphy, 2016). The variation in soil texture classes might be due to the differences in topography, weathering, and age of soils (Sireesha & Naidu, 2013). The Bulk density (BD) of the soil in the study forest decreases with an increase in elevation. It is within the range of very low (< 1.0) in all elevations. This indicates that the soil has better conditions for plant root growth and provides good aeration for microorganisms and has a good water retention capacity which is an important factor in soil fertility. Other studies also showed that BD decreases as elevation increases (Sakin, 2012; Saeed *et al.*, 2014; Obasi *et al.*, 2015; Shiferaw Addis *et al.*, 2019).

Soil pH affects the availability of mineral nutrients to plants as well as many soil processes (FAO, 2006), and the availability of plant nutrients in the soil may change as a result of reactions in the soil, which is largely controlled by soil pH (Neina, 2019). In Sida Forest the soil pH decreases with an increase in elevation, indicating an increase in acidity with elevation. The pH values of the study forest (4.6 to 7.1) lie within the range of very strongly acidic (4.5-5.0) to neutral (6.6-7.3). Species richness declines in both acidic and alkaline soils (Pausas & Austin, 2001). The possible reason could be an increase in elevation is linked to increased rainfall, which causes leaching, and reduction in soluble base cations leading to higher H^+ activity and decreased pH levels (Tsui *et al.*, 2004; Rezaei & Gilkes, 2005). There is higher EC in the higher elevation followed by lower and middle elevations. The EC value of the soil in the study forest (14 $mScm^{-1}$ to 630 $mScm^{-1}$) is within the range of moderately saline (8–16) to strongly saline (> 16) (Weldemariam Seifu *et al.*, 2020). The higher EC content of the soil in the higher elevation is linked with higher clay content that contains a higher accumulation of base-forming cations, and the lower elevations have more salt accumulation due to higher amounts of basic cations like Ca^{2+}, Mg^{+2}, and K^+. On the other hand, the lower EC value in the middle elevation might be due to the lowest amount of basic cations, which are removed by erosion and leaching. The lower EC value at the middle elevation could be associated with the loss of exchangeable bases by erosion and leaching (Berhanu Seyoum, 2016).

There was a positive correlation between the soil organic carbon and elevation in the study forest showing an increase in OC content with an increase in elevation, ranging from 0.78% to 1.24%, which is within the range of low (0.60–1.00) to moderate (1.00–1.80). The OC content depends on carbon input through plant residue decomposition and the amount of litter and the decrease in OC content in the lower elevation could be related to the levels of disturbances, livestock grazing, increase in soil erosion rate, removal of woody species, and dominance of invasive species (Terefe Tolessa & Feyera Senbeta, 2018; Pourbabaei *et al.*, 2020). The higher OC is associated with high clay and silt content, whereas the lowest OC is associated with high sandy soil. Shady area has higher OC than sunny areas (Durán Zuazo *et al.*, 2013; Bangroo *et al.*, 2017; Xiang *et al.*, 2021). Similarly, soil OM of the study forest increased with an increase in elevation, ranging from 1.31% to 25.1%, which is within the range of low (1.00–1.70) to very high (> 5.15). This is associated with high clay content at higher elevations.

The total nitrogen (TN) content of the soil of the study forest was positively correlated with elevation, ranging from 0.06% to 1.25%, which is within the range of low (0.05–0.15) to very high (> 0.5). Disturbances reduce the content of TN in the soil (Ambachew Demessie *et al.*, 2011; Peng *et al.*, 2013; Biyensa Gurmessa *et al.*, 2016; Terefe Tolessa & Feyera Senbeta, 2018). On the other hand, the carbon-to-nitrogen ratio decreases with an increase in elevation, ranging from 3.06% to 19.38%, which is within the range of very low (<10) to medium (5–25). The available phosphorus **(**Av. P) content was negatively correlated with elevation, showing a decrease with an increase in elevation, ranging from 1.43 mg/kg to 3.88 mg/kg, which is within the very low (< 5) range. This is associated with an increase in organic carbon at higher elevations. The increase in organic carbon content at higher elevations resulted in low available phosphorus (Mulugeta Lemenih & Fisseha Itanna, 2004).

There was a positive relationship between cation exchange capacity (CEC) and elevation in the study forest. The CEC value ranges from 1.4 meq/100g of soil to 49 meq/100g of soil, which is within the range of very low (< 6) at the lower elevation to very high (> 40) at the higher elevation. The higher clay content increases the CEC and fertility of the soil (Chinevu *et al.,* 2013; Ping *et al.*, 2013). Clay and humus are essential cation reservoirs of the soil, therefore the high clay content and OM in the higher elevation are associated with the high CEC, and the low CEC in the lower elevation is due to high sand and little organic matter. The decreases and losses of base cations from forest soils are linked with downward leaching, increased soil acidity, soil compaction, and decreased cation exchange capacity. Exchangeable Potassium (K^+) and Exchangeable Calcium (Ca^{2+}) decrease with an increase in elevation. K^+ content ranges from 0.04 meq/100g of soil to 2.3 meq/100g of soil, which is within the range of very low (0–0.2) to very high (> 2). The reduction in K^+ content with an increase in elevation is associated with its high leaching. Similarly, Ca^{2+} contents range from 0 meq /100g of soil to 38 meq /100g of soil, which is within the range of very low (0–2) to very high (> 20). The less leaching of soil at lower elevations can be a source of accumulation of soluble ions, including potassium, and calcium (Tsui *et al.*, 2004). However, Exchangeable Magnesium ($Mg^{2+)}$ increases with an increase in elevation, ranging from 0 meq /100g of soil to 16 meq /100g of soil at the higher elevation, which is within the range of very low (0–0.3) to very high (> 8). Diverse ranges of correlations were recorded among different soil variables with elevation. Elevation was positively correlated with soil OC, OM, TN, CEC, exchangeable Mg^{2+}, clay, and silt content, whereas, pH, EC, Av P, exchangeable Ca^{2+}, exchangeable K^+, BD, and sand were negatively correlated with elevation. Regular monitoring of soil quality and the up-to-date status of soil properties is very important for the management of forest ecosystems on a sustainable basis.

5.6. The ethnobotanical uses of *Piliostigma thonningii*

People around the world depend on the ethnobotanical use of native plants, to sustain their livelihoods. There are more than 40,000 useful plant species reported to fulfill a particular need of humans, animals, and the environment (Kor *et al.*, 2021). *Piliostigma thonningii* is a useful multipurpose tree species (Azene Bekele & Tengnäs, 2007; Kassahun Desalegn *et al.*, 2016) used for different purposes in many parts of Ethiopia. *Piliostigma thonningii* provides several economic, and ecosystem functions in the study area and it has become an integral part of the local culture. Martin (1995), Balick and Cox (1996), Kacholi (2014), and Amjad and Arshad (2014) describe the relationship between plants, people, and the environment and the knowledge of local communities about the uses of plants as a source of food, medicine, fuelwood, timber, fodder, shade, poles, and habitats for other organisms. In the study area, the two ethnic groups have similar ethnobotanical knowledge about the use of *P. thonningii*, this is due to the similarity in their culture and modes of life (pastoralist). In this regard, Tesfaye Awas *et al.* (2010) showed that the ethnobotanical knowledge of the Berta and Gumuz people of western Ethiopia equated with the age and educational level.

In South Omo Zone, *P. thonnngii* is consumed as a supplement to staple foods and to fill a variety of food gaps besides fighting food insecurity during periods of drought. This observation goes in line with the reports by Admasu Terefe *et al.* (2010), Getachew Addis *et al.* (2013), Leul Kidane and Alemu Kejela (2021) who showed that the collection of wild foods is used as a coping mechanism for climate variability and food insecurity. The works of Denbela Hidosa *et al.* (2015) and Tilahun Teklehaymanot (2017) had shown that people in semi-arid and arid regions survive times of severe hunger by consuming wild edible plants. The fruit (pulp) of *P. thonningii* is consumed raw, this has an advantage as an emergency quick-fix facility at critical moments. The fruit and seeds of *P. thonningii* is nutritious and contain protein, starch, fat, and lignin (Jimoh & Oladiji, 2005; Egharevba & Kunle, 2010; Deshi *et al.*, 2014; Jemiseye *et al.*, 2019). In addition to improving food security, wild edible plants are nutritionally rich and supply vitamins and micronutrients (Poulton & Poole, 2001; Tesfaye Awas, 2007; Adhikari *et al.*, 2016). The consumption of fruits improves blood circulation, prevents diabetes, and reduces obesity, cancer, and chances of being affected by heart diseases (Jeambey *et al.*, 2009).

In the study area, the mid-high wealth status families see the consumption of the fruit of *P. thonningii* as a sign of poverty, but poor families collect and consume the fruit to mitigate the risks of hunger and make it an important part of their daily dietary intake. According to the mid-high wealth status respondents, children are the main participants in the collection and consumption of the fruit than adults and elders. However, during food shortages adults and even elder members of the community are involved in the collection and consumption of the fruit. However, low-wealth status households reported that there is no difference in the collection and consumption of the fruit among the different age groups of poor families. *P. thonningii* is an important fodder tree, where, the leaves, pods, and seeds are nutritious and preferred by cattle, goats, and sheep.

The local community of the study area uses *P. thonningii* as a livestock feed. This observation goes in line with the reports by Takele Geta *et al.* (2014), and Almaz Ayenew (2019) who reported the use of *P. thonningii* as a livestock feed. The pods are nutritious and preferred by livestock and browser wild animals (Jimoh & Oladiji, 2005; Egharevba & Kunle, 2010; Jemiseye *et al.*, 2019). In the study area, livestock prefer the young leaves than the mature ones. This result is related to the report by Nwosu *et al.* (2016) who showed that higher crude protein content (20.5%) of *P. thonningii* at the early stage of the leaf than the mature leaf, and Takele Geta *et al.* (2014) showed that the leaves are nutritious and improve poor-quality roughage, and promote health, growth, and milk production.

Piliostigma thonningii improves agricultural productivity, allows good production of crops, and creates a suitable microclimate for other plants growing under or near the canopy. The majority (88%) of the respondents replied that *P. thonningii* sheds its nitrogen-rich leaves during the dry season, and the litter from the shed leaves improves the soil fertility and the shade conserves the available soil moisture by reducing the evapotranspiration under the tree. This result goes in line with the reports by Wood and Burley (1991), Debissa Lemessa (2010), and Chidumayo (2018) who showed that *P. thonningii* is an excellent shade tree that helps retain soil moisture and nutrients. The communities in the study area use *P. thonningii* as a source of fuelwood, for construction, for making household equipment, fences, beehives, and timber. Thulin *et al.* (1989), Azene Bekele and Tengnäs (2007), Orwa *et al.* (2009), and Chidumayo (2018) reported the use of *P. thonningii* as a source of fuelwood, poles, charcoal, carpentry, construction, to make a household material and farm implements. The local people use the inner part of the stem bark for making ropes. This result goes in line with the reports by Orwa *et al.* (2009) and Egharevba and Kunle (2010) who confirmed the use of the inner bark to make ropes/cordage. The local community uses *P. thonningii* as a traditional medicine for the treatment of liver disease. This goes in line with the report by Kidane Berhane *et al.* (2014) who showed that the leaf of *P. thonningii* is used for the treatment of similar diseases.

