ADDIS ABABA UNIVERSITY
COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCE
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Effects of integrated land management, landscape position and land-use types on soil physicochemical properties, discharge, species richness and carbon stock in Geda watershed, north Shewa, Ethiopia

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By Hailu Terefe

A Dissertation Presented to the Graduate Program of Addis Ababa

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Abstract

Watershed based integrated land management is a recent approach to curb land degradation in Ethiopia and introduced in 2012 in Geda watershed, central highlands of Ethiopia. However, the impacts of the interventions on indicators of some ecosystem services were not assessed. The objectives of this study were to explore the effects of the interventions on soil properties, soil moisture content and water discharge, plant species richness, biomass production and carbon stock by comparing treated site with integrated land management measures and the adjacent untreated site. Samples were collected from treated and untreated sites in the upper and lower landscape positions, from cropland, grazing land and Tree Lucerne plantation based on standard procedures for each objective. The collected data were analyzed following standard statistical procedures with respect to treatment, landscape position, land-use type, and soil depth. The introduced integrated land management significantly ($p \leq 0.001$) improved most of the soil physicochemical properties, the soil moisture content, water discharge, plant species richness, biomass production and carbon stocks. Clay, total N, available P and soil organic carbon were significantly higher at $p = 0.001$ and exchangeable K at $p = 0.05$ in the treated site compared to the untreated one. This could be due to higher organic matter accumulation and improved vegetation growth as a result of prohibited free grazing, and reduced erosion by the conservation structures. Sand and bulk density were significantly ($p = 0.001$) higher in the untreated site that could be attributed to erosion due to absence of conservation measures and compaction by livestock trampling during free grazing practice. Generally,in the treated site, the clay content of the soil was improved by 63.51%, OC by 133%, NPK of the soil by 69.84%, *78.49% and 22.73% respectively. The soil moisture content increased by 14.82 − 19.35% and water discharge increased by 588% over the untreated one; which could be due to reduced runoff and evaporation, improved infiltration and storage processes attributed by the conservation structures and vegetation covers. Besides, total plant richness, regeneration of shrubs and indigenous tree species were increased by 18%(N=27),70.59% (N=12) and 66.67% (N=2) respectively, in the treated site compared to the untreated one. In addition, an average 10.72±0.84 Mg ha^{-1} additional carbon stock was observed due to the intervention. Prohibited free grazing and land-use change could have contributed to higher species richness, regeneration of indigenous trees and accumulation of higher plant biomass and accumulation of higher carbon stocks. Tree Lucerne plot showed higher biomass production and carbon stock by plant biomass depicting the positive impact of land-use changes. Tree Lucerne plot significantly ($p = 0.05$) improved the upper soil (0−15 cm) carbon stock which could be due to its N fixing capacity and fast decomposition of the leaves. However, the lower soil (15−30 cm) carbon stock was significantly ($p = 0.001$) higher in the crop land of the treated site which could be ascribed to the conservation structures and tillage operations, that conservation structures trap and accumulate transported organic materials from upper landscape; and tillage facilitates aeration and decomposition processes. Planting Tree Lucerne combined with physical structures as a biological measure and on highly degraded part of the landscape resulted higher plant biomass production and carbon stock through plant biomass. Thus, integrating physical, biological and grazing management is a good land-use practice to be expanded to other degraded landscapes.*

Key words: *Biomass, Carbon stock, integrated land management, Landscape position, Treatment.*

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List of Acronyms

AGB	Above Ground Biomass
AI	Artificial Insemination
ANOVA	Analysis of Variance
CGIAR	Consultative Group For International Agricultural Research
CIAT	International Center for Tropical Agriculture
DBARC	Debre Berhan Agricultural Research Center
FDRE	Federal Democratic Republic of Ethiopia
FFW	Food for Work
GDP	Gross Domestic Product
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
IFPRI	International Food Policy Research Institute
ILRI	International Livestock Research Institute
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
MoA	Ministry of Agriculture
NGOs	Non-Governmental Organizations
NRM	Natural Resource Management
PLUP	Participatory Land-use Planning
AfricaRISING	Africa Research In Sustainable Intensification for the Next Generation
SAS	Statistical Analysis System
SCR	Silt to Clay Ratio
SLM	Sustainable Land Management

SLMP	Sustainable Land Management Program
SNNP(R)	Southern Nations Nationalities and People (Region)
SOC	Soil Organic Carbon
SWC	Soil and Water Conservation
TLU	Tropical Livestock Unit
TN	Total Nitrogen
USAID	United States Agency for International Development
USEPA	United States Environmental Protection Agency
WFP	World Food Program

CHAPTER ONE

1. INTRODUCTION

1.1 Background

The highlands of Ethiopia experienced severe land degradation through soil erosion by water due to proximate causes such as deforestation, overgrazing, over-cultivation, and underlying causes such as population pressure, steepness of the topography, poor farming practices, poverty and tenure insecurity (Gideon, 2004; Haile et al., 2006; Mushir, 2013; Gashaw et al., 2014;2015). Most of the mountainous landscapes of the country have been cultivated for decades without adequate use of soil and water conservation measures to minimize soil erosion by water. As a result, soil erosion by water affected about 50% of the Ethiopian highlands (Asfaw and Neka, 2017; Ebabu et al., 2019). Each year, about 1900 million tons of soil, equivalent to an average net of 100 tons ha^{-1} $year^{-1}$ soil eroded and annual soil loss from farmlands reached 200-300 tons $ha^{-1}year^{-1}$ which is equivalent to 8 mm soil depth (FAO, 1986; Tilahun et al., 2018).

In monetary terms, Ethiopia loses US$ 1 to 2 billion $year^{-1}$ (Dessalegn et al. 2015). Ayalew (2011) reported 17% of the potential annual agricultural GDP has been lost due to physical and biological soil degradation. It is estimated that the cost of land degradation in Ethiopia reached 23% of the country's GDP (Kirui and Mirzabaev, 2015). In addition, soil degradation brings about indirect costs such as loss of environmental services, silting of dams and river beds and reduced groundwater.

In the highlands of Ethiopia, soil erosion by water reduced soil fertility and water availability for agricultural and non-agricultural activities. Unpredictable and uneven distribution of rainfall coupled with lack of adequate water storage capacity increased water demand for agriculture, livestock and human use (Jemberu, 2018). Land-use changes due to soil erosion and human activity in these highlands also contributed to nutrient loss, reduced water holding capacity, reduced base flows and reduced landscape productivity (Yoseph et al., 2017).

Apart from soil erosion, loses in plant species richness and diversity are also increasing ecological problems in the highlands of Ethiopia (Haile et al., 2017; Kidane et al., 2019). Reduction of plant species richness and diversity further affects ecosystem sustainability through the negative effects on the food web connectivity and energy transfer among interacting species (Adu et al., 2017). Evidences showed that erosion controlling measures enhanced vegetation composition and diversity (Mekuria et al., 2011; Damtie, 2017).

Considering the severity of soil erosion and its associated consequences, conservation and restoration measures are essential to improve soil fertility, enhance primary production and nutrient cycling, and preserve biodiversity at farm and landscape levels (Adimassu et al., 2017; Damtie, 2017). Conservation measures can change the physical conditions of soils such as soil organic matter, soil structure, soil water holding capacity, soil bulk density, soil porosity, soil pH and its workability (Mulugeta and Karl, 2010).

Thus, the government of Ethiopian launched massive rehabilitation programs starting from mid–1970s (FAO, 1986; Ebabu et al., 2017) with an estimated investment of more than 1 billion US dollars during the years between 1974 to1991 (Adimassu et al., 2017). Despite the widespread effort to restore degraded areas in Ethiopia, success of the conservation measures were generally limited (Aune et al., 2002; Gashaw, 2015; Tiki et al., 2016). For example, from the rehabilitation works done between 1976 and 1990, only 30% of soil bunds, 25% of the stone bunds, 60% of hillside terraces, 22% of land planted with trees, and 7% of the reserve areas survived in the year 1990 (USAID, 2000). Some of the reasons mentioned for the failure were the ‘top-down’ approach that the government followed without involving local communities and stakeholders in planning and implementation (Tiki et al., 2016), limitations of technologies in benefiting smallholder farmers, poor implementation and maintenance of structures (Shiferaw and Holdern, 2016), lack of understanding of nature’s functioning and processes (Keesstra et al, 2018).

Thus, there was a change in approach towards integrated, participatory and watershed-based interventions as of 1980s (Haregeweyn et al., 2012; GIZ, 2015; Gashaw, 2015; Ebabu et al., 2017; Gashaw et al., 2017); and it has been extensively implemented by the government and NGOs. The basis of the integrated watershed-based intervention approach was that the local communities would take part as major actors in the process of planning and implementation of rehabilitation activities (Haregeweyn et al., 2012). Accordingly, recent efforts attempted to follow integrated and participatory approaches in their endeavor to restore degraded areas across different watersheds in Ethiopia (Mekuria et al., 2011; Haregeweyn et al., 2012; Ebabu et al., 2017). Integrated and watershed based land management practices include the construction of soil and or stone bunds, terraces, trenches, cut off drains, drainage channels, check dams, *fanya juu*, planting of shrubs or trees, establishing area exclosure, combinations of structural and vegetative measures, and reduction of household livestock numbers (IFPRI, 2009; Sultan et al., 2017; Ebabu et al., 2019).

Various NGOs have been supporting the government of Ethiopia in its effort to enhance overall system productivity and improve ecosystem services through integrated watershed management practices. In order to tackle the problem of limited data availability related to the performances of integrated and watershed based land management practices and define methods for scaling, some projects a establishing learning watersheds where integrated land management practices are co-implemented and evidences are generated for awareness creation and further scaling. The Africa RISING (Research In Sustainable Intensification for the Next Generation) program in the highlands of Ethiopia is one such projects promoting learning watersheds where integrated sustainable intensification (SI) and natural resources management (NRM) can be undertaken (Mekonnen, 2018). The program has six learning watersheds in which technologies, methods, tools, frameworks are tested before scaled to other areas. One such learning watershed is the Geda watershed of the Amhara region, north Shewa zone, characterized by a mixed crop-livestock farming system of the central highlands. This study assessed the effects of integrated land management practices on selected soil physicochemical properties, species richness, and water flow and carbon stock considering landscape position, soil depth and land-use type. This helps to understand the benefits of those practices in terms of livelihood improvement and indicators of ecosystem services.

1.2 Statement of the problem

Land degradation is severe in Geda watershed due to the steepness of the topography, traditional farming practices, overgrazing, and deforestation. To halt the problem and foster rehabilitation works, integrated land management practices having several intervention packages (physical, biological measures, restriction of free grazing) were introduced. Nevertheless, studies on the effects of such practices are limited and results are inconsistent. Moreover, best land management practices were not documented and identified. Hence, a comparative study is was essential to examine and document the effects of the practices and to recommend the best ones to expand to other degraded areas through scaling.

1.3 Justification of the study

The dominant farming practice in Geda watershed is a mixed crop-livestock system where crop production and livestock husbandry compete for spaces and resources incurring over exploitation of natural resources which further aggravate land degradation. To improve the ecosystem's productivity and adequately support both the crop and livestock production systems, the Amhara Region has introduced various integrated land management practices in Geda watershed since 2012. The introduced practices combined physical and biological measures and prohibitions of free grazing that could affect the soil physicochemical properties, discharge capacity, resources remaining in the landscape and leaving from the landscape; which intern affects species richness, and carbon stocks of the landscape. Africa RISING project in collaboration with CIAT, ILRI and other CGIAR centers and national partners started working in Geda watershed a few years ago to generate evidences on the impacts of the development interventions on controlling soil erosion, runoff and improve crop yield, and support government NRM initiatives (Mekonnen, 2018). In the country, researches on impacts of NRM interventions focused mainly on plot/farm levels and studies on watershed-level impacts are limited. Very few researchers such as Mulugeta and Karl (2010), Wolka et al. (2011), Hishe et al. (2017b), and Ademe et al. (2017) studied the impacts of SWC practices on soil physicochemical characteristics in northern and southern parts of Ethiopia highlands. Since the setup and agro-ecology of the central highlands are different from the northern and southern parts of the country and the current intervention integrated various rehabilitation measures than the classical SWC practices, watershed level comparative study is essential. Thus, exploring watershed level impacts of integrated land management practices on soil physicochemical characteristics, water discharge capacity, species richness, and carbon stock is of paramount importance. Pieces of evidence generated on these basic ecosystem indicators

(Wubet et al., 2013) would support policymakers for their decision to upscale best practices and improve the rehabilitation measures in the central highlands of Ethiopia as well as in various parts of the country.

1.4 Research objectives, hypothesis and research questions

1.4.1 General and specific objectives

This research is aimed at exploring the changes in indicators of ecosystem services associated with integrated land management practices and generating information and data from agricultural landscapes. The specific objectives are to:

- evaluate changes in selected soil physicochemical properties of the treated site taking the neighboring control site as a base
- quantify the change in water discharge due to integrated land management practices
- assess plant species richness in the watershed and compute changes due to integrated land management practices
- determine the plant biomass production and carbon stock of the watershed associated with integrated land management practices

1.4.2 Research hypothesis

We hypothesis that the treated and the adjacent control sites had at least similar conditions before the introduction of integrated land management practices in the treated site. Yet, it is common that the community and extension experts decide implementation of conservation practices at highly degraded landscapes that prove low biomass productivity. Thus, the treated site might be highly degraded compared to the untreated site in the beginning; if not, they might have at least similar conditions. Then, the following null hypotheses were tested in the course of the study.

- Integrated land management practices do not improve the soil physical and chemical properties in Geda watershed.
- There is no difference in stream flow between the treated and untreated sites.
- Integrated land management practices do not improve plant species richness in Geda watershed.
- There is no difference in plant biomass production and carbon stock between the treated and untreated sites in Geda Watershed.

1.4.3 Research questions

To achieve the stated objectives and to test the research hypothesis, the following questions were designed and addressed.

- What are the effects of integrated land management practices in soil physical and chemical characteristics in different landscape position, land-use type and soil depth?
- How do integrated land management practices improve water discharges in Geda watershed?
- What is the contribution of integrated land management practices in plant species richness under different landscape position and land-use types?
- How do integrated land management practice influence plant biomass production and carbon stocks under different landscape position and land-use types?

1.5 Structure of the thesis

This thesis is organized in five chapters. The first chapter provides general background information followed by the research problem, justification of the study, research objectives, hypotheses and research questions. The second chapter is a review of relevant literatures that gives existing evidences on the severity of land degradation, rehabilitation efforts and outcomes of rehabilitation works in Ethiopia, and the third chapter is the materials and methods section that begins with a description of the study area and explanations the research methods. Chapter four presents results and discussion of each research objective which are published in or submitted to peer-reviewed scientific journals and manuscripts under preparation. Chapter five provides the conclusions and recommendations of the research.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Definition and extent of land degradation

Land degradation is defined as a persistent decline in the productivity of land and its ecosystems (Hurni et al., 2010). Land degradation involves a natural process through the process of geological evolution (FAO, 1986) and accelerated by anthropogenic activities mainly due to deforestation, raising crops and livestock, mining and construction (FAO, 1986; Wolka et al., 2011; Gashaw, 2014; Berhanu et al., 2016). Interaction of the natural and social interlocking systems determine resource management situations that further threatens the long-term growth of agricultural productivity, food security, and the quality of life (Amare et al., 2013a; Berhanu et al., 2016). Both natural and anthropogenic causes determine the occurrence and spatial dynamics of land degradation (Kumar and Das, 2014).

Globally, nearly five billion ha (about 43% of Earth's vegetated surface) has been degraded due to deterioration of dryland vegetation and tropical moist forests; land degradation in the tropics amounts to 2.1 billion ha (Gebretsadik, 2013; Gashaw, 2015). Currently, the rate of global land degradation is 10 to 12 million ha year^{-1} (Thomas et al., 2018). The problem of land degradation has been undermining agricultural development and hinders environmental sustainability in many countries including Ethiopia (Berhanu et al., 2016; Ademe et al., 2017).

2.2 Severity of land degradation in Ethiopia

Land degradation mainly soil erosion by water is a primary environmental problem of Ethiopia (FAO, 1986; Atnafe et al., 2015; Berhanu et al., 2016; Dabi et al., 2017). Its impact is very serious in Ethiopia as compared to other countries in the world (Gashaw et al., 2015; Berhanu et al., 2016; Dabi et al., 2017). The Tigray and Amhara regions are the most seriously affected parts of the country (FDRE, 2015).

In Ethiopia, 27 million ha was extensively eroded, 14 million ha was seriously eroded and over two million ha became beyond reclamation in mid-1980s (FAO, 1986; Holden et al., 2005; Haile et al., 2006; GIZ, 2015; Gashaw, 2015). The total land degraded in Ethiopia between 1981 and 2008 is estimated to be 297,000 km^2 (Dabi et al., 2017). Soil erosion in Ethiopia ranges 3.4 to 84.5 tons $ha^{-1}year^{-1}$ with a mean value of 42 tons $ha^{-1}year^{-1}$ (Haile et al., 2006; Hurni et al, 2015; Gashaw, 2015; Dabi et al., 2017). Still, in the highlands of Ethiopia, estimates reach up to 130-300 tons ha^{-1} $year^{-1}$on croplands depending on the landscape and vegetation cover conditions (FAO, 1986; GIZ, 2015; Hurni et al, 2015; Gashaw, 2015). Gashaw et al. (2017) also reported annual soil loss of 237 tons ha^{-1} in the steep landscape areas of Geleda watershed.

In Ethiopia, soil erosion by water is severe on agricultural lands for it is concentrated on steep landscapes > 20% (FAO, 1986) and predominantly rain-fed (Hurni et al., 2015; Tiki et al., 2016). The northeastern parts of the country have been affected by soil erosion due to long time agricultural practices; however, currently, the western parts of the highlands are experiencing highest soil erosion rates (Mulugeta and Karl, 2010; Hurni et al., 2015). Agriculture is under continuous threat of soil erosion and nutrient depletion in the Ethiopia (FAO, 1986; Mulugeta and Karl, 2010; Adimassu et al., 2012; Gashaw et al., 2014). This seriously affects the country's economy and livelihood as a whole, since the country is highly dependent on the agricultural sector (FAO, 1986).

Although the government of Ethiopia took land degradation as a serious case and invested a lot of efforts in land rehabilitation and reclamation initiatives (Gebremichael et al., 2005; Amare et al., 2013a), it is still at a severe stage and it becomes the root cause of poverty with considerable negative impacts on the national economy (Mulugeta and Karl, 2010; FDRE, 2015; Gashaw, 2015).

2.3 Causes of land degradation in Ethiopia

The causes of land degradation in the country are multiple and interacting forces (Gashaw, 2015) attributed to a combination of biophysical, social, economic and political factors (Haile et al., 2006; Gashaw, 2015; FDRE, 2015). Rapid population growth, cultivation on steep landscapes, clearing of vegetation and overgrazing are the main factors accelerating soil erosion (Ayalew, 2011; Masebo et al., 2014; Gashaw, 2014, 2015; Atnafe et al., 2015). Accelerated soil erosion by water depends on rainfall erosivity; soil erodibility; landscape and land-use types. Land-use is the most important factor of soil erosion followed by landscape, soil erodibility and rainfall erosivity (FAO, 1986). Further, various authors (Haile et al., 2006; Gashaw, 2014; Atnafe et al., 2015; Shiferaw and Holden, 2016) considered subsistence agriculture, poverty, and illiteracy as important causes of land degradation. The use of wood biomass for fuel and encroachment of forests are also causes of land degradation (Bojo and Cassels, 1995; Ayalew, 2011; Gashaw, 2015; FDRE, 2015). Further, weak extension services and weak management of public lands are reported as causes for land degradation in Ethiopia (Mulugeta and Karl, 2010; Ayalew, 2011; Masebo et al., 2014).

Thus the causes of land degradation are multiple and intermingling (Gashaw, 2015); but grouped in to direct and indirect (Bojo and Cassels, 1995; Gashaw, 2015). The direct causes are forest clearance, poor cultivation practices, burning of dung, removal of crop residues, low vegetative cover of croplands, unbalanced crop and livestock production, and extensive use of charcoal.

Whereas, the indirect causes include poverty, tenure insecurity, economic policies, and population pressure. Thus, the above causes of land degradation can be summarized into proximate causes, underlying causes and policy implications (Fig. 1).

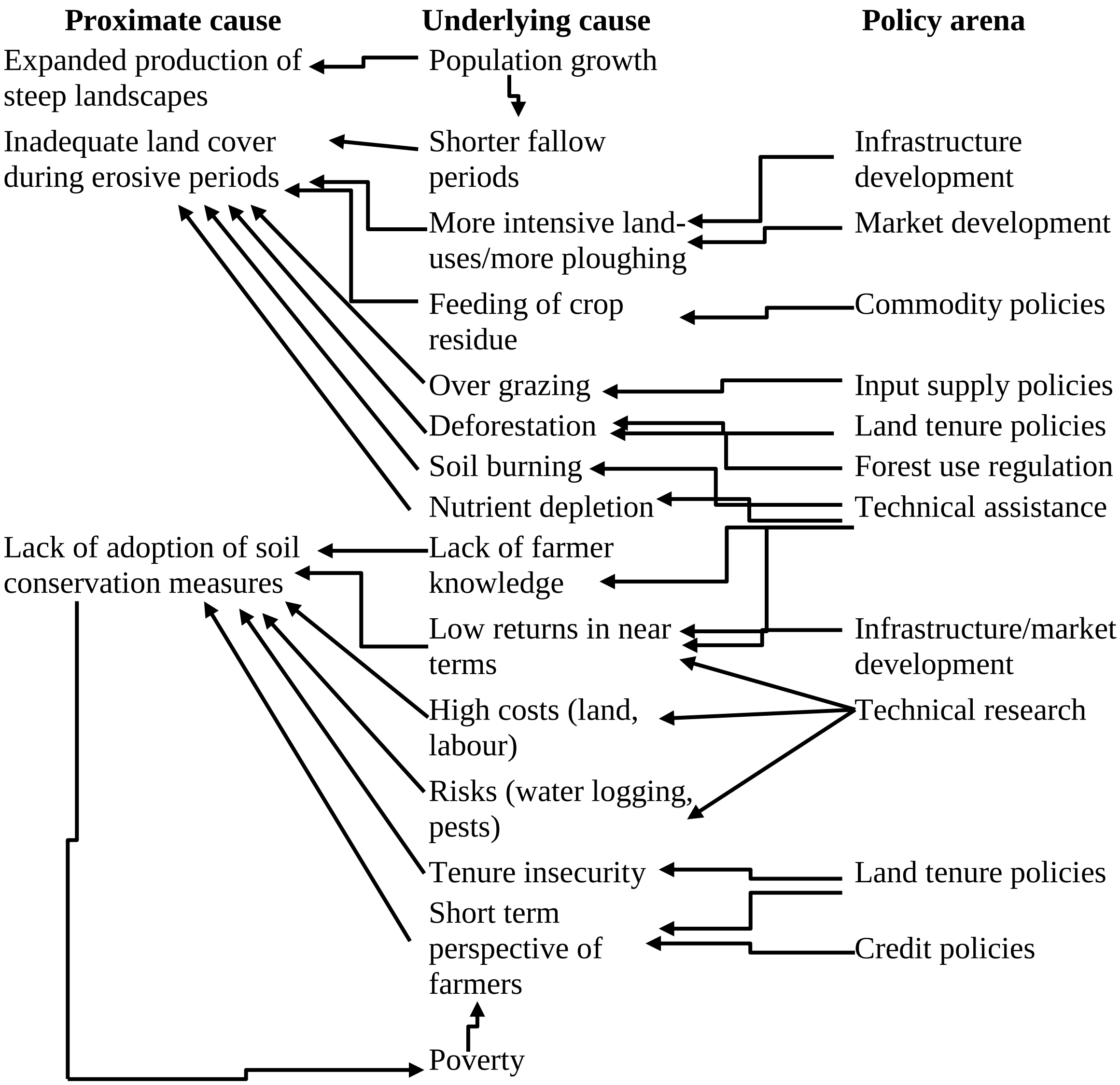

Figure 1. Schematic representation of the links of soil erosion causes (Source: Fitsum et al., 1999)

Population pressure, both human and livestock, is exceptionally severe in the highlands of Ethiopia (Keesstra et al, 2018). The highlands cover about half of the country's territory, over 95% of regularly cropped land, support about 88% of the population, two-thirds of the livestock, and over 90% of the national economic activity (FAO, 1986) The average population concentrations of the area was reported as 144 person km^{-2} (Sonneveld and Keyzer, 2003) but in some areas population density exceeds 300 person km^{-2} (Ebabu et al., 2017). The livestock density in the highlands is also high (160 tropical livestock units (TLUs) km^{-2}) as compared to the recommended densities of 19 - 42 TLU km^{-2} (Bojo and Cassels, 1995; Sonneveld and Keyzer, 2003).

2.4 Impacts of land degradation on the environment and landscape productivity

2.4.1 Impact on the environment

Ethiopia loses 30,000 ha of land $year^{-1}$, 1 billion tons of topsoil $year^{-1}$ and significant nutrient depletions due to water erosion (Berry, 2003). Haileslassie et al., (2006) estimated the national level nutrient depletion rate due to soil erosion as 122kg ha^{-1} $year^{-1}$N 13 kg ha^{-1} $year^{-1}$ P and 82 kg ha^{-1} $year^{-1}$ K. In addition, According to Wolka et al. (2011), soil erosion has a sorting action by its nature. It removes large proportions of the clay and humus from the soil, leaving behind the less productive coarse sand, gravel, and even stones in some cases. The removal of this organic matter affects soil quality such as texture, structure, nutrient availability and biological activity and makes the soil more susceptible to further erosion (Yoseph et al., 2017) and less productive.