5.7. The status of *P. thonningii* in South Omo Zone

The increasing rate of over-exploitation of woody tree species including *P. thonningii* is considered a threat to the species (Oni, 2001). In Africa over 5,000 plant species are expected to lose their suitable habitats due to climate change by 2085 (McClean *et al.*, 2005), and Ethiopia is one of the vulnerable country to climate change (Conway & Schipper, 2011). Two out of five plant species across the world are estimated to be at risk of extinction, prompting global conservation efforts (Kor *et al.*, 2021). In Nigeria and Malawi, *P. thonningii* has been reported as one of the national priority species for conservation and sustainable utilization (Oni, 2001; Ayisire *et al.*, 2009; Mwase & Mvula, 2011). Although the conservation status of *P. thonningii* in Ethiopia was not determined being described as data deficient, studies have shown that its existence is increasingly threatened by an increasing rate of over-exploitation, and degradation of its natural habitats (Assegid Assefa & Tesfaye Abebe, 2011; Mesfin Belete *et al.*, 2021), and climate change.

The abundance of *P. thonningii* in the study area is decreasing mainly due to the expansion of agricultural land, firewood collection, overgrazing, and harvesting wood for the construction of fences and charcoal production. Field observation by the researcher and interview and discussion with the local informants confirmed that there is a decrease in the status of *P. thonningii* because of the conversion of the habitats into agricultural land and illegal bushfire to acquire more agricultural land.

Agricultural expansion for crop cultivation is a major threat because nowadays the community of the study area is changing from a pastoral to an agro-pastoral way of life. The suitable habitats for the growth of *P. thonningii* are threatened by the continued conversion into farmlands. Assegid Assefa and Tesfaye Abebe (2011) showed that the community of the South Omo Zone is changing from a pastoral to an agro-pastoral way of life. The conversion of forested land into farmland and other land-use systems is the major cause of deforestation in Ethiopia (FAO, 2017). During field observation and group discussion, it was observed that agricultural development workers and local administrators push the pastoral community to be involved in crop cultivation without selecting appropriate land suitable for cultivation and without consideration of the agroforestry system. Rural and urban households use firewood predominantly as a domestic fuel including *P. thonningii*. Multi-purpose woody species are an important source of fuelwood for rural households (Zenebe Gebreegziabher, 2007).

The attitude and interest of the local community to maintain and conserve *P. thonningii* are different among gender, wealth status, and educational levels. The mid-high-wealth status, men, and educated members of the community practice some activities to manage and conserve *P. thonningii* that grow in their farms and homesteads. This tradition is a good implication of indigenous management strategies for the conservation and management of this species. However, the low-wealth status communities are not interested in maintaining and to conserve the species. They are constrained by the priority to ensure basic food self-sufficiency in their allocated land and give prior satisfaction to their needs to produce staple food. Low income households lack lands for the cultivation of wild edible fruits and they focus on the cultivation of crops that help them to ensure their basic food requirement on their lands (Poulton & Poole, 2001). Educated community members have more knowledge and willingness to maintain, and to plant trees, and men have more interest to maintain, and plant *P. thonningii* than women. The ecological knowledge held by local and indigenous users must be recognized and fully incorporated into biodiversity management and conservation plans.

5.8. Conclusion and Recommendations

Conclusion

The assessment of floristic composition, species diversity, population structure, community types, and regeneration status of the species in a forest is an important measure for a better understanding of the management, and conservation of the forest and its products. The results revealed that Sida Forest comprises of high floristic composition, species diversity, evenness, and endemic species. The presence of high species diversity with new records for this flora area and endemic species showed the potential of the area and the need for conservation. The total density of mature woody species of the study forest is 682.32 individuals/ha, showing the forest is dense in vegetation. The DBH and height class distribution showed higher density at the lower classes and gradually decreased towards the higher classes, generating an inverted J-shape distribution pattern, which is an indication of a healthy population structure and good regeneration status. The population density patterns of each tree species showed that four population distribution patterns were identified (Inverted-J shaped, bell-shaped, J shaped and Broken Inverted-J shaped). Different disturbance factors affect the population structure of tree species of the study forest differently. The basal area provides a better measure of the relative importance of the species in the forest and the total basal area of Sida Forest was 24.15 m^2/ha, which is within the range of the normal basal area value (23–37 m^2/ha) set for virgin tropical forests in Africa. The higher basal area was contributed by the species with large DBH classes, than species with lower DBH classes, even having many individuals of a species. The analysis of IVI results showed that few tree species are economically and ecologically very important than the others such as *Podocarpus falcatus*, *Syzygium guineense*, *Combretum molle*, *Ficus sycomorus*, *Croton macrostachyus*, and *Ficus thonningii* showed higher IVI values. On the other hand, species with small IVI values such as *Senegalia brevispica*, *Grewia villosa*, *Gardenia ternifolia*, *Searsia longipes*, *Dichrostachys cinerea*, and *Piliostigma thonningii* are very rare and locally threatened and they require high conservation measures to protect them from local extinction. The pattern of regeneration suggests that there are two categories, species able to regenerate and species that have difficulties to regenerate and reproduce. The forest is characterized by fair regeneration status as evidenced by the poor density of seedlings and saplings, as the density of seedlings was greater than that of saplings but less than mature trees. Fewer saplings than seedlings suggest the death of most seedlings before reaching the sapling stage due to various factors such as human interferences, browsers, grazers, desiccation, fire, and frequent livestock trampling and uprooting of seedlings.

The hierarchical classification revealed five plant community types and the pattern of community formation was determined by environmental and disturbance factors. Species richness, diversity, and evenness varied among the plant communities with the highest richness, diversity, and evenness were recorded in communities found at the intermediate elevation such as community types 1 (117), 2 (159), and 3 (145), whereas relatively the lowest were found in community types 4 (92) and 5 (61). The values of species diversity and evenness for each community of the study forest ranges within the range recorded for tropical forests. The CCA ordination result showed that the variation in species richness, diversity, and evenness among the plant community types is due to the variation in elevation, slope aspect, soil physicochemical properties, and disturbances, which were observed in most parts of the forest.

The physicochemical properties of the soil in the study forest exhibit variations along the elevation gradients. The values of some of the soils physicochemical properties increased along with an increase in elevation such as organic carbon, organic matter, total nitrogen, clay, silt, cation exchange capacity, and exchangeable Mg^{2+}. Others decreased along with an increase in elevation such as pH, EC, C/N ratio, Av P, exchangeable Ca^{2+}, exchangeable K^{+}, BD, and sand. The variation in soil physicochemical properties of the Sida Forest is not only related to elevation change but related to other factors including changes in vegetation, soil erosion, grazing, and other factors.

Communities in the South Omo Zone showed varying degrees of traditional knowledge on the use of plant species, like *P. thonningii*. The pastoral and agropastoral communities use *P. thonningii* for various purposes, and they acquire knowledge about the uses of *P. thonningii* mainly from their families. *P. thonningii* contributes to the nutritional intake of the local communities and helps to ensure food security during times of seasonal food shortage. It is an excellent fodder tree, used to feed livestock under open grazing conditions. It improves poor feed quality and the survival and productivity of livestock. It is an agroforestry tree, that improve soil fertility, and moisture retention capacity, and maintains soil structure. The local communities also use it for different purposes, such as a source of fuelwood, for the construction of huts, making beehives and household utensils (Borketas, chairs, and axe handles).

Recommendations

Based on the results of this research work, the following recommendations are forwarded:

1. Sida Forest is rich in plant diversity and endemic species, therefore, responsible authorities such as Zone Agricultural Office and NGOS, are advised to develop appropriate conservation measures (*in-situ* or *ex-situ*) to save the natural habitats and the ecologically important, rare, endemic, and valuable plant species.
2. The population density patterns of Sida Forest in DBH and height classes revealed a healthy status, however, the population density patterns of each tree species showed irregular patterns of population structure and reduced regeneration status. Therefore, the zone/woreda Agricultural Office need to involve the stakeholders such as clan leaders, local communities for urgent species-specific conservation and management measures to restore the diversity of the forest and to establish nursery sites to prevent local extinction.
3. The species with the lower IVI values such as *Senegalia brevispica*, *Grewia villosa*, *Gardenia ternifolia*, *Searsia longipes, Dichrostachys cinerea* and *Piliostigma thonningii* need high conservation measures to protect them from extinction. Hence the clan leaders, local people and agricultural development agents are reminded to protect and conserve these species both *in-situ* and *ex-situ*. Moreover, studies on soil seedbanks of woody species in general and regeneration capabilities of these species in particular are highly recommended.
4. The variation in soil physicochemical properties of Sida Forest is not only related to elevation changes but also related to other factors such as change in vegetation types, therefore researchers need to conduct through studies on the association between soil physicochemical properties and vegetation types.
5. *Piliostigma thonningii* contributes to the nutritional intake of the local communities and helps to ensure food security during times of food shortage. Therefore, the concerned bodies such as the zone agricultural offices and nongovernmental organizations should consider *P. thonningii* when they develop strategies to fight food insecurity and to improve rural livelihood systems. The local communities use *P. thonningii* for different purposes, thus educating and awareness-raising activities should be carried out by the concerned bodies such as the zone agricultural office and NGOS to protect the multipurpose and rare plant species from uncontrolled use that leads to their destruction. Therefore, it is necessary

for the local communities and farmers to integrate this useful plant species into the agroforestry systems and home-garden practices.

6. *Piliostigma thonningii* is less known for its medicinal use in the treatment of different diseases as compared to other African countries. Therefore, researchers need to undergo detail studies on its traditional medicinal value, phytochemical analysis and anti-microbial tests.
7. The results also showed that the status of *P. thonningii* is decreasing because of the pressures from various anthropogenic factors, such as agricultural expansion, firewood collection, harvesting for fencing, and overgrazing. Thus, the concerned bodies such as zone/woreda agricultural office and NGOs need to create public awareness and community-based management, and it is important to promote *P. thonningii* as a valuable tree to improve household food security, agricultural productivity, and income source of the local communities.
8. The community of the study area relies on forest resources for different activities that can cause depletion of the forest and forest resources. Therefore, community-based management and conservation of the forest must be undertaken through awareness raising training program guided by the relevant governmental organizations and NGOs.
9. The results of this study do not cover land use/cover changes in the study area and assist land use planners, policy makers and conservationists to design effective land use and forest conservation plans in the study area.

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Appendices

Appendix 1: Lists of plant species recorded from Sida Forest.