Generally, soil erosion in Ethiopia has brought a continuous decline in land productivity (Adimassu et al., 2012; Masebo et al., 2014) and affected the economy of the country (Ayalew, 2011; Dagnew et al., 2015). Thus, careful management of watersheds is a core element of good agricultural and forest restoration to minimize land degradation, stabilize water/stream flows, improve groundwater recharge and reduce sediment load (GIZ, 2015).

2.4.2 Impact on landscape productivity

Soil erosion affects half of the agricultural land in the country (Dagnew et al., 2015) and incurs production loses due to physical, chemical and biological deterioration of the soil (Elias, 2002; Ademe et al., 2017). Soil erosion removes chemically active parts of the soil such as organic matter and clay fractions that make the soil more productive. Furthermore, it deteriorates soil structure and moisture-holding capacity through lowering soil depth, increasing bulk density, forming soil crust, and reducing water infiltration (Wubet et al., 2013).

Soil degradation is the most serious limiting factor for crop production in Ethiopia. It includes soil erosion, chemical degradation, physical and biological deterioration of the soil that negatively affect crop production (Elias, 2002). Ayalew (2011) reported a loss of 17% of the potential annual agricultural GDP due to physical and biological soil degradation. Furthermore, Sonneveld and Keyzer (2003) predicted the reduction of land potential production by 30% in 2030, unless management interventions are not implemented. This reduces the annual value-added per capita in the agricultural sector by USD 162 in 2030. i.e. below the poverty line as defined by the World Bank (income of less than one USD day^{-1}). Besides, food availability per capita drops from 1971 to 686 Kcal day^{-1}. This is far below the World Health Organization threshold of the minimum: 2600 Kcal day^{-1} for adults and 1600 Kcal day^{-1} for children).

Irreversible changes in soil productivity due to soil erosion coupled with population pressure is leading to land scarcity (Ebabu et al., 2017), conflict, violence, drought, food scarcity and insecurity in Ethiopia (Adimassu et al., 2017).

2.5 Efforts to rehabilitate degraded lands in Ethiopia

2.5.1 Government initiatives

In order to tackle the outbreak of the 1973/74 drought and halt land degradation and its associated impacts, the government of Ethiopia launched massive rehabilitation programs starting from the mid-1970s (FAO, 1986; USAID, 2000; Haile et al., 2006; Ebabu et al., 2017; Adimassu et al., 2017). As a first initiative of SWC investment, the government established SWC division within the Ministry of Agriculture (MoA) (Amare et al., 2013a; Adimassu et al., 2017). In the beginning, SWC investment started in drought-prone areas using a food-for-work payment mainly funded by the World Bank, World Food Program (WFP) and the Food and Agricultural Organization (IFPRI, 2009; Atnafe et al., 2015; Adimassu et al., 2017).

SWC practices are categorized into physical, biological and agronomic; but sometimes there is an overlap in these categories. For example, grass strip is a biological SWC practice, by definition, but it has also the role of physical SWC practices (Adimassu et al., 2017). Nevertheless, widely implemented SWC practices are mostly physical structures which include stone bunds, soil bunds (level/graded), *fanya juu* (level/graded) (IFPRI, 2009; Adimassu et al., 2017). Biological SWC practices include maintaining natural vegetation and tree plantation in area closures, plantation of valley bottoms, and stabilization of physical structures through vegetation such as grass strips, vetiver grass, elephant grass, and so on (Berhanu et al., 2016). Agronomic SWC are also among the intervention options practiced in Ethiopia. These include minimum tillage, tied-ridging, application of compost, farmyard manure, mulching and so on (Adimassu et al., 2017). However, physical SWC practices are the widely practiced conservation options to curb soil erosion in Ethiopia (Wolka et al., 2011).

According to USAID (2000), between 1976 and 1990, the conservation structures in the country were 71,000 ha of soil and stone bunds, 233,000 ha of hillside terraces for afforestation, 12,000 km of check dams in gullied lands, 390,000 ha of closed areas for natural regeneration, 448,000 ha of land planted with different tree species, and 526,425 ha of bench terrace interventions. Berry (2003) reported that between 1976 and 1985, Ethiopia constructed some 600,000 kilometers of soil and stone bunds on cultivated land, about half a million kilometers of hillside terraces, 500 million tree seedlings were planted, and 80,000 ha were closed off for natural regeneration. Furthermore, Wubet et al. (2013) reported the construction of 800,000 km of soil and stone bunds on cultivated lands; 600,000 km of hillside terraces and 80,000 hectares were closed for regeneration and for afforestation on steep landscapes between 1976 and 1988, which was funded by food-for-work (FFW) programs of WFP.

Furthermore, various campaigns have been carried out since the early 1980s to build terraces on farmlands and steep areas with an emphasis on structural technologies over the vegetative measures (GIZ, 2015; Gashaw, 2015). The dominant SWC structures implemented in Tigray were soil and stone bunds with soil bunds covering 63%; in Amhara, stone bunds and waterways, in Oromia, soil bunds and waterways, in Benishangul Gumuz, waterways accounting 55%; and in SNNPR, tree plantations (IFPRI, 2009).

2.5.2 Ineffectiveness of past interventions

Despite tremendous efforts made to expand SWC practices in the earlier times, achievements did not match the vast needs of the country and weaknesses and in effectiveness of the SWC were more prominent. For example, conservation measures had covered only 1% of the highlands during mid-1980s (Bojo and Cassels, 1995). Many of the physical installations were based on simplistic rules of thumb making them less adapted to local conditions. Maintenance was lacking, survival rate of tree seedlings has been low, destruction of bunds and trees for short term benefit were practiced during political instability (Bojo and Cassels, 1995). Evaluation of success rates of the earlier conservation measures in 1990 revealed that only 30% of soil bunds, 25% of the stone bunds, 60% of hillside terraces, 22% planted trees, and 7% of the reserve areas survived (USAID, 2000).

According to Kassie et al. (2011) and Atnafe et al. (2015) adoptions of SWC technologies by smallholder farmers were low. The identified reasons for the low success rates were: a) lack of integrating biophysical measures and indigenous knowledge, b) due to the negative impacts of incentives (e.g. food for work), c) inappropriate perception of farmers, d) socio-economic reasons, e) lack of adequate design, f) inappropriate land-use, g) lack of strong maintenance of structures, h) lack of adequate monitoring and evaluation and i) lack of farmers' participation in decision making at all stages j) limitations of technologies in benefiting smallholder farmers (Zegeye et al., 2010; Tiki et al., 2016; Shiferaw and Holdern, 2016; Tiki et al., 2016; Dabi et al., 2017). Furthermore, the study of Atnafe et al. (2015) in Goromti watershed, west Ethiopia revealed as landscape of the area, tenure status, contacts with extension workers, training situations, age and family size determined adoption of SWC technologies. In addition, lack of understanding of nature’s functioning and processes by conservation experts determine the effectiveness of conservation measures (Keesstra et al., 2018)

2.5.3 Integrated watershed based approach

Degraded ecosystem is assisted to recover to the best possible level through integrating various compatible structural, biological and cultural methods (GIZ, 2015). Thus, starting the 1980s, formal and planned watershed development approaches by which local people play sufficient roles was introduced with a primary purpose of natural resource conservation and enhancing agricultural productivity through which livelihood improvement can be achieved (Haregeweyn et al., 2012; Tiki et al., 2016; Dabi et al., 2017). In the beginning, the approach puts a planning unit of developing large watersheds of 30-40,000ha (GIZ, 2015; Gashaw, 2015). However, large scale watershed developments were not satisfactory due to unmanageable planning units, lack of effective community participation, limitations in responsibilities for assets created (GIZ, 2015). Consequently, pilot watershed planning approaches based on smaller units and on a bottom-up basis were introduced in 1988-91 (GIZ, 2015).

Following the introduction of watershed development approach, MoA and United Nations World Food Program (WFP) staff developed participatory and community-based watershed planning guidelines called Local-Level Participatory Planning Approach (LLPPA) with a practical focus for development agents. The emphasis was on the integrated natural-resource management (NRM) interventions, productivity-intensification measures and small-scale community infrastructure such as water ponds and feeder roads (GIZ, 2015; Dabi et al., 2017). Watershed based natural resource management approaches across a range of hierarchies, from small catchments to larger streams better address upstream and downstream effects and interactions that exist among components of the natural system (USAID, 2000; Dabi et al., 2017).

Various programs such as Participatory Land-use Planning (PLUP), Sustainable Utilization of Natural Resources for Improved Food Security (SUN), Sustainable Land Management (SLM) incorporated best experiences of natural resource management gained from watershed approaches (GIZ, 2015). In Ethiopia, Sustainable Land Management Project (SLMP) was launched in 2008 and the first phase of the project finalized in September 2013 (FDRE, 2013; Adimassu, 2017). SLM practices include construction of soil and or stone bunds, terraces, trenches, cut of drains, drainage canals, check dams, *fanya juu*, planting of shrub or tree species, establishing area exclosure, combinations of structural and vegetative measures, and reduction of household livestock numbers (Ebabu et al., 2019). SLM practices are designed to increase agricultural productivity, improve ecosystem functions and enhance resilience to adverse environmental impacts (Liniger et al., 2011; Ademe et al., 2017).

In Ethiopia, SLM project has successfully introduced land management practices and rehabilitated thousands of hectares of degraded lands using physical and biological measures (FDRE, 2013). Currently the second phase of the project has been under implementation since September 2013 (FDRE, 2013). The focus has also included livelihood improving options to increase economic gains and promote adoption.

The SLM project presented different components and sub-components of natural resource restoration activities such as (FDRE, 2013):

1) Integrated Watershed and Landscape Management: intended to support scaling up and adoption of appropriate sustainable land and water management technologies and practices by small-holder farmers and communities in selected watersheds. This was planned to be achieved through different sub components:

a) Sustainable Natural Resource Management in Public Lands focuses on Afforestation and Reforestation of degraded communal land (hillside communal land treatment and management including woodlot establishment, gully rehabilitation using biophysical measures and seedling production); crop production to increase productivity and carbon sequestration (treatment of farmland < 30% landscape with suitable bio-physical measures, > 30% with suitable bio-physical measures, applying conservation agriculture, agro-forestry, and so on), improving livestock production/productivity and reducing carbon emission through promoting fodder or forage production, improve breed for stock reduction, improved poultry breed, improved beekeeping activities, artificial insemination (AI) service and cattle crush. Climate Resilience Building and Increasing Water Availability focused on supporting small scale irrigation, potable water supply - hand dug well and spring development, renewable energy potential for the rural setting.

b) Homestead and Farmland Development focuses on construction of water harvesting structures with water efficient irrigation methods, homestead development by promoting high value crops and multi- purpose fruit trees and forage tree planting, livestock improvement (e.g. small ruminant fattening, promotion of beekeeping and honey production, etc.), promoting bio-fuel/biomass, biogas energy, promotion of fuel saving and efficient technologies, and feeder road construction.

2) Rural Land Administration, Certification and Land-use*:* to enhance the tenure security of smallholder farmers in order to increase their motivation to adopt sustainable land management practices on communal and individual lands.

2.6 Impacts of conservation measures in degraded land rehabilitation

A number of researches were done at various times on the effectiveness and impacts of SWC practices on the environment, land productivity and livelihood improvements. Adimassu et al. (2017) reviewed and synthesized the impacts of SWC on crop yield, runoff, and soil and nutrient loses in Ethiopia. According to their report, most physical SWC practices such as soil bunds and stone bunds were very effective in reducing runoff, soil erosion and nutrient depletion.

However, SWC practices showed site-specific impacts on crop yield. For instance, soil and stone bunds increased crop yield up to 10% in Tigray, while this reduced crop yields up to 7% in other parts of the country mainly due to the reduction of the effective cultivable area (Adimassu et al., 2017; Shiferaw and Holden, 2016). Conservation measures occupy considerable space; for example, grass strips, bench terraces and *fanya juu* occupy 1-15%, 5-42% and 8-40% of cultivable lands, respectively (Dabi et al., 2017). Adimassu et al. (2017) suggested that the reduced areas by SWC structures can be compensated by growing high value trees/fodders for livestock feed. They further reported as agronomic SWC practices such as compost, farmyard manure, tied-ridging, minimum tillage and mulching are best alternatives to increase crop yields while conserving soil and water.

In low rainfall areas of Amhara and Tigray, Ethiopia, higher crop yields of an average 42 % and 23% respectively, were obtained from plots with stone terraces (Kassie et al., 2011). This is due to the moisture conserving property of the stone bunds in drier areas (Wolka et al., 2011). According to most of the research findings, introduction of stone bunds on cropland reduces soil loss (annual average of 61–68%) and the soil is deposited behind the bunds (Nyssen et al., 2007) having improved physicochemical characteristics (Bulk density, SOM, TN, pH, K+, available P, SOC, clay and CEC (Mulugeta and Karl, 2010; Ademe et al., 2017). For instance, Wolka et al. (2011) found higher values of clay and silt fractions on terraced plots than on non-terraced ones. Agroforestry based SWC showed higher organic matter content at treated plots in Tembaro district, southern Ethiopia (Masebo et al., 2014).