No.	**Scientific name**	**Family**	**Local names**	**Growth forms**	**Voucher No.**
1	*Abutilon mauritianum* (Jacq.) Medic.	Malvaceae	Lusti	Sh	MSB240
2	*Acacia goetzei* Harms	Fabaceae	Arke	T	MSB42
3	*Acacia hockii* De Wild.	Fabaceae	Cekenti	T	MSB25
4	*Acacia mellifera* (Vahl) Benth.	Fabaceae	Dile	Sh/out	MSB28
5	*Acacia nilotica* (L.) Willd. ex. Del.	Fabaceae	Pulenti	T/out	MSB29
6	*Acacia robusta* Burch.	Fabaceae	Dhera	T	MSB45
7	*Acacia seyal* Del.	Fabaceae	Ketse	T	MSB145
8	*Acalypha fruticosa* Forssk.	Euphorbiaceae	Septi	Sh	MSB02
9	*Acalypha ornata* A. Rich.	Euphorbiaceae	Ambisefti	Sh	MSB60
10	*Acalypha racemosa* Baill.	Euphorbiaceae	Ambisepti2	H	MSB238
11	*Acanthus polystachius* Delile	Acanthaceae	Ayishkoma	Sh	MSB160
12	*Acanthus sennii* Chiov.	Acanthaceae	Koma	Sh	MSB52
13	*Achyranthes aspera* L.	Amaranthaceae	Getena	H	MSB98
14	*Adenia gummifera* (Harvey) Harms.	Passifloraceae	Alphaqa	C	MSB135
15	*Agarista salicifolia* (Comm. ex Lam.) Don	Ericaceae	Gesa	T	MSB94
16	*Agrostis diffusa* S.M. Phillips	Poaceae	Gichila	G	MSB209
17	*Albizia gummifera* (J. F. Gmel.) C. A. Sm.	Fabaceae	Mereka/Dhocho	T	MSB146
18	*Albizia schimperiana* Oliv.	Fabaceae	Rumbe	T	MSB67
19	*Allophylus rubifolius* (Hochst. ex A. Rich). Engl.	Sapindaceae	Seniketeb	Sh/T	MSB200
20	*Aloe gilbertii Sebsebe* & Brandham	Aloaceae	Walko	H	MSB148
21	*Aloe otallensis* Baker	Aloaceae	Walko	H	MSB119
22	*Amaranthus hybridus* L.	Amaranthaceae	Zaphina (edible)	H	MSB186
23	*Amaranthus spinosus* L.	Amaranthaceae	Zaphina	H	MSB132
24	*Andropogon distachyos* L.	Poaceae	Suni	G	MSB36
25	*Arisaema schimperianum* Schott	Araceae	Tsela	H	MSB201
26	*Aspargus africanus* Lam.	Asparagaceae	Angerte=45	Sh/C	MSB103
27	*Asplenium theciferum* (HBK.) Mett.	Aspleniaceae	Epiphyticfern	F	MSB253
28	*Balanites aegyptiaca* (L.) Del.	Balanitaceae	Dumeko	T	MSB64
29	*Balanites rotundifolia* (van Tieghem) Blatter	Balanitaceae	Kuz	T	MSB125
30	*Becium obovatum* (E.Mey.ex Benth. In E.Mey.) N.E. Br.	Lamiaceae	Buranbutso	H	MSB217
31	*Bersama abyssinica* Fresen.	Melianthaceae	Azamir/kelshi	T/Sh	MSB100

32	*Bidens biternata* (Lour.) Merr. & Sherff	Asteraceae	Acenti	H	MSB117
33	*Bidens pilosa* L.	Asteraceae	Mognfikir	H	MSB224
34	*Bidens schimperi* Sch. Bip. ex Walp.	Asteraceae	Dhukaankedhesha	H	MSB142
35	*Biophytum umbraculum* Welw.	Oxalidaceae	Kintsikints	H	MSB38
36	*Boscia salicifolia* Oliv.	Capparidaceae	Moodkele	Sh/out	MSB77
37	*Boswellia neglecta* S. Moore	Burseraceae	Tubeke	T	MSB127
38	*Bridelia micrantha* (Hochst.) Baill.	Euphorbiaceae	Roza	T	MSB177
39	*Brucea antidysenterica* J. F. Mill.	Simaroubaceae	29	Sh/T	MSB174
40	*Cadaba farinosa* Forssk. Subsp.	Capparidaceae	Bereket Dhesha	Sh	MSB231
41	*Calpurnia aurea* (Ait.) Benth.	Fabaceae	Kayna	Sh	MSB50
42	*Canthium pseudosetiflorum* Bridson	Rubiaceae	Me’el	Sh/out	MSB183
43	*Capparis fascicularis* DC.	Capparidaceae	Kush jamo	Sh	MSB01
44	*Capparis tomentosa* Lam.	Capparidaceae	Melo	Sh	MSB236
45	*Cardiospermum corindum* L.	Sapindaceae	Musa/Atsets	L	MSB196
46	*Carduus nyassanus* (S. Moore) R.E. Fries	Asteraceae	Dega eshok	H	MSB208
47	*Carissa spinarum* L.	Apocynaceae	Culki	Sh	MSB10
48	*Celosia anthelminthica* Asch. in Schweinf.	Amaranthaceae	Seleyamudo	H	MSB06
49	*Chasmanthera dependens* Hoscht.	Menispermaceae	Coko	C	MSB61
50	*Cheilanthes hirta* Sw.	Sinopteridaceae	Fern	F	MSB247
51	*Chenopodium opulifolium* Schrader ex Koch & Ziz.	Chenopodiaceae	36	H	MSB190
52	*Cissampelos mucronata* A.Rich.	Menispermaceae	Untinkama	C	MSB204
53	*Cissus petiolata* Hook. f.	Vitaceae	Dobikele	L	MSB46
54	*Cissus rotundifolia* (Forssk.) Vahl	Vitaceae	Kele	C /L	MSB203
55	*Clausena anisata* (Willd.) Benth.	Rutaceae	Zumi	Sh/T	MSB83
56	*Clematis simensis* Fresen.	Ranunculaceae	Gayadenpo	L	MSB15
57	*Clerodendron myricoides* (Hochst.) Vatke	Lamiaceae	Dindo	Sh	MSB116
58	*Clutia abyssinica* Jaub. & Spach.	Euphorbiaceae	Tirantira	Sh	MSB17
59	*Coffea arabica* L.	Rubiaceae	Bunna	Sh	MSB101
60	*Combretum collinum* Fresen.	Combretaceae	Debden	T	MSB138
61	*Combretum molle* R. Br. ex G. Don.	Combretaceae	Sebe	T	MSB14
62	*Commelina benghalensis* L.	Commelinaceae	Geneya	H	MSB48
63	*Commelina diffusa* Burm.f.	Commelinaceae	Gishta	H	MSB173
64	*Cordia africana* Lam.	Boraginaceae	Ashe	T	MSB129
65	*Croton macrostachyus* Del.	Euphorbiaceae	Beta	T	MSB43
66	*Cucurbita pepo* L.	Cucurbitaceae	Puto/Duba	H/out	MSB149
67	*Cyathula polycephala* Bak.	Amaranthaceae	Dhaksa	H	MSB241
68	*Cycnium erectum* Rendle	Scrophulariaceae	Archaro1	H	MSB166
69	*Cynoglossum lanceolatum* Forssk.	Boraginaceae	Untinachenti	H	MSB40
70	*Cyperus longibracteatus* (Cherm.) Kuk	Cyperaceae	Bez kontsele	H	MSB181
71	*Cyphostema panossum* Vollesen	Vitaceae	48	H	MSB216

72	*Cyphostemma niveum* (Hochst. ex Schweinf.) Descoings	Vitaceae	Benzikele	C	MSB214
73	*Debregeasia saeneb* (Forssk.) Hepper & Wood	Urticaceae	Ayishkom/44	Sh	MSB206
74	*Dichrostachys cinereal* (L)	Fabaceae	Kalensa	T/Sh	MSB158
75	*Digitaria abyssinica* (Hochst. ex. A.Rich.) Stapf	Poaceae	Piranphiso	G	MSB115
76	*Dioscoria bulbifera* var. bulbifera L.	Dioscoreaceae	Peodo	C	MSB137
77	*Diospyros abyssinica* (Hiern) F. White	Ebenaceae	Kur	T	MSB207
78	*Diospyros mespiliformis* Hochst. ex A. DC.	Ebenaceae	Koshim	T	MSB233
79	*Diospyros scabra* (Chiov.) Cufod.	Ebenaceae	Zoboko	T	MSB234
80	*Discopodium penninervium* Hochst. ex A.Rich.	Solanaceae	Buzi	Sh	MSB151
81	*Dodonaea angustifolia* L. f.	Sapindaceae	Serko	Sh	MSB70
82	*Dombeya torrida* (J. F. Gmel.) P. Bamps	Sterculiaceae	Kami	T	MSB73
83	*Dracaena afromontana* Mildbr.	Dracaenaceae	Wusha	Sh/T	MSB88
84	*Dregea schimperi* (Decne.) Bullock	Asclepiadaceae	Shabina	C	MSB152
85	*Droguetia iners* (Forssk.) Schweinf.	Urticaceae	52	H	MSB229
86	*Dryopteris schimperiana* (Hochst. ex A.Br.) C.Chr.	Dryopteridaceae	Fern	F	MSB248
87	*Ekebergia capensis* Sparrm.	Meliaceae	Gomi	T	MSB239
88	*Eleusine jaegeri* Pilg.	Poaceae	Suwa	G	MSB185
89	*Entada abyssinica* Steud. Ex A. Rich.	Fabaceae	Longa	T	MSB75
90	*Eragrostis longifolia* Hochst. ex Steud.	Poaceae	Gilma	G	MSB49
91	*Eragrostis virescens* Presl	Poaceae	Felki	G	MSB74
92	*Euclea racemosa* Murr.	Ebenaceae	Unsi	Sh/T	MSB68
93	*Eugenia bukobensis* Engl.	Myrtaceae	Kakay	T	MSB78
94	*Euphorbia schimperiana* Scheele.	Euphorbiaceae	Keyra	H	MSB122
95	*Ferula communis* L.	Apiaceae	Ensilal	H	MSB162
96	*Ficus ovata* Vahl	Moraceae	Wela	T	MSB218
97	*Ficus sur* Forssk	Moraceae	Sema	T	MSB225
98	*Ficus sycomorus* L	Moraceae	Wompho	T	MSB11
99	*Ficus thonningii* Blume	Moraceae	Welwel	T	MSB175
100	*Ficus vasta* Forssk	Moraceae	Shaf	T	MSB189
101	*Galiniera saxifraga* (Hochst.) Bridson	Rubiaceae	Sele	Sh/T	MSB56
102	*Galinsoga parviflora* Cav.	Asteraceae	Ababula	H	MSB41
103	*Gardenia ternifolia* Schumach. & Thonn.	Rubiaceae	Gembela	T	MSB215
104	*Girardinia bullosa* (Steudel) Wedd.	Urticaceae	Dosi	H	MSB202
105	*Gnidia involucrata* Steud.ex A. Rich.	Thymelaeaceae	Ela koyisha	H	MSB171
106	*Gnidia lamprantha* Gilg.	Thymelaeaceae	Koysha	Sh	MSB159
107	*Gomphocarpus purpurascens* A. Rich.	Asclepiadaceae	22	H	MSB155
108	*Grewia mollis* Juss.	Tiliaceae	Dhuka bereza	Sh/T	MSB118