SWC measures also play a significant role in reducing runoff and on-site sediment deposition. Sultan et al. (2017) found a runoff reduction of 49% through the combination of soil bunds with vegetation on cultivated lands while the use of trenches across the landscape on non-cultivated plots reduced runoff by 65%. According to Adimassu et al. (2012), soil bunds reduced average annual runoff by 28% and average annual soil loss by 47% (39% in Tigray and 50% in Anjeni). The average annual runoff reduction due to soil bunds at Galessa Watershed, was 28% (Adimassu et al., 2012) and at Enabered watershed, was 27 % (Haregeweyn et al., 2012). Taye, et al. (2013) and Masebo et al. (2014) also generally agree as SWC practices are effective in reducing runoff and increasing soil moisture content and base flow.

Furthermore, integrated watershed management at Enabered watershed (Tigray) decreased runoff by 27 % and soil loss due to sheet and rill erosion by 89 % and reclaimed gully channels and converted them for agricultural purposes (Haregeweyn et al., 2012). Integration of terraces and infiltration furrows reduced runoffs and sediment concentration at Debre Mewi watershed (Dagnew et al., 2015). The study of Wubet et al. (2013) at Anjeni watershed, northwest Ethiopia, also reported that SWC structures improved soil quality and land suitability to crop production. According to their study, lands that were moderately (S2) and marginally (S3) suitable for major crops of the watershed such as tef, barley, wheat, and maize in 1984 and 1997 were improved to highly suitable (S1) for wheat and tef, and a large proportion of the remaining area was changed to moderately suitable class (S2) for barley and maize in 2010.

Subhatu et al., (2017) studied on-site sediment deposition and net soil loss in terraced crop lands at Minchet catchment in the sub-humid Ethiopian highlands and showed that narrow terrace spacing (<13m) had more sediment deposition than wider spaced terraces due to off-site removal of sediments through waterways in wider catchments. Furthermore, they reported that fields with higher landscapes produced more sediment yield than gentle landscapes; and found out average soil loss by water from 31 to 37 t $ha^{-1}year^{-1}$. However, if terraces are constructed on crop lands, 54–74% of soil loss was deposited there.

In addition, catchment management has resulted in higher infiltration rate and a reduction of direct runoff volume by 81% (Nyssen et al., 2010). The yearly rise in water table after the onset of the rains (WT) relative to the water surplus (WS) over the same period increased between 2002-2003 (WT/WS = 3.4) and in 2006 (WT/WS >11.1).

An area exclosure also showed a significant positive impact on reducing soil loses and improving soil fertility. Descheemaeker et al. (2006) reported a mean sediment deposition of 26 to 123 Mg ha^{-1} $year^{-1}$ and development of Phaeozems (dark soils rich in organic matter on area exclosure), Further, they noted that area exclosure increased regeneration of natural vegetation; stabilized the land and reinstalled microclimate, reduced runoff, sheet and rill erosion. The exclosure showed 47% reduction of soil erosion compared to the grazing areas (Mekuria et al. (2009).

An area enclosures of about 20-30 years enhanced vegetation regrowth, increased biomass production that covered up to 15 % of the land in several districts of Tigray region (Nyssen et al., 2008). Increased vegetation cover decrease downstream sediment deposition and flooding, provides ecosystem services such as growth of grass and trees, increased firewood production, improved wildlife habitat and enhanced biodiversity which further contribute to climate regulation, drought mitigation, and carbon sequestration (Nyssen et al., 2008; Hishe et al. (2017a). Exclosure improve environmental resources on degraded and generally open access lands so that natural regeneration of plant species is conditioned (Mekuria et al., 2009).

A recent meta-analysis by Abera et al. (2019) revealed that integrated conservation measures resulted higher positive impacts compared to a single practice. According to Abera et al. (2019), combination of bunds and biological interventions and conservation agriculture showed 170% and 18% mean effects on agricultural productivity, respectively. Bunds supported by biological measures increased soil organic carbon by 139% while exclosure increased by 90%. However, monolithic measures of biological intervention and terracing (*fanya juu*) revealed negative effects on agricultural productivity. Thus, low adoption rate and weaknesses of the conservation measures in the earlier times could be among others-due to lack of integrating different compatible measures. Therefore, according to Adimassu et al. (2017) and Abera et al. (2019), it is critically important to integrate different practices appropriately in order to rehabilitate degraded landscapes and enhance the provisioning and regulating ecosystem services.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Description of the study area

The study was conducted in Geda watershed, located in the North Shewa Zone of Amhara National Regional State in central Ethiopia. The watershed is at the upper part of the Blue Nile basin in the eastern escarpment of the Ethiopian highlands. It is situated at 165 km north of Addis Ababa (the capital of Ethiopia), on the way from Addis Ababa to Dessie, and 35 km to the north east of Debre Berhan town (the capital of North Shewa Zone). Specifically, the study site is located between $39^{0}40'30''$ to $39^{0}41'30''$ East longitude and $9^{0}48'30''$ to $9^{0}49'30''$ North latitude in the Blue Nile basin (Fig. 2).

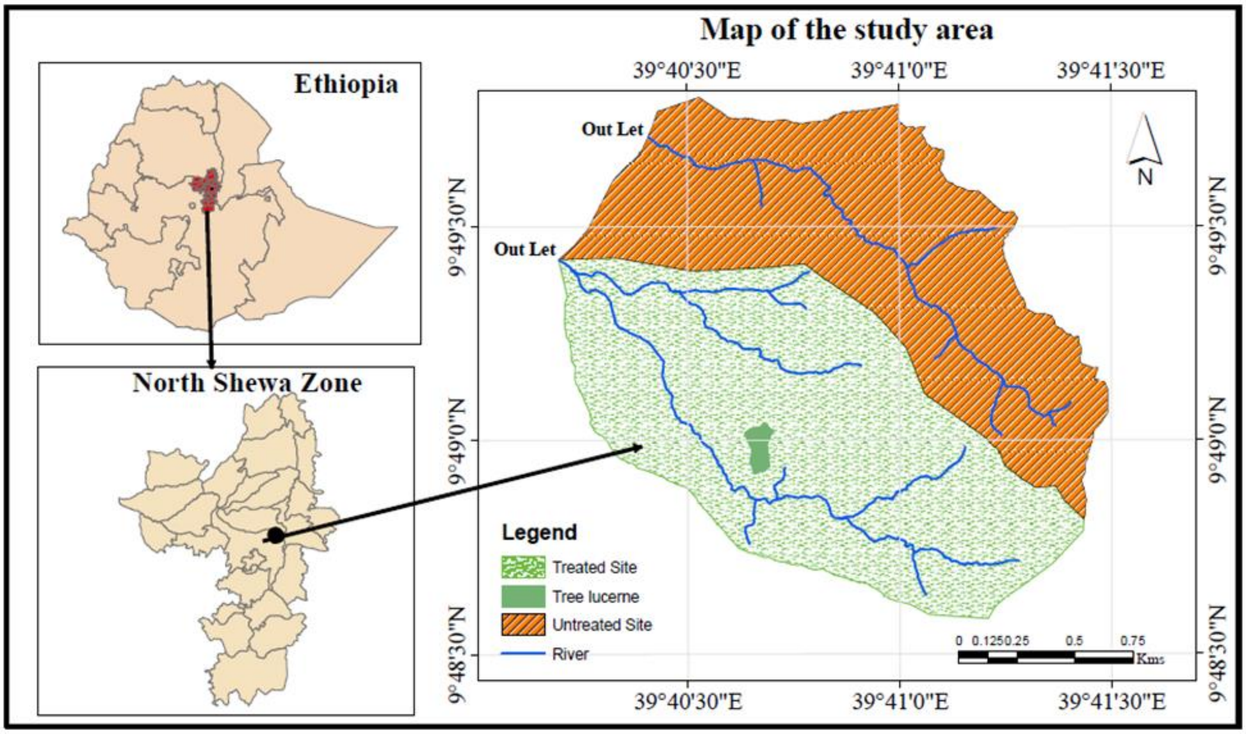

Figure 2. Map of the study area in Geda watershed

Geda watershed has a total area of 1056 ha; with more than 66% cultivable, 25% grazing and 6% woodlot (Tamene, 2017). The altitude range of the watershed is between 2700 and 3500 masl. However, the study was conducted in part of the watershed with in the altitude range of 2947 to 3156 masl; covering about 365 ha of land; of which about 202.45 ha was treated by integrated land management technologies and about162.95 ha was under the conventional practice.

The total annual rainfall of the watershed ranges 1225.04 − 2061.3mm. The area receives an average annual rainfall of 1632.42 mm. The annual minimum temperature of the study watershed was within a range of 2.46^{o}C to 8.49^{o}C. The maximum annual temperature ranged from 16.64 to 19.21^{o}C (Fig. 3).

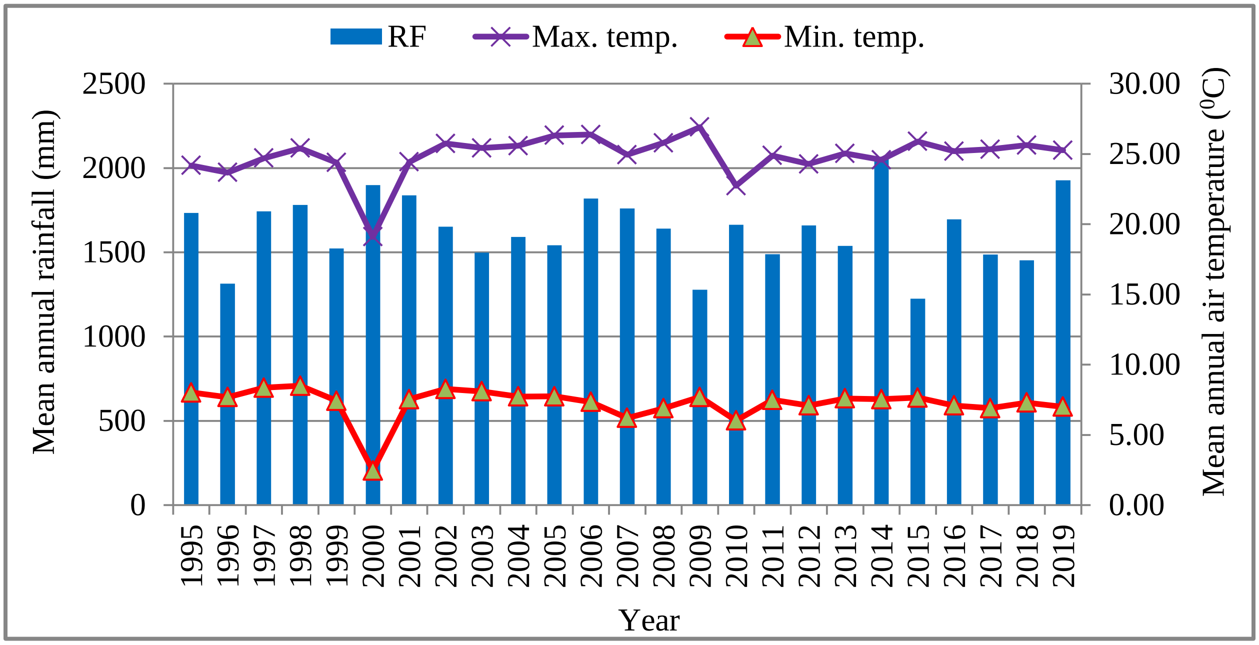

Figure 3. Mean annual rainfalls and temperatures in the study area (Data source: DBARC); RF: Rain fall; Max. temp: Maximum temperature; Min. temp.: Minimum temperature

Based on the slope classification of FAO (2006), the dominant topography of the study area ranges from gently sloping (2-5%) covering 34% of the area to strongly sloping (5-10%) covering 34.11% of the area (own data). Geda watershed is characterized by volcanic rocks such as rhyolites, trachites, tuffs and basalts. Major soils of the area are Leptosol on steep landscape, Fluvisol at the Valley bottoms, and Regosol at eroded parts (Ashagrie, 2009; Amare et al., 2013b). Major farming system in Geda watershed is a mixed crop-livestock system. Cultivated land in the watershed covers more than 66%, grazing land 25% and wood lot 6% (Tamene, 2017). Farmers cultivate cereals such as barley and wheat; pulses such as faba bean and field peas; and rarely lentil and linseeds (Ashagrie, 2009). Sheep, poultry and cattle are major livestock types of the watershed (Ellis-Jones et al., 2013).

Recently, the population pressure and continuous cropping with less or no fallow periods is putting less regeneration chance of the landscape (Kuria et al., 2014). The fertile top soils are removed by surface runoff (Ashagrie, 2009). Farmers have limited income and are unable to buy artificial fertilizers to improve the productivity of the land and slow the process of degradation. Furthermore, dungs (natural fertilizers) are used for cooking fuel instead of adding to the soil to improve the soil fertility (Ashagrie, 2009). With this context Geda watershed was designed to be a learning watershed for an integrated land management interventions in the crop-livestock mixed farming system of the central highlands.