109	*Grewia tenax* (Forssk.) Fiori	Tiliaceae	Mageza	Sh	MSB58
110	*Grewia trichocarpa* Hochst. ex A. Rich.	Tiliaceae	Kebi	Sh/T	MSB195
111	*Grewia velutina* (Forssk.) Vahl.	Tiliaceae	Bereza	T	MSB34
112	*Grewia villosa* Willd.	Tiliaceae	Gergecha	Sh	MSB243
113	*Guizotia scabra* (Vis.) Chiov.	Asteraceae	Arbi	H	MSB199
114	*Gymnosporia addat* (Loes.)	Celastraceae	Gal	Sh/T	MSB93
115	*Hagenia abyssinica* (Bruce) J.F.Gmelin	Rosaceae	Koso	T	MSB228
116	*Heteromorpha arborescens* (Spreng.) Cham. & Schltdl. var. abyssinica	Apiaceae	8	Sh	MSB110
117	*Hymenodictyon floribundum* (Hochst. & Steud.) Robinson	Rubiaceae	Tsekaro	Sh/T	MSB144
118	*Hypericum quartinianum* A. Rich.	Hypericaceae	42	Sh/T	MSB212
119	*Hypoestes aristate* (Vahl) Roem. & Schult.	Acantaceae	Makeysa	H	MSB130
120	*Hypoestes forskaolii* (Vahl) R.Sch.	Acantaceae	Busunta	H	MSB03
121	*Impatiens hochstetteri* Warb. subsp. hochstetteri	Balsaminaceae	Wusho	H	MSB230
122	*Indigofera arrecta* Hochst. ex. A. Rich.	Fabaceae	7 & 24	Sh	MSB107
123	*Indigofera hirsute* L.	Fabaceae	Erbo	H	MSB114
124	*Inula paniculata* (Klatt) Burtt-Davy	Asteraceae	40	H	MSB210
125	*Ipomoea kituiensis* Vatke	Convolvulaceae	Gali	Sh	MSB47
126	*Jasminum abyssinicum* Hochets. Ex DC.	Oleaceae	Tenkaraw hareg	L/c	MSB90
127	*Juniperus procera* Hochst ex Endl	Cuprussaceae	Tid	T	MSB92
128	*Justicia bizuneshiae* Ensermu	Acanthaceae	Goltota	H	MSB65
129	*Justicia diclipteroides* Lindau	Acanthaceae	Key abeba	H	MSB84
130	*Justicia flava* (Vahl) Vahl	Acanthaceae	Gotsa	H	MSB237
131	*Justicia heterocarpa* T. Anders subsp. vallicola Hedren	Acanthaceae	Keyabeba 45	H	MSB97
132	*Kalanchoe marmorata* A. Rich.	Crassulaceae	Kordo	Sh	MSB221
133	*Kalanchoe petitiana* A. Rich.	Crassulaceae	Kordo	H	MSB140
134	*Kosteletzkya adoensis* (Hochst. ex A. Rich.) Mast.	Malvaceae	Waribeshi	H	MSB82
135	*Laggera alata* (D. Don) Oliv.	Asteraceae	Ye chibo enchet	H	MSB235
136	*Laggera pterodonata* (DC.) Sch.-Bip.	Asteraceae	Ye chibo enchet	H	MSB99
137	*Landolphia buchananii* (Hall.f.) Stapf	Apocynaceae	Mula	L	MSB252
138	*Lannea fruticosa* (A. Rich.) Engl.	Anacardiaceae	Defi	T	MSB13
139	*Lannea schimperi* (A. Rich.) Engl.	Anacardiaceae	Tulungo	T	MSB72
140	*Lantana camara* L.	Verbanaceae	Tsedaki	Sh	MSB222
141	*Lantana trifolia* L.	Verbanaceae	Weliesin	Sh	MSB154
142	*Leptadenia hastata* (Pers.) Decne.	Asclepiadaceae	Metsa	Sh/out	MSB250
143	*Leucas abyssinica* (Benth.) Briq.	Lamiaceae	Shokoni	Sh	MSB39
144	*Lippia adoensis* Hochst. ex Walp.	Verbenaceae	Kesse	Sh	MSB223
145	*Lobelia giberroa* Hemsl.	Lobeliaceae	Purzi	H	MSB251

146	*Maerua angolensis* DC.	Capparidaceae	Kedhi	Sh/Tout	MSB134
147	*Maesa lanceolata* Forssk.	Myrsinaceae	Kelaho/teri	T	MSB86
148	*Maytenus arbutifolia* (A.Rich.) Wilczek	Celastraceae	Ezine	T/Sh	MSB62
149	*Maytenus undata* (Thunb.) Blakelock	Celastraceae	Gal_fruit	Sh	MSB249
150	*Micromeria imbricate Var. imbricata*	Lamiaceae	41	H	MSB213
151	*Millettia ferruginea* (Hochst.) Bak.	Fabaceae	Zagi/birbira	T	MSB102
152	*Mimusops kummel* A. DC.	Sapotaceae	Buldi	T	MSB254
153	*Momordica foetida* Schumach.	Cucurbitaceae	Gaya buta	C	MSB133
154	*Myrsine africana* L.	Myrsinaceae	Kechemo	Sh	MSB87
155	*Nicandra physaloides* (L.) Gaertn.	Solanaceae	33	H	MSB187
156	*Nuxia congeta* R.Br. ex Fresen.	Loganiaceae	Goa	T	MSB147
157	*Ocimum basilicum* L.	Lamiaceae	Lama	H	MSB66
158	*Ocimum lamiifolium* Hochst ex Benth.	Lamiaceae	Cultu/damakesse	Sh	MSB139
159	*Ocimum urticifolium* Roth	Lamiaceae	Kerko	H	MSB05
160	*Olea europaea Subsp. cuspidata* (Well ex.G.Don) c.f	Oleaceae	Rimit	T	MSB71
161	*Olinia rochetiana* A. Juss.	Oliniaceae	Tife/Dalecho	T/Sh	MSB112
162	*Oncoba routledgei* Sparague.	Flacourtiaceae	Gaya buki	Sh/T	MSB128
163	*Oncoba spinosa* Forssk.	Flacourtiaceae	Edi buki	Sh/T	MSB26
164	*Oplismenus hirtellus* (L.) P. Beauv.	Poaceae	Yila	G	MSB167
165	*Ormocarpum trichocarpum* (Taub.)	Fabaceae	Moshko	Sh	MSB33
166	*Osyris quadripartita* Decn	Santalaceae	Undulich	T/Sh	MSB27
167	*Oxygonum sinuatum* (Meisn.) Dammer	Polygonaceae	Mugri	H	MSB141
168	*Ozoroa insignis* Del.	Anacardiaceae	Selbena	Sh/T	MSB180
169	*Panicum maximum* Jacq.	Poaceae	Warka	G	MSB109
170	*Panicum maximum* Jacq./subalbidum	Poaceae	Pushenti	G	MSB172
171	*Panicum porphyrrhizos* Steud.	Poaceae	Zombo	G	MSB55
172	*Pentas lanceolata* (Forssk.) Defl.	Rubiaceae	12/ Afi deshe	H	MSB121
173	*Periploca linearifolia* Quart. -Dill. & A. Rich.	Asclepiadaceae	Singa	L	MSB53
174	*Phoenix reclinata* Jacq.	Aricaceae	Metsa/zembab	T	MSB80
175	*Phyllanthus ovalifolius* Forssk.	Euphorbiaceae	Kole roko	Sh	MSB131
176	*Phyllanthus rotundifolius* Willd.	Euphorbiaceae	Tenta	H	MSB07
177	*Physalis peruviana* L.	Solanaceae	Dhumo	H	MSB170
178	*Phytolaca dodecandra* L' Her't	Phytolaccaceae	Tolsi	Sh	MSB193
179	*Piliostigma thonningii* (Schumach.) Milne-Redh.	Fabaceae	Olofoo	T	MSB35
180	*Piper capense* L.	Piperaceae	51	H	MSB226
181	*Plantago lanceolate* L.	Plantaginaceae	Qortobi /09	H	MSB111
182	*Plectranthus lanuginosus* (Hochst. ex Benth.) Agnew	Lamiaceae	Ruze (wuz)	H	MSB194
183	*Plectranthus laxiflorus* Benth.	Lamiaceae	Shokmi	H	MSB220

184	*Plectranthus punctatus* (L.f.) L`Her.	Lamiaceae	55	H	MSB232
185	*Podocarpus falcatus* (Thunb.) Mirb.	Podocarpaceae	Zigim	T	MSB79
186	*Polygala sphenoptera* Fresen	Polygalaceae	19	H	MSB150
187	*Portulaca oleracea* L.	Portulacaceae	Mooleza	H/out	MSB126
188	*Premna schimperi* Engl.	Lamiaceae	Dhankuso	Sh	MSB165
189	*Protea gaguedi* J.F. Gmel.	Proteaceae	Shiragechi	Sh/T	MSB106
190	*Prunus africana* (Hook.f.) Kalkm.	Rosaceae	Gorfok	T/out	MSB245
191	*Pseudocyclosorus pulcher* (Willd.) Holttum	Thelypteridaceae	Apidhesha	F	MSB37
192	*Psychotria orophila* Petit	Rubiaceae	Shawbuno	Sh	MSB19
193	*Pteridium aquilinum* (L.) Kuhn	Dennstaedtiaceae	Gichira	F	MSB246
194	*Pterolobium stellatum* (Forssk.) Brenan	Fabaceae	Beneka	Sh	MSB30
1895	*Pupalia lappacea* (L.) A. Juss.	Amaranthaceae	Achenti	H	MSB18
196	*Pycnostachys abyssinica* Fresen.	Lamiaceae	Anchief	Sh	MSB32
197	*Rhamnus prinoides* L'Herit.	Rhamnaceae	Gesho/kulmi	Sh	MSB89
198	*Rhoicissus tridentata* (L. f.) Wild & Drummond	Vitaceae	Orodo	L/C	MSB59
199	*Rhus natalensis* Krauss	Anacardiaceae	Kufri	Sh	MSB22
200	*Rhus tenuinervis* Engl.	Anacardiaceae	Kole tenta	Sh	MSB123
201	*Rhus vulgaris* Meikle	Anacardiaceae	Shikni/embus	Sh/T	MSB96
202	*Rhynchospora corymbosa* (L.)	Cyperaceae	Kontsele	H	MSB04
203	*Ricinus communis* L.	Euphorbiaceae	Ati	Sh	MSB169
204	*Rubus apetalus* Poir.	Rosaceae	Enjori	Sh	MSB182
205	*Rubus steudneri* Schweinf.	Rosaceae	Dega enjori	Sh	MSB184
206	*Rumex abyssinicus* Jacq.	Polygonaceae	Mekmeko	H	MSB227
207	*Satureja abyssinica* (Benth.) Briq.	Lamiaceae	41	H	MSB211
208	*Scadoxus multiflorus* (Martyn) Raf.	Amaryllidaceae	Ketsi	H	MSB91
209	*Schefflera abyssinica* (Hochst. ex A. Rich.) Harms	Araliaceae	Yirchi	T	MSB95
210	*Searsia longipes* Var. longipes	Anacardiaceae	Tselko	Sh	MSB242
211	*Securidaca longepedunculata* Fresen.	Polygalaceae	Tsemani	Sh/out	MSB179
212	*Senegalia brevispica* (Harms) Seingler & Ebinger	Fabaceae	Gelensa	Sh	MSB120
213	*Senna obtusifolia* (L.) Irwin & Barneby	Fabaceae	30	H	MSB176
214	*Senna occidentalis* (L.) Link	Fabaceae	34	H	MSB188
215	*Senna singueana* (Del) Lock	Fabaceae	Zinzeke	Sh/T	MSB12
216	*Sida rhombifolia* L.	Malvaceae	Cukisha	Sh	MSB44
217	*Solanum americanum* Mill.	Solanaceae	Tsephe	H	MSB108
218	*Solanum anguivi* Lam.	Solanaceae	Anzegobe	Sh	MSB198
219	*Solanum incanum* L.	Solanaceae	Garenti	Sh	MSB31
220	*Sporobolus africanus* (Poir.) Robyns & Tournay	Poaceae	Aren	G	MSB161