The land management intervention covered more than 80 km soil bund with trenches, 71 m^3 of gabion check- dams, 730 m^3 wooden check dams, 19 percolation pits and planting Tree Lucerne on highly degraded plots (Tamene, 2017). Currently the adjacent untreated site is under intensive crop production growing mainly barley (*Hordeum vulgare)*, wheat (*Triticum aestivum)*, faba bean (*Vicia faba),* and field pea (*Pisum sativum)* during the main cropping season (June to September). After the crop is harvested in mid- October, livestock start grazing on stubbles and plot margins. Thus, after harvest, each farmer transports the produce and hay to homesteads as quickly as possible in order to protect from livestock damage in the field when free gazing starts.

Then, the area is left for free grazing from November to mid-June until tillage for the next season's crop planting is taking place. Cattle, sheep, donkeys and horses are the major livestock groups that freely graze for about eight months, leaving hardly any soil cover in the landscape; and the cycle continues each year.

3.2 Study design

Systematic sampling method (Pearson et al., 2005) was employed in the main and the dry seasons of 2018/2019 to gather data from the treated and untreated sites, upper and lower landscape positions and different land-use types at each landscape position (Table 1; Fig. 4). The landscape positions of the sites were classified into upper (3031–3156 masl) and lower (2947–3024 masl). Since there was a village in between the upper and lower landscape positions (3024-3057 masl) in the treated site that live following the conventional land-use practices, we skip collecting data from this landscape range. The land-uses in the treated site were crop land and grazing land in the upper landscape and crop land, grazing land and Tree Lucerne plantation in the lower landscape position. Land-use types in the untreated site were crop land and grazing land in both landscape positions. Similar land-uses and landscape positions were purposely selected to collect representative data for all parameters. Since Tree Lucerne plot is found only in the treated site, data from this plot was compared across all land-uses and the grazing land in the untreated site when necessary.

The main land management measures practiced in the crop lands were soil/stone bunds supported by Phalaris (mixture of *Phalaris acquatica* and *Phalaris arundinacea*) and Tree Lucerne (*Chamaecytisus palmensis*); whereas, soil bunds and water collecting ditches were the dominant land management measures in the grazing lands, and the Tree Lucerne plantation has water collecting ditches and soil bunds. Percolation pits in different location and check-dams at river banks were also done. Free grazing was prohibited at both landscape positions and land-uses in the treated site. The landscape position, land-use types and major conservation measures are summarized in Table 1 below.

Table 1. Characterization of the treated and untreated sites

	Treated site (202.45 ha or 2.02km^2)			**Untreated site (162.95 ha or 1.63km^2)**
Landscape position*	Upper (3057-3135 masl) Lower (2947-3024 masl)			Upper (3031-3156 masl) Lower (3006-3031 masl)
	Slope class	**Area (ha)**	**Description**	**Area (ha)**
Slope classification (FAO, 2006)	0-2%	1.42	Flat to very gently sloping	1.35
	2-5%	14.10	Gently sloping	12.09
	5-10%	52.37	Sloping	71.57
	10-15%	75.51	Strongly sloping	48.81
	15-30%	59.04	Moderately steep	29.13
Major land-use types	a) **Field crops** (wheat, barley, faba bean, field pea, flax) in main cropping season b) **Vegetables** (carrot, cabbage, garlic) with irrigation **Grazing** **Tree Lucerne** **Eucalyptus woodlot**			**Field crops** (wheat, barley, faba bean, field pea, flax) in main cropping season and lentil with irrigation **Grazing** - **Eucalyptus woodlot**
Livestock type	Cattle, sheep, poultry, goat, donkey and horse			Cattle, sheep, poultry, goat, donkey and horse
Major Integrated land management measures	Soil/stone bunds, soil/stone bunds supported by biological interventions mainly with Tree Lucerne and Phalaris, percolation pits, water collecting ditches, Tree Lucerne plantations on highly degraded section of the land, prohibited free grazing with bylaws			- No conservation measures - Free grazing not prohibited, - no bylaws

* There is a village practicing the conventional land-use practices between 3024-3057 masl in the treated site. Thus, we didn't collect data from this elevation range.

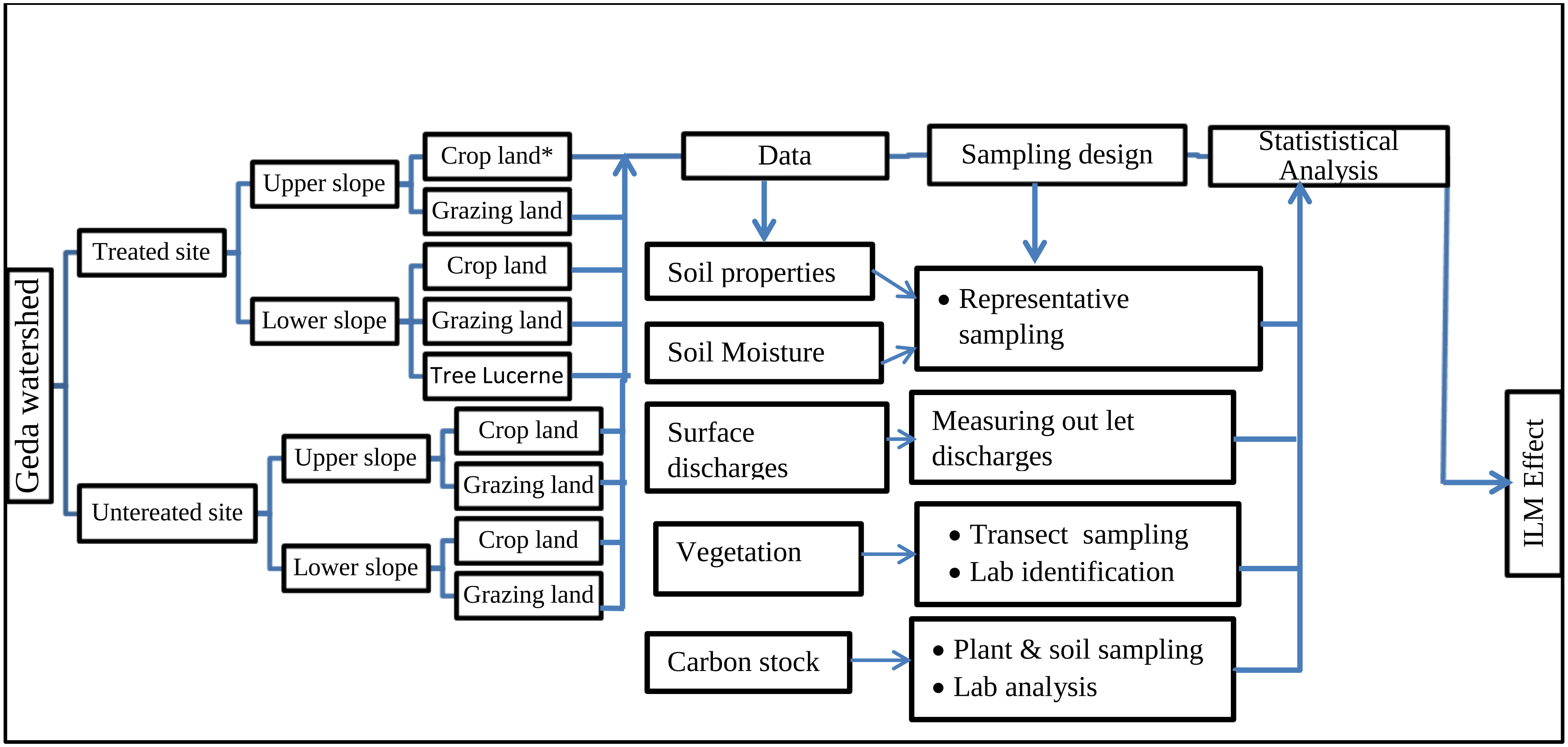

Figure 4. Schematic representation of the study design

[*] Two soil depths (0–15cm and 15– 30 for analysis of soil properties and 0–20 cm and 20–40 cm for moisture analysis) were used at each land-use type; ILM = Integrated Land Management.

3.3 Determination of selected soil physicochemical properties

3.3.1. Soil sampling

Judgment sampling method (USEPA, 2002; Wolka et al., 2011; Mekuria, 2018) was followed to locate a representative sampling plot for both treated and untreated sites, landscape positions and land–use types at two different soil depths (0–15 cm and 15–30 cm). Although the introduced land-use practices are expected to change the top soil at this younger age, data collection included 15‒30 cm depths to compare changes, if any, in the soil physicochemical properties. In order to maintain homogeneity of crop lands, fields planted with cereals such as barley and wheat were purposely selected. Soil samples were collected using an Edelman auger (Tor-Gunnar et al., 1999) following a triangular sampling pattern (Wilke, 2005) (Fig. 5).

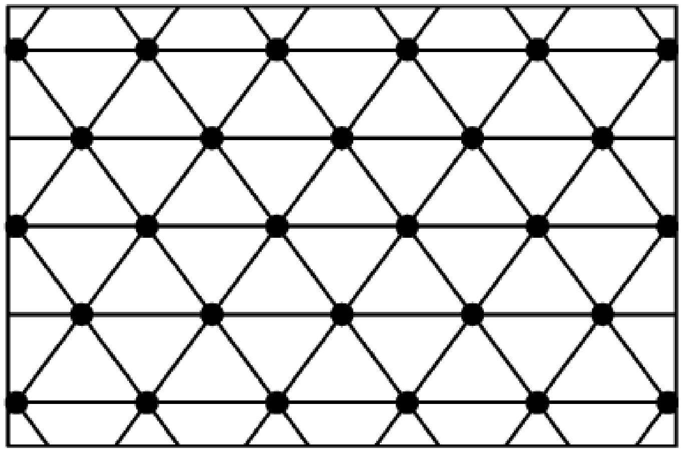

Figure 5. Triangular soil sampling method where sampling points in the parallel rows are staggered and form a triangular grid (Source**:** Wilke, 2005)

Due to high cost of laboratory analysis we limited the samples into two comparable land-uses in the treated and untreated sites. Thus, a total of 48 samples were collected (two sites × two landscape positions × two land-uses × two depths × three replications). Samples were collected at five sampling points per plot and mixed to make a composite sample (Paetz and Wilke, 2005; Wolka et al., 2011). After thoroughly mixing point samples, about 1 kg of composite sample was packed in a plastic bag and taken to the laboratory for analysis. For determination of bulk density, undisturbed soil samples were taken using core sampler (Masebo et al., 2014) having 5 cm height and 5 cm diameter (Volume = 98.125 cm^3).

3.3.2 Soil lab analysis

The collected soil samples were analyzed at the laboratory of Debre Berhan Agricultural Research Center. In the laboratory, the samples were air dried, crushed and sieved by 2 mm mesh sieve and passed through 0.5 mm diameter sieve to prepare for the following analysis. Particle size analysis (% sand, clay, silt) was carried out using the hydrometer procedure (van Reeuwijk, 2002). The soil reaction (pH) was measured using pH meter in a 1:2.5 soil/water suspension (Torn–Gunnar et al., 1999; Descheemaeker et al., 2006). Exchangeable cation (Na^+ and K^+) were analyzed by adding 1 M ammonium acetate solution at pH 7 (Rowell, 1994; Haldar and Sakar, 2005). Available P was determined following Olsen's extraction method (Olsen et al., 1954). Total nitrogen (TN) was determined following Kjeldahl procedure as described in Wilke (2005). Organic carbon (OC) was determined based on the Walkley–Black (Torn-Gunnar et al., 1999) rapid titration method. Bulk density of the soils was determined by dividing the mass of an oven dried soil at 105°C for 24 hours by the volume of the core sampler (Wilke, 2005; Masebo et al., 2014; Tiki et al., 2016; Alemayehu and Fisseha, 2019).

3.3.3 Soil moisture analysis

Soil water content can be measured directly or indirectly (Bittelli, 2011). Directly by measuring its weight as a fraction of the total soil weight (gravimetric method) based on the weight of a wet and dry samples before and after oven drying at 105^0C. Although it is the oldest method, gravimetric method is still considered as the most satisfactory method for one-time data collection (Johnson, 1992). It is also the only method for direct measurement and for equipment calibration for other methods (Johnson, 1992). In this case soil samples are removed from the field to be dried and analyzed in the laboratory by taking the weights of the samples before and after drying (Johnson, 1992; Bittelli, 2011). Gravimetric water content (w) is equal to the fraction of the differences in weight, i.e. the weight of liquid water (ml) to the weight of dry soil (ms).

$w = ml/ms$ (Bittelli, 2011).

Soil moisture content can also be detected by sensors. This indirect measurement minimizes the time needed to take samples from fields in gravimetric method. We purposely selected two months: the end of the heavy rainy season and the beginning of the dry season (October) and the peak dry season (January); because July to September is the summer season in the highlands of Ethiopia that uniform saturation can be created at both treated and untreated sites. Thus, the capacity of soils in moisture retention can be well captured in October before it gets too dry. That is why the first data collection for soil moisture content was carried out in October. The peak dry season in the area is January; however, a short rain, locally known as *belg*, might happen starting mid-January up to April. If this happen, there might be uneven intensity and distribution of rain throughout the watershed and create technical variation in soil moisture content. Thus, we conducted our measurement early in January before the short rain occurred.