221	*Stachys aculeolata* Hook. f.	Lamiaceae	Rukunta	H	MSB24
222	*Stereospermum kunthianum* Cham.	Bignoniaceae	Zolpho	Sh/T	MSB21
223	*Syzygium guineense subsp. afromontanum* (Wild.) DC.	Myrtaceae	Lema	T	MSB178
224	*Syzygium guineense subsp. Guineense* (Wild.) DC.	Myrtaceae	Lema	T	MSB81
225	*Tagetes minuta* L.	Asteraceae	Ankedhesha	H	MSB16
226	*Teclea nobilis* Del.	Rutaceae	Tsaki	Sh /T	MSB23
227	*Tephrosia elata* Deflers.	Fabaceae	21	H	MSB153
228	*Tephrosia purpurea* (L.) Pers.	Fabaceae	23	H	MSB156
229	*Terminalia brownii* Fresen.	Combretaceae	Ara	T	MSB20
230	*Terminalia macroptera* Guill.	Combretaceae	Kewshi	T	MSB51
231	*Thunbergia annua* Hochst. ex Nees	Acanthaceae	26	H	MSB164
232	*Tinnea aethiopica* Kotschy ex Hook.f.	Lamiaceae	17	Sh	MSB143
233	*Tragia abortiva* M. Gilbert	Euphorbiaceae	Wususo	Sh	MSB244
234	*Tragia brevipes* Pax	Euphorbiaceae	Lusha	H	MSB85
235	*Triumfetta cordifolia* A. Rich.	Tiliaceae	Lagi	Sh	MSB105
236	*Triumfetta rhomboidea* Jacq.	Tiliaceae	Lagi (folded)	H	MSB157
237	*Vachellia dolichocephala* Harms	Fabaceae	Wurer	T	MSB219
238	*Vachelia tortilis* (Forssk.) Galasso & Bonfi	Fabaceae	Sewti	T	MSB57
239	*Vangueria apiculata* K. Schum	Rubiaceae	Dhuka gara	Sh	MSB205
240	*Vangueria madagascariensis* J.F.Gmel.	Rubiaceae	Gara	Sh	MSB09
241	*Vatovaea pseudolablab* (Harms) Gillett	Fabaceae	Turna	L	MSB54
242	*Vernonia adoensis* Sch. Bip. ex Walp.	Asteraceae	Terara geri	Sh	MSB76
243	*Vernonia amygdalina* Del. in cail.	Asteraceae	Geri	Sh	MSB63
244	*Vernonia auriculifera* Hiern.	Asteraceae	5	Sh	MSB104
245	*Vernonia bipontini* Vatke	Asteraceae	Archaro	Sh	MSB69
246	*Withania somnifera* (L.)	Solanaceae	Mutimura	Sh	MSB197
247	*Xanthium strumarium* L.	Asteraceae	37	H	MSB191
248	*Ximenia americana* L.	Olacaceae	Gaya mekela	Sh/T	MSB113
249	*Ximenia caffra* Sond.	Olacaceae	Edi mekela	Sh/T	MSB124
250	*Zanthoxylum chalybeum* Engl.	Rutaceae	Gedek	Sh	MSB136
251	*Zehneria scabra* (Linn.f.) Sond.	Cucurbitaceae	Nech hareg	C	MSB168
252	*Ziziphus abyssinica* Hochst. ex A. Rich.	Rhamnaceae	Onoko	Sh/T	MSB163
253	*Ziziphus mucronata* wild.	Rhamnaceae	Gurchenti	Sh/T	MSB08
254	*Ziziphus pubescens* Oliv.	Rhamnaceae	Anshel	T	MSB192

N.B. VN-Voucher Number; MSB –Mesfin Belete and number is the order number of vouchr specimen)

Appendix 2. Plant species recorded in Sida Forest but not reported in Gamo Gofa Floristic Region of the Flora of Ethiopia and Eritrea.

No.	**Scientific name**	**Family**	**Habit**	**F.Volume**	**Gamo Floristic region**
1	*Agarista salicifolia*	Ericaceae	T	V4P1P48	NOT

2	*Albizia gummifera*	Fabaceae	T	V3P96	NOT
3	*Brucea antidysenterica*	Simaroubaceae	Sh	V3P430	NOT
4	*Clausena anisata*	Rutaceae	Sh/T	V3P429	NOT
5	*Clutia abyssinica*	Euphorbiaceae	Sh	V2P2P286	NOT
6	*Coffea arabica*	Rubiaceae	Sh	V4P1P266	NOT
7	*Combretum collinum*	Combretaceae	T	V2P2P116	NOT
8	*Croton macrostachyus*	Euphorbiaceae	T	V2P2P326	NOT
9	*Cyathula polycephala*	Amaranthaceae	H	V2P1P317	NOT
10	*Cyperus longibracteatus*	Cyperaceae	H	V6P456	NOT
11	*Cyphostemma niveum*	Vitaceae	C	V3P415	NOT
12	*Debregeasia saeneb*	Urticaceae	Sh	V3P320	NOT
13	*Diospyros abyssinica*	Ebenaceae	T	V4P1P50	NOT
14	*Diospyros mespiliformis*	Ebenaceae	T	V4P1P50	NOT
15	*Discopodium penninervium*	Solanaceae	Sh	V5P150	NOT
16	*Dracaena afromontana*	Dracaenaceae	Sh/T	V6P76	NOT
17	*Dregea schimperi*	Asclepiadaceae	C	V4P1P151	NOT
18	*Droguetia iners*	Urticaceae	H	V3P322	NOT
19	*Dryopteris schimperiana*	Dryopteridaceae	F	V1P152	NOT
20	*Eragrostis longifolia*	Poaceae	G	V7P118	NOT
21	*Eragrostis virescens*	Poaceae	G	V7P122	NOT
22	*Eugenia bukobensis*	Myrtaceae	T	V2P2P75	NOT
23	*Gardenia ternifolia*	Rubiaceae	T	V4P1P253	NOT
24	*Gomphocarpus purpurascens*	Asclepiadaceae	H	V4P1P124	NOT
25	*Hagenia abyssinica*	Rosaceae	T	V3P43	NOT
26	*Indigofera hirsute*	Fabaceae	H	V3P135	NOT
27	*Jasminum abyssinicum*	Oleaceae	L/c	V4P1P85	NOT
28	*Juniperus procera*	Cuprussaceae	T	V1P193	NOT
29	*Lantana trifolia*	Verbanaceae	Sh	V5P507	NOT
30	*Maytenus arbutifolia*	Celastraceae	T/Sh	V3P335	NOT
31	*Millettia ferruginea*	Fabaceae	T	V3P108	NOT
32	*Momordica foetida*	Cucurbitaceae	C	V2P2P42	NOT
33	*Myrsine africana*	Myrsinaceae	Sh	V4P1P66	NOT
34	*Nicandra physaloides*	Solanaceae	H	V5P156	NOT
35	*Nuxia congeta*	Loganiaceae	T	V4P1P72	NOT
36	*Olinia rochetiana*	Oliniaceae	T/Sh	V2P1P409	NOT
37	*Oncoba spinosa*	Flacourtiaceae	Sh/T	V2P1P443	NOT
38	*Periploca linearifolia*	Asclepiadaceae	L	V4P1P104	NOT
39	*Phyllanthus rotundifolius*	Euphorbiaceae	H	V2P2P280	NOT

40	*Physalis peruviana*	Solanaceae	H	V5P153	NOT
41	*Piper capense*	Piperaceae	Sh	V2P1P59	NOT
42	*Plectranthus lanuginosus*	Lamiaceae	H	V5P595	NOT
43	*Premna schimperi*	Lamiaceae	Sh	V5P519	NOT
44	*Prunus africana*	Rosaceae	T	V3P41	NOT
45	*Pteridium aquilinum*	Dennstaedtiaceae	F	V1P106	NOT
46	*Rhoicissus tridentata*	Vitaceae	L/C	V3P401	NOT
47	*Rhus longipes*	Anacardiaceae	Sh	V3P528	NOT
48	*Rhus vulgaris*	Anacardiaceae	Sh/T	V3P529	NOT
49	*Satureja punctata*	Lamiaceae	H	V5P557	NOT
50	*Schefflera abyssinica*	Araliaceae	T	V3P539	NOT
51	*Senna singueana*	Fabaceae	Sh/T	V3P59	NOT
52	*Solanum anguivi*	Solanaceae	Sh	V5P129	NOT
53	*Stereospermum kunthianum*	Bignoniaceae	Sh/T	V5P323	NOT
54	*Tagetes minuta*	Asteraceae	H	V4P2P281	NOT
55	*Thunbergia annua*	Acanthaceae	H	V5P355	NOT
56	*Vernonia adoensis*	Asteraceae	Sh	V4P2P98	NOT
57	*Vernonia auriculifera*	Asteraceae	Sh	V4P2P83	NOT
58	*Vernonia bipontini*	Asteraceae	Sh	V4P2P84	NOT

Appendix 3. Structure (frequency, abundance, density, basal area, relative frequency, relative density, relative dominance and important value index) of woody species in Sida Forest.

No.	Species	F (%)	BA	D/ha	BA(m^2)/ha	RF	RD	RDO	IVI
1	*Podocarpus falcatus*	25.61	195	59.45	2.267	1.97	3.26	9.391	14.62
2	*Syzygium guineense subsp. afromontanum*	20.73	208	63.41	1.837	1.59	3.48	7.606	12.68
3	*Combretum molle*	42.68	193	58.84	1.253	3.28	3.23	5.188	11.70
4	*Ficus sycomorus*	13.41	13	3.96	1.898	1.03	0.22	7.862	9.11
5	*Croton macrostachyus*	26.83	127	38.72	0.864	2.06	2.13	3.578	7.77
6	*Ficus thonningii*	17.07	109	33.23	1.099	1.31	1.82	4.551	7.69
7	*Vangueria madagascariensis*	42.68	181	55.18	0.103	3.28	3.03	0.428	6.74
8	*Terminalia brownii*	24.39	120	36.59	0.659	1.88	2.01	2.731	6.62
9	*Terminalia macroptera*	26.83	118	35.98	0.519	2.06	1.97	2.149	6.19
10	*Phoenix reclinata*	20.73	139	42.38	0.465	1.59	2.33	1.924	5.85
11	*Juniperus procera*	12.20	66	20.12	0.878	0.94	1.10	3.635	5.68
12	*Entada abyssinica*	18.29	91	24.09	0.628	1.41	1.52	2.602	5.53
13	*Hagenia abyssinica*	4.88	19	5.79	1.081	0.38	0.32	4.479	5.17
14	*Eugenia bukobensis*	20.73	104	31.71	0.416	1.59	1.74	1.721	5.06
15	*Rhus vulgaris*	30.49	116	35.37	0.106	2.35	1.94	0.439	4.73
16	*Calpurnia aurea*	23.17	144	43.90	0.096	1.78	2.41	0.396	4.59

17	*Discopodium penninervium*	26.83	132	40.24	0.025	2.06	2.21	0.104	4.38
18	*Osyris quadripartita*	20.73	124	37.80	0.169	1.59	2.08	0.701	4.37
19	*Diospyros mespiliformis*	3.66	8	2.44	0.923	0.28	0.13	3.821	4.24
20	*Maesa lanceolata*	19.51	120	36.59	0.153	1.50	2.01	0.633	4.14
21	*Ficus sur*	6.10	13	3.96	0.827	0.47	0.22	3.423	4.11
22	*Acacia goetzei Harms*	20.73	50	15.24	0.304	1.59	0.84	1.259	3.69
23	*Acacia hockii*	20.73	66	20.12	0.227	1.59	1.10	0.939	3.64
24	*Senna singueana*	25.61	78	23.78	0.043	1.97	1.31	0.178	3.45
25	*Bersama abyssinica*	12.20	71	21.65	0.320	0.94	1.19	1.327	3.45
26	*Ficus vasta*	4.88	5	1.52	0.713	0.38	0.08	2.951	3.41
27	*Dombeya torrida*	6.10	40	12.20	0.548	0.47	0.67	2.269	3.41
28	*Cordia africana*	10.98	25	7.62	0.497	0.84	0.42	2.059	3.32
29	*Ziziphus mucronata*	21.95	87	26.52	0.040	1.69	1.46	0.167	3.31
30	*Albizia gummifera*	9.76	30	9.15	0.493	0.75	0.50	2.043	3.30
31	*Grewia velutina*	14.63	61	18.60	0.277	1.13	1.02	1.145	3.29
32	*Coffea arabica*	15.85	118	35.98	0.023	1.22	1.97	0.093	3.29
33	*Grewia tenax*	20.73	89	27.13	0.028	1.59	1.49	0.116	3.20
34	*Olea europaea Subsp. cuspidata*	8.54	69	21.04	0.302	0.66	1.15	1.249	3.06
35	*Lannea fruticosa*	14.63	62	18.90	0.209	1.13	1.04	0.864	3.03
36	*Ekebergia capensis*	6.10	28	8.54	0.417	0.47	0.47	1.726	2.66
37	*Ficus ovata*	1.22	8	2.44	0.584	0.09	0.13	2.419	2.65
38	*Dodonaea angustifolia*	17.07	71	21.65	0.027	1.31	1.19	0.111	2.61
39	*Nuxia congeta*	12.20	43	13.11	0.182	0.94	0.72	0.755	2.41
40	*Millettia ferruginea*	10.98	49	14.94	0.168	0.84	0.82	0.694	2.36
41	*Diospyros abyssinica*	4.88	12	3.66	0.418	0.38	0.20	1.730	2.31
42	*Maytenus addat*	15.85	54	16.46	0.008	1.22	0.90	0.033	2.16
43	*Schefflera abyssinica*	9.76	35	10.67	0.158	0.75	0.59	0.654	1.99
44	*Combretum collinum*	8.54	26	7.93	0.179	0.66	0.44	0.741	1.83
45	*Stereospermum kunthianum*	13.41	37	11.28	0.040	1.03	0.62	0.167	1.82
46	*Maytenus arbutifolia*	7.32	55	16.77	0.038	0.56	0.92	0.159	1.64
47	*Dracaena afromontana*	8.54	47	14.33	0.026	0.66	0.79	0.106	1.55
48	*Mimusops kummel*	3.66	20	6.10	0.224	0.28	0.33	0.928	1.54
49	*Olinia rochetiana*	8.54	22	6.71	0.104	0.66	0.37	0.431	1.46
50	*Maytenus undata*	7.32	44	13.41	0.012	0.56	0.74	0.051	1.35
51	*Bridelia micrantha*	1.22	2	0.61	0.278	0.09	0.03	1.150	1.28
52	*Teclea nobilis*	8.54	28	8.54	0.015	0.66	0.47	0.061	1.19
53	*Clausena anisata*	7.32	28	8.54	0.025	0.56	0.47	0.102	1.13
54	*Acalypha fruticosa*	8.54	24	7.32	0.004	0.66	0.40	0.015	1.07
55	*Protea gaguedi*	7.32	23	7.01	0.027	0.56	0.38	0.110	1.06

56	*Agarista salicifolia*	6.10	8	2.44	0.082	0.47	0.13	0.341	0.94
57	*Oncoba spinosa*	6.10	26	7.93	0.008	0.47	0.44	0.034	0.94
58	*Syzygium guineense subsp. Guineense*	4.88	13	3.96	0.083	0.38	0.22	0.342	0.93
59	*Euclea racemosa*	6.10	23	7.01	0.013	0.47	0.38	0.054	0.91
60	*Acacia seyal*	3.66	7	2.13	0.115	0.28	0.12	0.475	0.87
61	*Galiniera saxifraga*	4.88	20	6.10	0.026	0.38	0.33	0.106	0.82
62	*Vangueria apiculata*	4.88	23	7.01	0.008	0.38	0.38	0.034	0.79
63	*Vernonia amygdalina*	4.88	19	5.79	0.013	0.38	0.32	0.056	0.75
64	*Lannea schimperi*	3.66	10	3.05	0.068	0.28	0.17	0.283	0.73
65	*Ximenia caffra*	4.88	17	5.18	0.015	0.38	0.28	0.061	0.72
66	*Grewia trichocarpa*	4.88	17	5.18	0.012	0.38	0.28	0.051	0.71
67	*Rhus natalensis*	3.66	21	6.40	0.011	0.28	0.35	0.044	0.68
68	*Oncoba routledgei*	4.88	16	4.88	0.007	0.38	0.27	0.029	0.67
69	*Hymenodictyon floribundum*	4.88	12	3.66	0.006	0.38	0.20	0.027	0.60
70	*Ziziphus pubescens*	3.66	15	4.57	0.015	0.28	0.25	0.063	0.60
71	*Debregeasia saeneb*	3.66	17	5.18	0.005	0.28	0.28	0.023	0.59
72	*Ziziphus abyssinica*	3.66	16	4.88	0.003	0.28	0.27	0.013	0.56
73	*Acacia dolichocephala*	3.66	7	2.13	0.037	0.28	0.12	0.154	0.55
74	*Boswellia neglecta*	3.66	4	1.22	0.044	0.28	0.07	0.182	0.53
75	*Acacia robusta*	2.44	7	2.13	0.047	0.19	0.12	0.193	0.50
76	*Phytolaca dodecandra*	2.44	17	5.18	0.005	0.19	0.28	0.020	0.49
77	*Ximenia americana*	3.66	11	3.35	0.005	0.28	0.18	0.019	0.48
78	*Balanites rotundifolia*	1.22	2	0.61	0.080	0.09	0.03	0.333	0.46
79	*Albizia schimperiana*	2.44	5	1.52	0.039	0.19	0.08	0.162	0.43
80	*Acacia tortilis*	2.44	5	1.52	0.038	0.19	0.08	0.159	0.43
81	*Balanites aegyptiaca*	2.44	3	0.91	0.040	0.19	0.05	0.167	0.40
82	*Diospyros scabra*	1.22	4	1.22	0.050	0.09	0.07	0.208	0.37
83	*Brucea antidysenterica*	2.44	8	2.44	0.003	0.19	0.13	0.011	0.33
84	*Grewia mollis*	2.44	8	2.44	0.002	0.19	0.13	0.008	0.33
85	*Ricinus communis*	2.44	8	2.44	0.001	0.19	0.13	0.004	0.33
86	*Allophylus rubifolius*	2.44	7	2.13	0.001	0.19	0.12	0.005	0.31
87	*Piliostigma thonningii*	2.44	5	1.52	0.002	0.19	0.08	0.006	0.28
88	*Dichrostachys cinereal*	1.22	3	0.91	0.025	0.09	0.05	0.104	0.25
89	*Rhus longipes*	1.22	8	2.44	0.003	0.09	0.13	0.011	0.24
90	*Gardenia ternifolia*	1.22	3	0.91	0.009	0.09	0.05	0.038	0.18
91	*Grewia villosa*	1.22	4	1.22	0.003	0.09	0.07	0.011	0.17
92	*Acacia brevispica*	1.22	2	0.61	0.001	0.09	0.03	0.004	0.13

Appendix 4. Environmental data of Sida Forest

Plot	Altitude	Slope	Aspect	Disturbance	Sand	Clay	Silt	PH	EC	OC	OM	TN	Av. P	CEC	Ca++	Mg++	K+	BD
1	1505	12	3.3	2	70	10	20	6.2	45	1.5	2.6	0.13	12.12	17.2	11	5	0.32	0.503
2	1631	14	1.3	1	78	10	12	6.3	67	1.66	2.8	0.14	13.05	7	5	1	0.65	0.26
3	1647	11	1.3	2	70	12	18	6.1	88	2.03	3.5	0.18	16.79	8.6	5	3	0.8	0.268
4	1678	9	1.3	4	70	16	14	6.4	66	2.71	4.7	0.235	4.24	16.4	6	6	0.18	0.501
5	1843	5	3.3	1	70	10	20	5.7	86	1.61	2.7	0.135	12.59	18	4	10	0.2	0.195
6	2092	12	1.3	1	56	20	24	6.2	286	4.75	8.18	0.4	20.27	25.2	9	8	1.6	0.25
7	2176	45	3	0	70	10	20	6	630	1.55	1.6	0.08	12.59	20.4	0	13	1.5	0.131
8	2104	50	3.3	0	66	20	14	4.9	119	3.01	5.2	0.26	4.69	9.4	1	4	0.18	0.141
9	2051	27	2.5	0	62	16	22	5	42	3.59	6.05	0.3	7.52	16.4	4	3	0.17	0.315
10	1761	50	3	1	72	18	10	5.8	154	3.05	5.14	0.255	6.39	12.4	6	7	0.04	0.503
11	1714	36	3.3	1	80	8	12	6	53	0.95	1.6	0.08	3.88	1.4	1	0	0.09	0.461
12	1581	12	3.3	4	78	16	6	6.7	170	2.27	3.79	0.2	15.5	13.2	11	3	0.4	0.37
13	1589	10	3	2	60	20	20	6.8	382	10.45	18	0.9	5.75	38.2	38	5	0.4	0.54
14	1650	15	2.5	1	60	20	20	4.6	208	4.35	7.5	0.38	7.83	14.2	4	4	0.24	0.506
15	1763	8	3.3	1	60	20	20	5.8	287	5.56	9.6	0.48	6.18	26.4	12	11	0.37	0.481
16	1847	32	3	0	78	12	10	6.5	145	2.22	3.8	0.19	16.14	15	6	8	0.32	0.197
17	1973	8	4	1	72	8	20	6.3	71	1.33	2.3	0.11	7.79	8.6	3	6	1.02	0.249
18	2058	3	3	0	60	18	22	5.5	84	1.8	3.1	0.155	7.62	8.4	4	7	0.5	0.314
19	2076	16	3.3	0	76	2	22	6.1	105	1.41	2.4	0.12	35.09	20.4	10	0	0.63	0.28
20	2092	50	3.3	0	70	16	14	6	205	5.25	9	0.45	5.05	15	8	11	0.3	0.271
21	1979	54	2	0	74	20	6	5.9	144	2.66	4.58	0.23	6.53	29	10	9	0.32	0.249
22	1863	4	2	0	72	10	18	6.4	140	1.7	2.9	0.145	37.37	11	2	0	1.7	0.133
23	1691	10	2	3	74	12	14	6.1	225	3.4	5.7	0.28	18.05	11	10	5	0.22	0.501
24	1564	10	3	2	60	18	22	7.1	105	0.78	1.31	0.06	15.3	14.4	5	6	2.3	0.253
25	1644	10	2	1	60	26	14	6.1	59	1.97	3.27	0.16	13.8	16.4	10	10	0.09	0.463
26	1715	10	2	2	72	20	8	5.8	83	1.42	2.41	0.12	21.36	12	5	6	0.2	0.504
27	1861	13	1	0	78	10	12	5.5	37	2	3.4	0.17	1.43	13.2	3	8	0.17	0.136
28	1985	16	1.3	0	60	24	16	5.4	146	2.14	3.5	0.18	16.47	17.6	10	2	0.2	0.245