Representative sampling sites were purposely selected on crop and grazing lands at both sites and landscape positions. Water collecting trenches and plant roots of the biological supporting measures could lead to store higher moisture in the lower soil depth. Thus, two soil depths (0-20 cm and 20-40 cm) were used to estimate the moisture content of the soil.

Samples were collected from ten crop lands and ten grazing lands at both sites and landscape positions. Consequently, 80 samples from 0-20 cm and 80 samples from 20-40 cm depths were collected using Edelman auger for gravimetric moisture content analysis (Wilke, 2005) in October. In addition, a total of 80 samples were taken from 0-20 cm depth in January using HD2 mobile moisture meter through directly inserting the sensor probes into the soil profile in the field (Walt, 2016). During this period, we couldn't measure the soil moisture from 20-40 cm depth because of compaction and drying. HD2 mobile moisture meter was preferred over the gravimetric method to determine the dry season moisture content for two basic reasons:

1) availability and accessibility of the apparatus, 2) to minimize moisture loss due to evaporation at this drier month (high temperature) in the process of augering, packing and sealing practices. Furthermore, it reduces labour demand for digging, sealing and transporting the samples to the laboratory.

Samples collected in October were put in plastic bags weighed immediately in the field and brought to the laboratory for drying. All samples were dried in an oven at 105^0C for 48 hours (to reach constant mass) (Craze, 1990; Wilke, 2005) and dry weight was measured using a digital balance of 0.01g precision. Then the moisture content of the soil was determined as a percentage of its oven dried weight calculated from the moist sample weight before and after drying (Fredlund and Xing, 1993; Fig. 6).

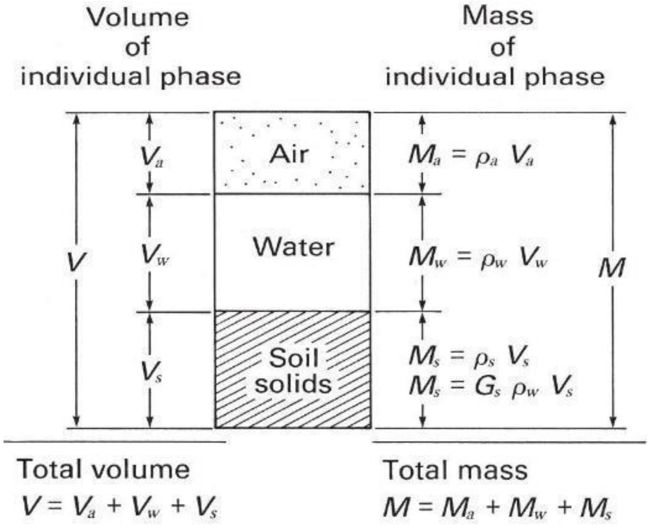

Figure 6. Phase diagram and elements of unsaturated soil (Source: Fredlund and Rahardjo, 1993)

Weight of moist soil was determined by deducting the weight of the bag from the weight of the moist sample in the bag while dry weight of the soil was determined by subtracting the weight of the container (aluminum foil) from the weight of the dry soil in the container. Finally, percent moisture content of the soil was calculated as the percentage of the weight difference between the moist soil sample and dry soil sample as follows (Craze, 1990; Wilke, 2005):

$$\text{MC \%} = \left[\frac{\text{W1-W2}}{\text{W1}}\right] \times 100$$

Where; MC % = percent moisture content of the soil,

W1= Weight of moist soil

W2= Weight of dry soil

Soil moisture content (%) measured by HD2 mobile moisture meter was directly measured in the field.

3.4 Determination of water discharge

Water discharge was directly measured at the lower outlets of the respective sites (untreated and treated) during the drier months from December 2018 to June 2019 on a weekly basis. The drier months were purposely selected to maximize the chance of measuring surface and subsurface water that came out of the storage capacities of the sites. Appropriate locations where all water lines (river flow and springs) join were identified at the lower most outlets of the sites. All water sources were directed by the metal board to flow into a measuring bucket without seepage. The arms of the metal sheet were inserted into the ground and the surroundings were sealed with mud, so that all water flows were led into the measuring bucket (Fig. 7). However, deep subsurface water sources and surface evaporation along river lines remained un-captured.

Graduated bucket with twenty liters capacity was used to collect the water; and a stop watch was used to record the time taken to fill the bucket. Two workers: one time keeper and one taking care of the water flow and tell the filling of the bucket were recruited. Each week, mean discharge values were taken from 10 repeated measurements at each site. Besides, measurements were taken in the morning before people and livestock start using the water. After measuring the amount of water discharge, weighted values were recorded for comparative analysis. To compute weighted values, volumes of water discharge (Ls^{-1}) were divided by the area (in km^2) of the respective sites.

Figure 7. Measuring water flow at the outlets of the sites

Livelihood improvement was explored by interviewing irrigation users at the lower positions of the respective sites. Farmers were asked about the current size of their irrigated farmland and the type of crops they grow comparing the sizes and crop types before integrated land management measures were introduced in the treated site; and farmers in the untreated site were interviewed about their current (2018) farm size and type of crops they grow compared to the 2012.

3.5 Assessment of plant species richness

Systematic sampling method (Fidelibus and Aller, 1993) was employed to collect data on plant species richness in the study area. Thus, different habitats were systematically sampled along a line transect in the treated and untreated sites, upper and lower landscape positions and different land-use types. Four line transects 75m apart were established (Mekuria & Veldkamp, 2012; Tsechoe et al., 2014). Along the line transect 10m × 10m main sampling plots were established at 100 m interval. Within each 10m × 10m plot, five sub-plots of 2m × 2m for shrubs and 1m × 1m for herbaceous plants were used (Pearson et al., 2005). The sub-plots were laid down five times: one at the center and four at each corner of the main plot (Mekuria et al., 2011; Mekuria & Veldkamp, 2012; Tsechoe et al., 2014) (Fig. 8). The direction of the line transects was controlled by a compass from the upper landscape to the lower landscape. Species inventory was carried out in the sub-plots while trees were inventoried in the main plot. Plant species in the sub-plots were identified, recorded, labeled, pressed using plant press and taken to the herbarium for confirmation and identification of some species which were not identified in the field.

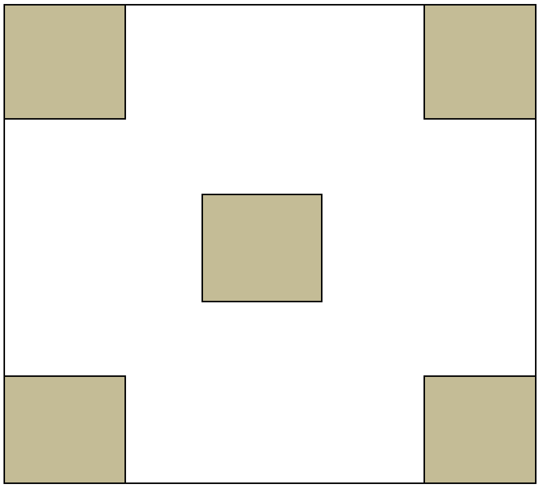

Figure 8. Sampling layout for assessing plant species richness. Shaded parts represent sub-plots (Tsechoe et al., 2014)

Most plant species were identified in the field by a botanist. Some of the species that need further identification and confirmation were brought to the herbarium of Debre Berhan University for identification. In the laboratory, plant specimens were safely taken from the plant press and displayed for identification. Further, identification was carried out using identification guides such as Flora of Ethiopia and Eritrea volumes 6, 7 and 8. For colour images, triangulation was made with Flora: the gardener's bible, East Bay Regional park district 2013, a photographic guide to the wild plants of Pleasanton ridge regional park; and web based sources such as flora of Israel online at http://flora.org.il/en/plants/ GERDIS/, The University of Arizona photo library at https://cals.arizona.edu/crop/images/database/weeds/weedphotos.html& University of California, Berkeley at https://calphotos. berkeley.edu/ browseimgs/plantsci230. html.

Species similarities for the untreated and treated sites, as well as upper and lower landscape positions were determined using Sorenson's similarity index (Sorensen, 1948):

$Ss = 2C/ (2C+A + B)$;

Where; Ss = Sorensen's similarity coefficient

C = the number of species common in both sites;

A= the number of species found in site A only, and

B = the number of species found in site B only. This index can be modified to a coefficient of dissimilarity by taking its inverse: Sorensen's dissimilarity coefficient D = 1−Ss.

3.6 Assessment of carbon stock

Samples on plant biomass were collected in the main season of 2018 (October for grasses and early maturing crops, and November for late maturing crops) and in the dry season (February 2019), the peak biomass exporting period of the landscape through harvesting and free grazing. These periods were selected to make adequate comparison of carbon stock between the treated and untreated sites. In order to increase accuracy and precision of estimation, the study area was grouped into: 1) treated with integrated land management interventions and untreated, 2) landscape position such as upper landscape and lower landscape, 3) land-use type such as crop land, grazing land and Tree Lucerne plantation (Pearson et al., 2005). Then, samples on plant biomass, soil bulk density and soil organic carbon were collected from both treated and untreated sites in the upper and lower landscape positions, from crop land, grazing land and Tree Lucerne plantation. Accordingly, ten representative plots were identified for each of the two land-use type in each landscape position and each site; and ten plots for Tree Lucerne plantation in the lower landscape of the treated site. Consequently, a total of 90 samples were collected (two sites × two landscape positions × two land-use types × ten replications) including ten samples from Tree Lucerne plantation in the lower landscape position of the treated site. A main quadrant of 10 m by 10 m was laid down at each representative plot (Zerihun et al. 2011); and 2m by 2m sub-quadrant was used for shrubs (mainly Tree Lucerne) and 1m by 1m sub-quadrant was used for grasses, herbs and crops within the 10m by 10m main quadrant (Pearson et al. 2005).

Above ground biomass for grass, herbs and the crop was determined by cutting all the vegetative parts of the plants (grass, herbs, crops) above the soil surface (Asmare and Gure, 2019) using sickles and shaver in a 1m by 1 m quadrant at four corners and the center of the main quadrant (Fig. 9). The total weight of the fresh samples and sub-samples were measured on the spot using spring balance (Fig. 8), the weight of composite fresh sub-samples were also measured, labeled and put in cloth bags and taken to the laboratory to determine the dry masses (Pearson et al., 2005; Mekuria et al, 2011; Muluken et al., 2015). To estimate remaining biomass in the dry period, samples were also collected in February 2019 following similar procedures as in the main cropping season.

In order to determine the biomass of the Tree Lucerne, partial harvest method was used (Mekuria et al., 2011) because, harvesting all the Tree Lucerne in the sampling plot is destruction of the conservation measures that could negatively affect the conservation outcomes on one hand and show wrong practice to the community on the other hand. Accordingly, a total 35 individual Tree Lucerne plants were harvested; 25 of which from crop and grazing lands where they provide biological support and ten of which from Tree Lucerne plantation in the lower landscape position of the treated site. After partial harvesting of the Tree Lucerne small branches with leaves, big branches and stem were separated and fresh weight of all parts was measured on spot; and the weight of sub-samples were taken from all parts as per the ratio of the weight of the parts, brought to the laboratory to determine the dry mass. Below ground biomass for Tree Lucerne was determined by multiplying the above ground biomass (AGB) by 0.27 (Manaye et al, 2019) as recommended by IPCC (2006) using root to shoot ratio of the tropical mountain system.

Figure 9. Measuring fresh biomasses of crops, grasses and herbs during the main cropping season (October-November 2018) for biomass and carbon stock estimation

Belowground biomass was estimated in Tree Lucerne but not in other plant species because the roots of herbs and crops are expected to decompose in the given conservation periods and can be thus captured in the soil C pool which is not true for the main roots of Tree Lucerne. However, active roots of some crop/herb/grass in all land-uses were not included in C stock estimation. Thus, the ecosystem C stock might be under estimated.

In the laboratory, all bags were put open to allow evaporation of moisture, which otherwise might create suffocation and rotting until oven drying. Then, all sub-samples were oven dried at

70^0C for 48 hours (Pearson et al., 2005; Mekuria et al, 2011, Muluken et al., 2015) and weighed using digital balance (Fig. 10).

Figure 10. Drying samples in the oven (a) and measuring the dry mass using digital balance (b)

Dry mass per plot was calculated as:

$$\text{Dry mass of the sample per plot} = \frac{\text{sub sample dry mass}}{\text{sub sample wet mass}} \times \text{total mass of the sample} \ldots \text{eq1}$$

This was converted into hectare basis by multiplying the plot dry mass by an expansion factor calculated from the plot size. $\text{Extension factor} = \frac{10{,}000\text{m}^2}{\text{plot area m}^2} \ldots \text{eq. 2 (Pearson et al., 2005)}$.

Carbon stock for Tree Lucerne was determined by multiplying the oven dry mass by the default value of C fraction (0.47) as recommended by IPCC (2006) (Muluken et al., 2015); whereas, C stock for grasses, herbs and crops were determined by multiplying the oven dry mass by 0.5 (IPCC, 2006; Mekuria et al, 2011). In order to understand CO_2 mitigation potential of SLM intervention options in the study area, the carbon stock was converted to tons of CO_2 equivalent by multiplying the C stock by 3.67 (Molecular weight ratio of CO_2 to O_2 which is 44/12) (Muluken et al., 2015).

SOC stock was determined from bulk density (gcm^{-3}), sampling depth (cm) and OC concentration (%) obtained from the laboratory analysis (Pearson et al., 2005; Mekuria et al., 2011; Muluken et al., 2015; Manaye et al, 2019). Thus, soil samples were taken to determine SOC at two depths: 0–15cm and 15–30cm from five points where plant biomass was taken and composited to take to the laboratory; the samples were air-dried in the laboratory, ground and sieved for OC analysis (Pearson et al., 2005). Furthermore, undisturbed soil samples were taken using a core sampler having 5cm height and 5cm diameter (Volume = 98.125 cm^3) (Masebo et al. 2014) for each depth at each sampling plots. Then, the samples were taken to the laboratory of Debre Berhan Agricultural Research Center.

SOC was analyzed using the Walkley–Black method (Walkley and Black, 1934). Bulk densities of the soils were determined from the mass of an oven dried soil at 105^0C for 48 hours and volume of the core sampler (Pearson et al., 2005; Masebo et al., 2014; Tiki et al., 2016). The oven dry mass was divided by the volume of the core sampler as described by Wilke (2005); (Alemayehu and Fisseha, 2019).

SOC stocks (Mg C ha^{-1}) in the 0–15cm and 15–30cm depth were separately calculated as:

SOC= OC (%) × Bd x depth (m) × 10,000m^2 ha^{-1}(Mekuria et al., 2011). ---- eq. 3

Where; SOC = Soil Organic Carbon (t ha^{-1});

OC = the soil C concentration (%);

Bd = bulk density (Mg m^{-3}) and;

Depth = soil sampling depth (m);

10,000 m^2 ha^{-1}= conversion factor to hectare basis.

Finally, the landscape carbon stocks were determined by adding all carbon pools from the plant biomass and the soil for both the treated and untreated sites; and the exported C stock was determined by subtracting the dry season C stock by plant biomass from the main season C stock by plant biomass.

3.7 Data Analysis

Analysis of variance (ANOVA) was employed using General Linear Model of SAS version 9.4 statistical software (SAS Institute, 2016). Duncan’s multiple range tests at $p \leq 0.05$ was used to separate treatment means when there was a significant treatment effect. Data for normality was assessed using Shapiro-Wilk normality test. Two samples t test was performed when comparing temporal differences in irrigated land and cropping patterns at the out let of the two sites. In order to evaluate treatment effects on selected soil properties, biomass production and carbon stock, comparisons were made among sites, landscape positions, land-use types and soil depths. Discharge and irrigation practices were compared between sites. The degree of species similarities was calculated using Sorenson’s similarity index (Sorenson, 1948). Plant species richness was assessed against sites, landscape positions, land-use types, aspects and conservation types. Excel spreadsheet was also used to group data into their relative sites, landscape positions and land-use types as well as to produce different graphs.

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1 Effects of integrated land management on selected soil properties

4.1.1 Effects of integrated land management on soil physical properties

Integrated land management significantly ($p \leq 0.001$) affected the physical properties of the soils in Geda watershed. However, significant differences were not observed on silt content between the treated and untreated sites (Table 2). Landscape position significantly ($p < 0.0001$) affected sand, silt and bulk density of the soil in the untreated site. For sand and bulk density, significantly higher mean values were observed in the upper landscape position; whereas, for silt, the lower landscape position revealed significantly higher mean value in the untreated site.

Table 2. Effects of integrated land management, landscape positions and land-use types on selected soil physical properties

		Particle size distribution (%)			Silt to Clay ratio	BD (g/cm^{3})	Textural class
		Sand	Clay	Silt			
Site (S)							
Treated site		31.38^{b}	36.92^{a}	31.71	0.87^{b}	1.07^{b}	Clay loam
Untreated site		46.63^{a}	22.58^{b}	30.79	1.37^{a}	1.26^{a}	Loam
Landscape position (SP)							
Treated	Upper	31.17^{c}	37.33^{a}	31.50^{b}	0.85^{c}	1.10^{c}	Clay loam
	Lower	31.58^{c}	36.50^{a}	31.92^{b}	0.89^{c}	1.05^{c}	Clay loam
Untreated	Upper	52.33^{a}	23.58^{b}	26.08^{c}	1.22^{b}	1.34^{a}	Sandy clay loam
	Lower	40.92^{b}	21.58^{b}	35.50^{a}	1.53^{a}	1.19^{b}	Loam
Land-use (Lu)							
Treated	Crop	30.92^{b}	35.92^{a}	33.17	0.93^{b}	1.06^{b}	Clay loam
	Grazing	31.83^{b}	37.92^{a}	30.25	0.80^{b}	1.09^{b}	Clay loam
Untreated	Crop	47.17^{a}	23.08^{b}	29.75	1.31^{a}	1.24^{a}	Loam
	Grazing	46.08^{a}	22.08^{b}	31.83	1.44^{a}	1.28^{a}	Loam
	SE	1.374	1.126	0.753	0.051	0.020	
	p-S	***	***	ns	***	***	
	p-SP	***	***	***	***	***	
	p-Lu	***	***	ns	***	***	

Means within columns under each subtopic followed by different letter(s) are significantly different from each other at $p \leq 0.05$; *** = significant at $p \leq 0.001$; ns = not significant; BD = Bulk density.

Landscape position didn’t significantly influence the soil physical properties in the treated site. However, both landscape positions in the treated site showed significantly lower sand and higher clay contents compared to both landscape positions of the untreated site. On the other hand, land-use types didn’t significantly affect major soil physical properties in both sites.

Generally, sand, silt and bulk density are higher in the untreated site and clay in the treated site; but effect of landscape position is low when supported with conservation structures. Silt is significantly higher at the lower part of the untreated site showing higher landscape position effect; but although the total silt percentage is similar in the treated and untreated sites, the distribution in the upper and lower part of the treated site seems even indicating lower landscape position effect when supported with conservation.

The higher clay fraction in the treated site could be due to the conservation structures that could have protected soil particles from erosive runoff and trapped the eroded soils so that there is an in situ deposition behind the conservation structures as explained by Wolka et al. (2011) and Adimassu et al. (2012).

Moreover, in the treated site, organic inputs from the decomposition of supportive biological interventions such as Tree Lucerne and Phalaris grass could have contributed to the increased clay content of the soils since more stubble and grass remained in the landscape due to prohibited free grazing. Whereas these organic sources were continuously exported from the fields through free grazing in the untreated site, making the soil poorer in clay contents. Furthermore, the higher sand content in the upper and higher silt content in the lower landscape positions of the untreated site could be due to removal of the fine particles from the upper part by soil erosion, leaving heavier sand particles behind, while the transported silts deposited at the lower landscape.

The silt to clay ratio (SCR) was significantly ($p \leq 0.001$) affected by land management measure (Table 3). The untreated site revealed the higher silt to clay ratios in all landscape positions and land uses compared to the treated site; indicating young developing soil dominating the untreated site. The mean value of SCR in the untreated site is 1.37±0.35 while in the treated site it is

0.87±0.23. This indicates that the soil in the treated site has better stability and resistance to erosion while the soil in the untreated site is vulnerable (Onweremadu et al., 2007). Furthermore, the untreated site revealed textural classes of sandy clay loam in the upper landscape position and loam in the lower landscape position indicating a takyric horizon which experiences preferential removal of the fine clay particles (FAO, 2006).

Except sand in the untreated site, the effect of soil depth on other soil physical properties, with respect treatment, landscape position and land-use, was not significant. Sand showed significantly ($p < 0.0001$) higher mean values in the upper 0-15 cm depth than the lower 15-30 cm depth in both landscape positions in the untreated site and on crop land. Furthermore, SCR was not significantly affected by land-use and soil depths in all sites (Table 3).

Table 3. Effects of soil depth, landscape position and land-use types on soil physical properties

		Particle size distribution (%)			Silt/ Clay	BD (g/cm^3)	Textural class
		Sand	Clay	Silt			
Soil depth by landscape position SdLp)							
Treated upper	0–15 cm	32.17^{e}	36.50^{a}	31.33^{bc}	0.87^{c}	1.14^{bc}	Clay loam
	15–30 cm	30.17^{e}	38.17^{a}	31.67^{bc}	0.84^{c}	1.06^{cd}	Clay loam
Treated lower	0–15 cm	33.50^{e}	34.83^{a}	31.67^{bc}	0.92^{c}	1.08^{bcd}	Clay loam
	15–30 cm	29.67^{e}	38.17^{a}	32.17^{bc}	0.85^{c}	1.01^{d}	Clay loam
Untreated upper	0–15 cm	55.83^{a}	19.83^{b}	24.33^{d}	1.24^{b}	1.36^{a}	Sandy loam
	15–30 cm	48.83^{b}	23.33^{b}	27.83^{cd}	1.21^{b}	1.31^{a}	Loam
Untreated lower	0–15 cm	43.33^{c}	23.33^{b}	33.33^{a}	1.45^{ab}	1.19^{b}	Loam
	15–30 cm	38.50^{d}	23.83^{b}	37.67^{a}	1.59^{a}	1.18^{b}	Loam
Soil depth by land-use (Sdlu)							
Treated crop	0–15 cm	32.17^{c}	34.33^{b}	33.50	0.98^{b}	1.09^{bc}	Clay loam
	15–30 cm	29.67^{c}	37.50^{ab}	32.83	0.88^{b}	1.02^{c}	Clay loam
Treated grazing	0–15 cm	33.50^{c}	37.00^{ab}	29.50	0.80^{b}	1.14^{bc}	Clay loam
	15–30 cm	30.17^{c}	38.83^{a}	31.00	0.81^{b}	1.05^{c}	Clay loam
Untreated crop	0–15 cm	50.83^{a}	21.67^{c}	27.50	1.29^{a}	1.28^{a}	Sandy clay loam
	15–30 cm	43.50^{b}	24.50^{c}	32.00	1.32^{a}	1.20^{ab}	Loam
Untreated grazing	0–15 cm	48.33^{ab}	21.50^{c}	30.17	1.41^{a}	1.27^{a}	Loam
	15–30 cm	43.83^{b}	22.67^{c}	33.50	1.48^{a}	1.29^{a}	Loam
SE		1.374	1.126	0.753	0.051	0.020	
p-SdLp		***	***	***	***	***	
p-Sdlu		***	***	ns	***	***	

Means within columns under each subtopic followed by different letter(s) are significantly different from each other at $p \leq 0.05$; *** = significant at $p \leq 0.001$; ns = not significant; BD = Bulk density.

Insignificant effects of the soil depth on soil physical properties in the treated site could be due to the young age of the conservation measures and the closeness of the sampling depth. Although not significant, the lower clay content on the upper 0-15 cm soil compared to the lower 15-30 cm soil in croplands of the treated site could be attributed to erosion impacts on the top soil which could be susceptible to aggregate disturbance by plowing since soil erosion is a natural processes taking place anywhere including the treated site (erosion zone) although trapped by conservation structures in the deposition zone. Soil particles eroded from upper parts are deposited in the lower part of each plot making the proportion of soil particles closer than the untreated site in which finer soil particles transported far in to the down landscape. The in situ conservation of soil particles in the treated site, could have contributed to the observed close proportion of sand, clay and silt across the landscapes and land-use types compared to the untreated site (Figs 11& 12).