29	2139	13	2	0	62	18	20	6.2	184	3.46	5.86	0.29	20.6	14.6	9	9	0.73	0.132
30	2037	3	3	0	64	22	14	6.2	182	4.16	6.9	0.345	14.2	19	15	6	0.5	0.241
31	1907	20	1.3	0	54	24	22	6	163	3.99	6.7	0.335	2.29	27.4	13	9	0.4	0.133
32	1889	9	3.3	1	78	12	10	6.2	48	0.78	1.34	0.07	26.72	15	5	9	0.1	0.141
33	1871	20	3.3	0	56	16	28	5.9	14	0.84	1.41	0.07	14.29	16.4	3	0	0.1	0.135
34	1890	18	3	0	66	16	18	5.4	47	3.76	6.48	0.34	26.11	8.4	5	8	0.1	0.137
35	1784	26	3	1	68	12	20	5.7	113	1.41	2.43	0.12	28.23	13.6	3	5	0.9	0.501
36	1786	8	3.3	4	68	20	12	5.7	161	2.63	4.5	0.2	10.67	16	6	9	0.29	0.503
37	1716	17	3.3	1	68	10	22	5.2	87	1.9	3.2	0.16	7.62	16.4	0	14	0.04	0.504
38	1650	18	3.3	1	60	20	20	6	145	3.9	6.7	0.335	4.78	24.4	11	13	0.4	0.502
39	1541	13	3	0	70	18	20	6.8	153	3.55	6	0.3	8.25	22.2	17	7	0.37	0.506
40	1521	2	3	4	68	10	22	6.8	163	4.29	7.2	0.36	13.8	15	14	7	1.25	0.462
41	1667	10	3	2	72	8	20	6.5	350	3.75	6.9	0.35	9.49	13.4	10	7	1.4	0.503
42	1776	20	3.3	0	72	8	20	5.5	90	2.06	3.5	0.18	8.95	10.6	6	4	0.23	0.432
43	1840	9	3.3	0	68	16	16	6.4	79	2.04	3.5	0.17	5.72	13.4	8	11	0.17	0.193
44	1950	13	1	0	70	16	14	6.4	66	2.71	4.7	0.235	3.88	16.4	6	6	0.18	0.246
45	2066	8	1.3	0	60	26	14	5.9	153	4.81	8.1	0.4	4.48	22.4	10	4	0.18	0.251
46	2146	45	1.3	0	58	20	22	6.2	139	3.01	5	0.25	4.26	20	10	9	0.58	0.138
47	2209	16	1.3	0	60	20	20	6.5	170	4.7	7.9	0.4	3.91	22.6	16	8	0.4	0.196
48	2316	17	1	1	48	22	30	5.8	145	1.99	3.3	0.65	7.49	21.6	7	8	0.3	0.141
49	2343	14	1	0	52	22	26	4.9	37	8.8	15.2	0.76	5.76	49	12	16	0.5	0.14
50	2335	1	1.3	0	32	38	30	6.5	86	5.94	9.99	0.5	2.78	34.2	9	6	0.6	0.13
51	2178	14	3.3	0	80	10	10	6.4	105	2.7	4.5	0.22	10.71	8.4	4	1	0.1	0.142
52	2228	47	2.5	0	54	22	24	5.7	292	5.52	9.5	0.48	5.95	24	11	9	0.36	0.193
53	2220	10	2.5	0	74	6	20	5.5	115	1.24	2	0.1	3.47	7.8	4	3	0.32	0.136
54	2106	13	3.3	0	66	22	12	6.1	84	2.69	4.5	0.225	5.1	18.4	4	5	0.8	0.148
55	1985	18	3.3	0	72	8	20	6.6	101	1.89	3.17	0.16	6.67	14.4	14	2	0.34	0.231
56	1800	23	2.5	0	68	18	14	6.1	135	3.9	6.6	0.33	3.54	19	15	3	0.5	0.193
57	1834	13	2.5	0	56	28	16	6.3	30	1.12	1.87	0.09	1.85	20	10	4	0.15	0.132
58	1768	6	1.3	3	70	12	18	5.7	102	1.81	3.1	0.155	14.62	18	15	3	0.6	0.541

59	1690	8	1.3	2	66	18	16	6.5	208	4.61	7.94	0.4	6.79	36.4	20	10	0.3	0.46
60	1618	2	3.3	3	76	12	12	6.4	183	9.17	15.34	0.8	6.66	29.6	24	6	0.5	0.495
61	2310	11	3.3	0	72	12	16	6.5	276	5.78	9.7	0.49	7.42	26.4	15	16	0.5	0.145
62	2288	9	3.3	0	70	10	20	6.9	169	3.02	4.99	0.25	31.72	4.6	11	0	0.96	0.139
63	2275	7	3.3	0	64	22	14	6.7	155	4.75	8	0.4	6.37	30.4	18	7	0.5	0.192
64	2265	48	3.3	0	70	8	22	5.5	67	1.84	3.1	0.155	11.12	17.8	6	12	0.1	0.19
65	2283	15	3.3	0	74	14	12	6.2	85	3.04	5.2	0.26	11.16	13	7	5	0.8	0.138
66	2264	6	3.3	0	70	10	20	5.7	135	3.45	5.9	0.3	44.06	21.2	10	9	0.26	0.132
67	2286	10	4	0	72	6	22	5.5	56	1.75	2.93	0.15	21.62	14.4	8	8	0.09	0.137
68	2309	24	4	0	76	14	10	6.1	99	3.42	5.9	0.3	10.51	21	11	9	0.32	0.135
69	1775	50	4	3	68	20	12	6.5	225	5.13	8.62	0.4	8.14	26.6	21	7	0.35	0.194
70	1783	49	4	2	72	6	22	6.2	228	4.89	8.3	0.4	7.26	29	13	15	0.58	0.195
71	1714	10	4	1	70	16	14	6.3	264	5.27	8.96	0.45	5.23	26.8	16	7	0.58	0.138
72	1640	14	3.3	2	74	12	14	6.1	125	2.31	4	0.2	10	14	10	4	0.14	0.135
73	2041	48	1	0	75	17	8	6.5	64	5.6	9.7	0.48	6.69	10.4	7	8	0.3	0.246
74	2172	38	1	0	68	17	15	6.2	109.3	2.8	4.7	0.23	6.69	15.6	6	5	0.49	0.139
75	2294	22	1	0	67	25	8	6.5	185.3	9.13	15.74	0.78	7.56	27.2	17	15	0.3	0.195
76	2330	22	2	0	48	34	18	5.9	118.3	8.93	15.41	0.75	7.23	38.4	15	12	0.27	0.194
77	2386	51	2	0	47	31	22	6	78.5	11.5	19.8	0.99	3.95	21.2	9	8	0.7	0.139
78	2375	23	3	0	51	31	18	5.5	180.3	10.43	17.98	0.9	7.56	41.6	15	7	0.74	0.136
79	2357	5	3	0	45	37	18	5.6	81.2	14.56	25.1	1.25	2.97	29.2	9	6	0.3	0.194
80	2335	26	3	0	45	37	18	5.9	130	8.6	14.86	0.7	7.53	37.6	12	12	0.3	0.195
81	2409	16	4	0	39	43	18	6.2	69.2	14.21	24.5	1.2	7.55	33.6	10	14	0.3	0.138
82	2339	5	1.3	0	51	31	18	5.9	106.6	9.26	15.96	0.8	7.11	39.2	17	11	0.24	0.135

Appendix 5: Interview questions for ethnobotanical data collection of *Piliostigma thonningii*

Are you willing to participate in this study of *Piliostigma thonningii*?

"Do you know *Piliostigma thonningii*?" ☐ Yes ☐ No, If yes, continue with the interview.

Section 1: Basic information about the area

Date of interview:	Start time of interview:
Name of interviewer:	
Region:	Zone:
WEREDA/District:	KEBELE/Sub-District:
Latitude (in decimal degrees):	Longitude (in decimal degrees):
Altitude (in meter)	
Agroecological classification (e.g. H1, SH2):	
Relative Wealth status of respondent: ☐High/Middle income ☐Low income	

Section 2: General information about Informant

Name of informant:	
Language spoken during interview: ☐ Amharic ☐ Other (specify):	
Age (observed): ☐ 18 to 30 ☐ 31 to 45 ☐ 46 to 60 ☐ 61 and older	
Gender (observed): ☐ Male ☐ Female	
Is the informant the household head? ☐ Yes ☐ No	
Family size of respondent: ☐≤ 3 ☐4-6 ☐7-9 ☐≥ 10	
Education of respondent: ☐Illiterate ☐read and write ☐Grade 1st -4th☐Grade 5th -8th☐Grade 9th -10th☐Grade 11th -12th☐Certificate ☐Diploma ☐≥Degree	
Land size of respondent (ha): (only for farmers and agro-pastoralists	☐≤ 0.5 ☐0.51-1 ☐1.1-1.5 ☐1.51-2 ☐ ≥2.1
How many parcels of land do you hold?	

Section 3: Information about *Piliostigma thonningii*

1. Do you know *Piliostigma thonningii* personally?

Yes B) No

2. Are there any other local names for *Piliostigma thonningii* tree? ....
3. Where are *Piliostigma thonningii* tree more available?
   A) Farmland B) Wild C) both D) Not identified E) Other
4. Has the presence/abundace of *Piliostigma thonningii* tree changed when you compare with the past?
   A) Increasing B) Decreasing C) It is the same D) It is difficult to estimate E) Other
5. How many kinds of *Piliostigma thonningii* tree do you recognize in your locality? …….
6. If your answer for question 5 is more than one, what are the local names for each kind? ......

Section 4: Uses of *Piliostigma thonningii* as food for humans and feed/fodder for livestock

1. Do you use *Piliostigma thonningii* as a source of food?
   A) Yes B) No
2. Which part of *Piliostigma thonningii* is edible or consumed as food?
   A) Seed ☐ B) Fruit ☐ C) Leaf ☐ D) Root ☐ E) Stem ☐ F) Bark ☐ G) If other part (Specify)……….
3. Which part is the most commonly consumed? ……………….……………
4. Which gender and age group collects the different parts of the tree for food consumption?

Male children B) Female childern C) Male adult D) Female adult E) Male elder F) Female elder

5. How do you consume *Piliostigma thonningii*?

A) Raw B) As a drink C) Cooked D) as a spice E) if other (specify)? …………

6. Which gender and age groups consume *Piliostigma thonningii*?

A) Male children B) Female childern C) Male adult D) Female adult E) Male elder F) Female elder

7. How frequently do you consume the plant part, when it is available?

A) Three time per day B) Two times per day C) Once per day D) Once in a week

E) Every four day F) During food scarcity only G) if other (specify)? ....

8. Where do you obtain *Piliostigma thonningii* edible part?

A) Grazing land B) From farmland C) Homegarden D) From Market

E) Forest/woodland

9. How far from your home? (Estimate in minutes)……………………………………..

10. Have you ever been faced with side effects of *Piliostigma thonningii* on your health during consumption?

A) Yes B) No

11. Do livestock feed on *Piliostigma thonningii*?

A) Yes B) No

Section 5: Ethnobotanical uses of *Piliostigma thonningii* for traditional human and livestock medicinal purpose

1. Do you use *Piliostigma thonningii* for the treatments of human ailments?

A) Yes B) No

2. If yes, for what human ailment do you use it? What part do you use?

3. Do you use *Piliostigma thonningii* for the treatments of animal ailments?

A) Yes B) No

4. If yes, for what livestock ailment do you use it? What part do you use?

5. Among the following ethnobotanical uses of plants, which one is contributed by *Piliostigma thonningii?* And give number in ascending order 1 for the most important and 8 to the least?

A) Medicinal values ☐ B) Food sources ☐ C) Timber ☐ D) Fuel wood ☐ E) shade ☐

F) Increasing soil fertility ☐ G) Fodder for livestock ☐ H) Honeybee forage I) If any other (specify)?

....

Section 6: Management, utilization and conservation practice of *Piliostigma thonningii* tree

1. Do you know how *Piliostigma thonningii* is established?

A) Yes B) No

2. Have you ever planted it?

A) Yes B) No

3. Do you give any care for the establishment of *Piliostigma thonningii*?

A) Yes B) No

4. Once established do you take care of the tree?

A) Yes B) No

5. Are you doing anything to keep *Piliostigma thonningii* available for use in your area for the future?

A) Yes B) No

6. Are there bylaws/cultural rules to control illegal activities related to the *Piliostigma thonningii* tree in your locality?

Yes B)No

7. Do you cultivate crops under the *Piliostigma thonningii* tree canopy?

A) Yes B) No

8. Do you cultivate crops near *Piliostigma thonningii* trees (not under the canopy)?

A) Yes B) No

9. Does the tree coppice?

10. Does the tree regenerate from seeds under natural conditions?

11. Does the tree propagate from cuttings?

12. Is there any disease or pests that attack *Piliostigma thonningii* trees?

A) Yes B) No

13. Is there any loss of *Piliostigma thonningii* Tree in your locality?

Yes B) No

14. What is your attitude towards maintaining this plant in your area?

A) Interested B) Moderately interested C) Not interested

Section 7: Closing and follow-up questions:

We are looking for both men and women who have a lot of knowledge about different varieties of *Piliostigma thonningii*. Is there anyone from your community who you recommend?	
Thank you very much for answering my questions. Do you have any comments and/or questions you would like to raise at this time?	
Time interview was completed:	*Duration of interview (minutes):*

Semi-structured Interview with Key Informant

Informed Oral Consent: Do you agree to participate in this study of *P. thonningii*?

Section 1: Basic information about Key Informant

Date of interview:	Start time of interview:
Name of interviewer:	
Region:	Zone:
WEREDA/District:	KEBELE/Sub-District:
Language spoken during interview: ☐ Amharic ☐ Other (specify):	
Name of informant:	
Age (observed): ☐ 18 to 30☐ 31 to 45☐ 46 to 60☐ 61 and older	
Gender (observed): ☐ Male ☐ Female Household head? Yes or no	

Section 2: Information about *Piliostigma thonningii*tree

1. Are there any other local names for *Piliostigma thonningii* tree? ....
2. What does the name refers to? ....
3. How many kinds of *Piliostigma thonningii* tree do you recognize in your locality?
4. If your answer for question no3 is more than one, what are the local names for each kind? ………………………………………………………………………………………………
5. How do you differentiate? What are the key identifying criteria (like, growing habit (Shape, color, size), use, agroecology, phenology (flowering, fruiting etc), or others) ………….

Section 3: Uses of *Piliostigma thonningii* as human food and for livestock feed

1. Which part of *Piliostigma thonningii* is edible or consumed as human food?

A) Seed B) Fruit C) Leaf D) Root E) Stem F) Bark

2. If you listed more than one, which part is the most commonly consumed? Write in ascending order by giving number 1 for the most consumed part.

A) Seed ☐ B) Fruit ☐ C) Leaf ☐ D) Root ☐ E) Stem ☐ F) Bark ☐ G) If other part (Specify)………………………………………………………………………………..

3. How much is harvested per category? ....……

4. Have you ever faced any side effects on your health during consumption of *Piliostigma thonningii*?

A) Yes B) No

5. If yes to question 9, what type of side effect did you face because of consumption?

A) Indigestibility B) Constipation C) Loss of appetite D) Diarrhea E) if other (Specify) ………

6. Do livestock feed on *Piliostigma thonningii*?

A) Yes B) No

7. If yes to question 11, which part is more consumed by the livestock? Give number 1 for the most consumed part and 2, 3… in ascending from the most to the least.

A) Seed ☐ B) Fruit ☐ C) Leaf ☐ D) Root ☐ E) Stem ☐ F) Bark ☐

8. Which livestock type prefers more *Piliostigma thonningii* as a fodder than the other? Give number in ascending order giving number 1 to the livestock type for which *Piliostigma thonningii* is most preferred.

A) Cattle ☐ B) Goats ☐ C) Sheep ☐ D)Horse ☐ E) Donkey ☐ F) Camel ☐ G) If others?...

9. At what time of the season and maturity stage do animals feed on the parts used? ....

10. Is it given to animals as a sole feed or mixed, if so with what and at what proportion?

…………………………………………………………………………………………….

Section 4: Ethnobotanical uses of *Piliostigma thonningii* for human and livestock medicinal purpose

1. Do you use *Piliostigma thonningii* tree for the treatment of human ailments?

A) Yes B) No

2. Mention the types of human disease treated, symptom, parts used, preparation method, Route of administration, dosage and other uses.

3. Who harvests the plant for medicinal use? ……………………………………………….

4. Are there any restrictions/taboos in collecting this plant?

A) Yes B) No

5. If yes for question 19, describe the restrictions/taboos in collecting this plant? ....

6. When did you harvest the parts you have used?

Early morning B) In the afternoon C) In the evening D) not time dependent

7. Mention the types of animal disease treated, symptom, parts used, preparation method, route of administration, dosage and other uses.
8. Who harvests the plant for use? ……………………………………………….
9. When did you harvest the parts you have used to treat animal disease? ………………………

Section 5: Management, utilization and conservation practice of *Piliostigma thonningii* tree

1. Do you know how *Piliostigma thonningii* is established?

A) Yes B) No

2. If yes, how is *Piliostigma thonningii* established?

A) From agricultural bureau B) From NGO C) Soil seed bank D) through propagation E) cuttings

3. Have you ever planted it?
A) Yes B) No
4. Where did you plant it?
A) Farm land B) Home garden C) Degraded land D) If other (specify)? ……………..
5. Why did you choose or recommend the respective planting area (commercial, protection, management etc)? ....
6. Once established do you take care of the tree?
A) Yes B) No
7. If yes, how do you take care of the tree?
A) Cultivating/hoeing B) Watering C) Pruning/Pollarding D) Weeding (when small) E) Thinning to reduce competition F) Removing sick/damaged plants G) Other:
8. What are you doing to keep *P. thonningii* available for use in your area for the future?
Planting B) Maintaining natural regeneration C) Preventing encroachment
D) Preventing cutting E) other ………………………………………
9. Are there bylaws/cultural rules to control illegal activities related to the *P. thonningii* tree in your locality?
Yes B)No
10. If yes for question 33, what type of cultural rules do you use to control illegal activities? ....
11. Do you cultivate crops under the *P. thonningii* tree canopy?
A) Yes B) No
12. If yes for question 35, describe which crops do you cultivate more? …………………………
13. Why do you plant the crops under the tree canopy?
A) Shade helps B) Soil fertility is higher C) Moisture is higher D) If other (specify)? ....
14. Do you cultivate crops near *P. thonningii* trees (not under the canopy)?
A) Yes B) No
15. Why do you plant the crops near the tree (outside of the canopy)?
A) Soil fertility is higher B) Moisture is higher C) If other (specify) ……………………
16. Do herbs grow under/near the *P. thonningii* tree?
A) Yes B) No
17. If yes for question 40, describe which herbs grow under/near the *P. thonningii*? …………
18. Describe the coppicing behavior of the species?
19. Did you observe any significant problem in keeping or cultivating crops near or under the tree? Describe………………………………………………………………………
20. Is there any disease or pests that attack *P. thonningii* trees?
A) Yes B) No
21. If yes to question 44 (Specify)? .... and show me the pest (if possible)..........
22. How do you prevent or treat this disease or pest? ....
23. Is there any loss of *P. thonningii* tree in your locality?
Yes B) No
24. What are the most destructive/threatening factors to *P. thonningii* trees in your locality? Give in ascending order one for the most treating factor to the least.
A) Timber ☐B) Charcoal ☐C) Grazing ☐D) Fire wood collection ☐
E) House hold utensils☐ F) Farm material ☐ G) If other (Specify)………………………
25. Do you have any question regarding *Piliostigma thonningii?* ....

26. How do you think the sustainable use of this plant could be possible/sound?

Appendix 6: Plant species observed and recorded growing under/near *P. thonningii* tree

No.	**Scientific name**	**Family**	**Local name (Benna Language)**	**Local name (Hamer Language**	**Habit**
1	*Acacia robusta* Burch.	Fabaceae	Dhera	Dhera	T
2	*Acacia goetzei* Harms	Fabaceae	Arke	Arki	T
3	*Acacia hockii* De Wild.	Fabaceae	Chekanti	Chakanti	Sh
4	*Acacia seyal* Del.	Fabaceae	Pulanti	Fulante	T
5	*Acalypha fruticosa* Forssk.	Euphorbiaceae	Septi	Septi	Sh
6	*Adenium obesum* (Forssk.) Roem. & Schult.	Apocynaceae	Gurdo	Gurdo	Sh
7	*Becium obovatum* (E.Mey.ex Benth.	Lamiaceae	Buranbutso	Butamberohat a	H
8	*Cissus rotundifolia* (Forssk.) Vahl	Vitaceae	Kelle	Kelle	C
9	*Clematis simensis* Fresen.	Ranunculaceae	Gayadenpo	Gayatenpo	C
10	*Cynodon dactylon* (L.) Pers.	Poaceae	Zersi	Zersi	G
11	*Dalbergia lactea* Vatke	Fabaceae	Zinzek	Zinzeke	Sh
12	*Entada abyssinica* Steud. Ex A. Rich.	Fabaceae	Longo	Longo	T
13	*Erythrococca abyssinica* Pax	Euphorbiaceae	-	Koda	Sh
14	*Euclea racemosa* Murr.	Ebenaceae	Unsi	Kunsi	Sh
15	*Gardenia ternifolia* Schumach. & Thonn.	Rubiaceae	Gembela	Gembela	T
16	*Grewia velutina* (Forssk.) Vahl.	Tiliaceae	Bereza	Berez	T
17	*Grewia villosa* Will.	Tiliaceae	Gergecha	Gergesho	Sh
18	*Hypoestes forskaoli*i (Vahl) R.Sch.	Acanthaceae	Busunta	Busente	H
19	*Ipomoea kituiensis* Vatke	Convolvulaceae	Gali	-	Sh
20	*Kalancboe citrina* Scweinfurth.	Crassulaceae	Gaya dempo	Gaya tampo	H
21	*Ozoroa insignis* Del.	Anacardiaceae	Selbena	Salbana	Sh
22	*Psychotria orophila* Petit	Rubiaceae	Shawbuno	Shawuno	Sh
23	*Pterolobium stellatum* (Forssk.) Brenan	Fabaceae	Beneka	Gorsa	C
24	*Rhus natalensis* Krauss	Anacardiaceae	Kufure	Kufuri	Sh
25	*Schoenoplectus subulatus* (Vahl) Lye	Cyperaceae	Kontsele	Kuntsele	H
26	*Solanum americanum* Mill.	Solanaceae	Tsepe	Tsepi	H
27	*Teclea nobilis* Del.	Rutaceae	Tsaki		Sh
28	*Terminalia brownii* Fresen.	Combretaceae	Ara	Ara	T
29	*Zanthoxylum chalybeum* Engl.	Rutaceae	Gedek	Gedeka	Sh