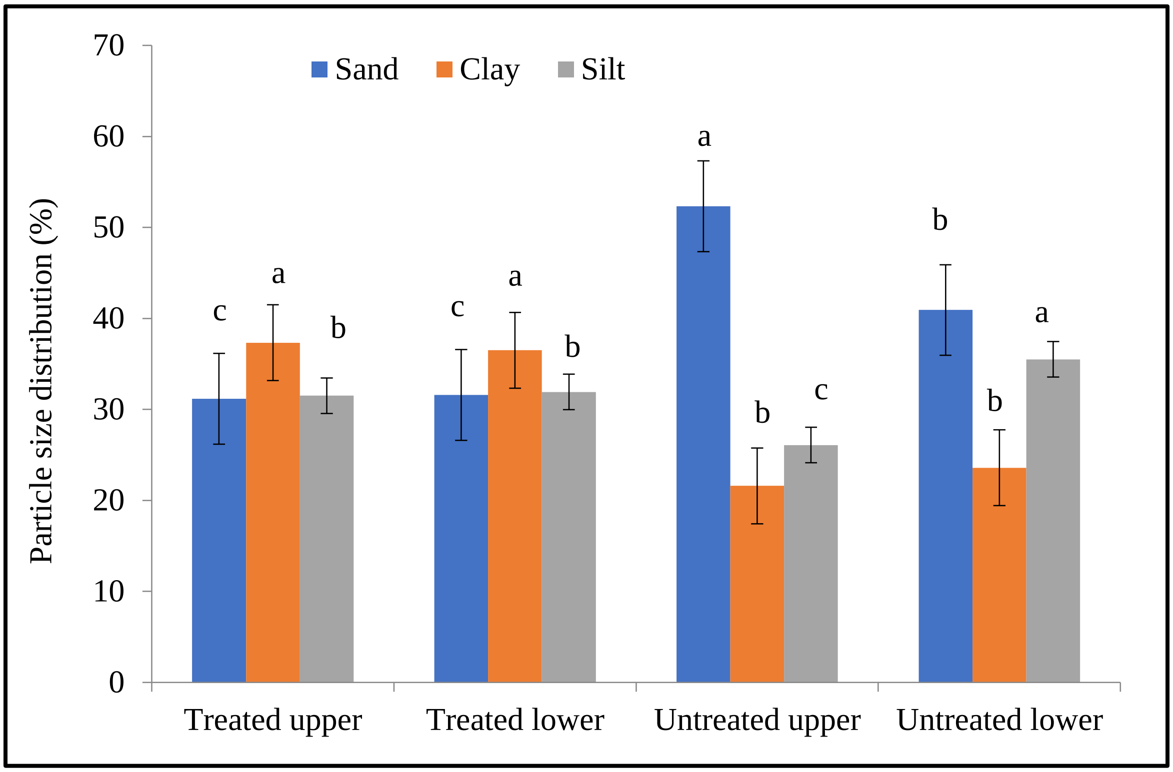

Figure 11. Particle size distribution by treatment and landscape position. Bars with different letters are significantly different for each soil particle

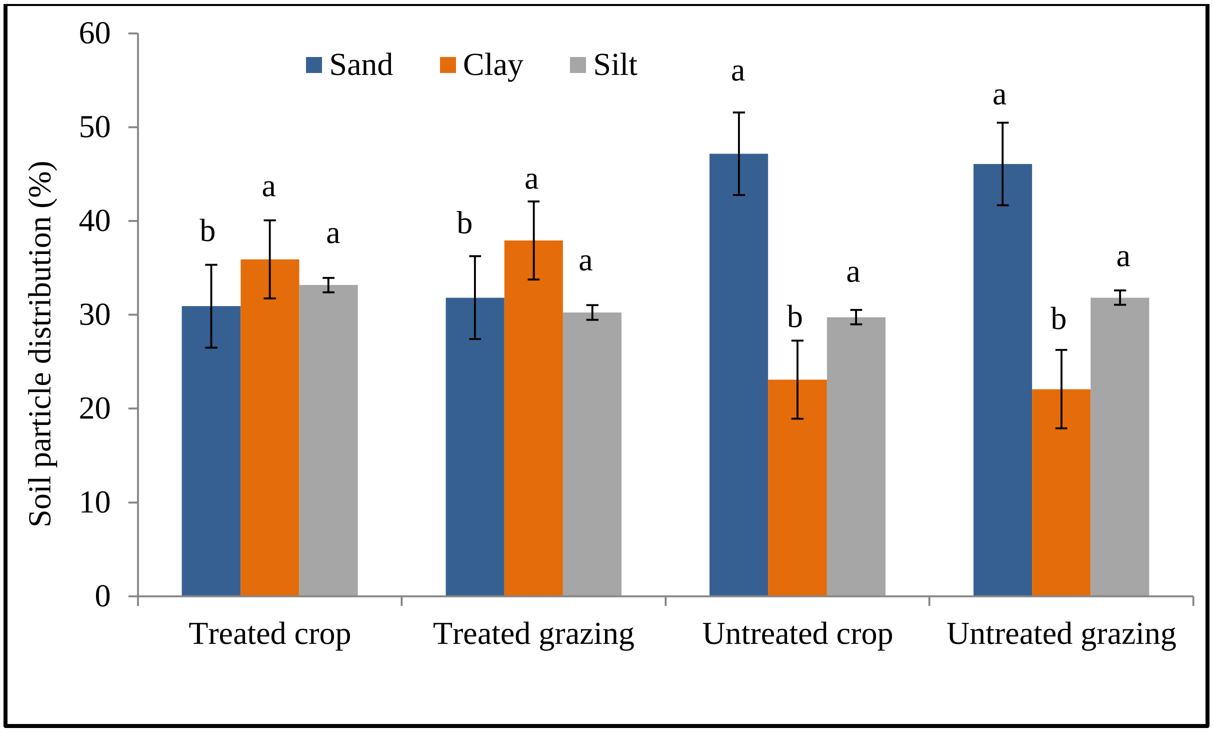

Figure 12. Particle size distribution by treatment and land-use types. Bars with different letters are significantly different for each soil particle

The current finding agrees with the findings of Ademe et al. (2017) and Tufa et al. (2019). Ademe et al. (2017) found higher sand and silt contents, but lower clay content in the untreated watershed than the treated watershed; furthermore, Tufa et al. (2019) found no significant difference in sand particle proportions under land–use types, soil depths and in the interaction of land–use types with soil depth. Both studies found significantly higher sand content on the surface and higher clay content at subsurface of the soils.

However, Demelash and Karl (2010) and Alemayehu and Fisseha (2019) presented highest mean value of clay and the lowest mean value of sand in the non–conserved compared to the conserved landscapes. Their explanation was that tillage exposes the high clay content of subsoil to the surface, but this might be true for landscapes with deep clay soils. In highly degraded landscapes, tillage exposes the thin surface soils for erosion and leaves sand and stone behind. The watershed in the current study had experienced severe soil erosion, especially at the upper landscape and had thin top soil depth at most of the sampling locations which could be the reason for low clay content at the surface in the untreated site.

The higher bulk density in the untreated site compared to the treated site could be attributed to the relatively higher sand content of the soil in the untreated site than the treated one. Soil bulk density is significantly influenced by sand content more than other soil properties (Askin and Ozdemir, 2010; Chaudhari et al., 2013). These authors found a significant correlation between bulk density and sand content. According to Askin and Ozdemir (2010), sand content of soils is the most important soil property that determines the soil bulk density. Nevertheless, various factors such as soil texture, organic matter content, land–use, and management that changes the soil physical structure or organic matter content also changes bulk density (Chaudhari et al, 2013). Soil bulk density is also an indicator of soil compaction (Houlbrooke, 1997; Kaufmann et al. 2010). It indicates the status of aeration and permeability and varies with structural conditions of the soil (Wilke, 2005). Thus, compaction due to livestock trampling in the free grazing system could have contributed to the higher bulk density in the untreated site. Still, the bulk densities of the soils in both sites are ideal for plant growth (Kaufmann et al., 2010). The current finding agrees with the findings of Demelash and Karl (2010) and Alemayehu and Fisseha (2019) who found higher bulk density in non–conserved landscapes than the conserved landscapes. Furthermore, Tufa et al. (2019) reported higher bulk density on the surface 0–20 cm soil depth and at cropland.

4.1.2 Effects of integrated land management on soil moisture content

Integrated land management significantly ($p \leq 0.001$) improved the soil moisture content in Geda watershed (Table 4). At the end of the rainy season and the beginning of the dry season (October), the soils in the treated site contained 4.22 % and 3.53% more moisture than the untreated site in the upper 0–20cm and lower 20–40cm depths respectively. In addition, in the drier month (January), the soils in the treated site showed 0.66% more moisture over the untreated one. However, landscape position and land-use types didn't statistically influence the soil moisture content in both sites.

The higher soil moisture content in the treated site compared to the untreated one could be due to the contribution of the introduced conservation structures and prohibition of free grazing. The introduced conservation measures such as soil bunds, trenches, percolation pits and terraces reduce runoff concentration and trap it to be stored in the soil profile; and roots of plants such as Tree Lucerne and Phalaris which were introduced to reinforce the physical structures enhance percolation of the trapped runoff. Furthermore, the presence of relatively higher soil cover by enhanced vegetation due to prohibited free grazing and accumulation of organic inputs in the treated site could have reduced surface evaporation by serving as mulch, which overall could have improved the soil moisture in the treated site compared to the untreated site. The more plant species proliferation and more soil cover, the higher infiltration rate and enhanced organic input in to the soil which later retains more moisture in the soil (Hishe et al., 2017a).

Table 4. Effects of integrated land management and landscape positions on soil moisture content

	Soil moisture content (%)		
	October-2018 (Gravimetric)		January-2019 (HD2)
	0 − 20cm	20 − 40cm	0 − 20cm
Site (S)			
Treated	25.92^{a}	27.35^{a}	10.16^{a}
Untreated	21.70^{b}	23.82^{b}	9.50^{b}
Landscape position (Lp)			
Treated upper	25.37^{a}	26.87^{a}	10.26^{a}
Treated lower	26.47^{a}	27.84^{a}	10.07^{ab}
Untreated upper	20.93^{b}	23.18^{b}	9.44^{c}
Untreated lower	22.47^{b}	24.45^{b}	9.56^{bc}
Land-use (Lu)			
Treated crop	26.07^{a}	27.25^{a}	10.28^{a}
Treated grazing	25.77^{a}	27.46^{a}	10.03^{ab}
Untreated crop	20.95^{b}	22.89^{b}	9.56^{b}
Untreated grazing	22.44^{b}	24.74^{b}	9.44^{b}
SE	0.425	0.408	0.106
p-S	***	***	***
p-Lp	***	***	*
p-Lu	***	***	*

Means within columns under each subtopic followed by different letter(s) are significantly different from each other at $p \leq 0.05$; * = significant at $p \leq 0.05$; *** = significant at $p \leq 0.001$; HD2: soil moisture measured using HD2 mobile moisture meter.

The current finding is in line with various researchers (e.g. Descheemaeker et al., 2006, Nyssen et al., 2008; Wubet et al., 2013; Masebo et al., 2014; Sultan et al., 2017; Hishe et al., 2017a;

Adimassu et al., 2017) who assessed the contribution of SWC measures on hydrological processes in different parts of Ethiopia.

Descheemaeker et al. (2006) reported as area exclosure increased soil moisture, Masebo et al. (2014) found higher moisture content on plots with SWC than the control plots. According to Nyssen et al. (2008), Wubet et al. (2013) and Hishe et al. (2017a) increased vegetation cover also increased infiltration rates. Sultan et al. (2017) and Adimassu et al. (2017) reported that soil and stone bunds reduced runoff and increased soil moisture.

Acceding to Nyssen et al. (2010), catchment management in semi-arid areas decreased direct runoff during the rainy season and improved water availability in the dry season. The average annual runoff reduction due to soil bunds at Galessa Watershed, central highlands of Ethiopia was 28% (Adimassu et al., 2012) and at Enabered watershed, northern Ethiopia was 27 % (Haregeweyn et al., 2012). Likewise, stone bunds with trenches were also effective SWC measures to reduce runoff in Tigray (Taye, et al., 2013). Furthermore, increased vegetation covers significantly reduced run off while it increased infiltration rate (Nyssen et al., 2008; Wubet et al., 2013; Hishe et al., 2017a). Soil moisture enhances various soil physicochemical reactions and improves various soil activities; these intern influence crop growth, nutrient availability, nutrient transformations and soil biological activities (Brady and Weil, 2002). Thus, the introduced land management practices would positively enhance the soil health on which other ecosystem services base.

4.1.3 Effects of integrated land management and landscape positions on selected soil chemical properties

Land management considerably improved selected soil chemical properties in the study area. The treated site showed significantly ($p \leq 0.05$) higher OC, TN, Available P and K^+ compared to the untreated site; but pH and Na^+ were significantly ($p \leq 0.05$) higher in the untreated site (Table 5).

Table 5. Effects of treatment and landscape position on selected soil chemical properties

	pH	OC	TN	Av.P	Na^+	K^+
Site (S)						
Treated	6.11^b	0.98^a	0.107^a	11.12^a	0.391^b	0.54^a
Untreated	6.30^a	0.42^b	0.063^b	6.23^b	0.485^a	0.44^b
Landscape position (Lp)						
Treated upper	5.94^b	0.919^b	1.00^a	11.53^a	0.367^c	0.46^b
Treated lower	6.28^a	1.047^a	0.117^a	10.71^a	0.415^b	0.63^a
Untreated upper	6.40^a	0.442^c	0.059^b	6.06^b	0.468^a	0.36^c
Untreated lower	6.20^a	0.400^c	0.068^b	6.40^b	0.502^a	0.52^b
SE	0.046	0.053	0.006	0.561	0.087	0.025
p-S	*	***	***	***	***	*
p-Lp	**	***	***	***	***	**

Means under each heading within columns followed by different letters are significantly different from each other at $p \leq 0.05$; * = significant at $p \leq 0.05$; ** = significant at $p \leq 0.01$; *** = significant at $p \leq 0.001$; ns = non-significant; pH = Soil reaction (pH meter); OC = Organic carbon; TN= Total nitrogen; Adv. = Available phosphorus; Na^+ = Exchangeable sodium; K^+ = Exchangeable potassium.

As can be seen in Table 5 above, landscape position affected pH, OC, Na^{i}ad K^+ in the treated site with significantly ($p \leq 0.01$) higher mean values in the lower landscape position; whereas, it affected only K^+ in the untreated site with significantly ($p = 0.01$) higher mean value in the lower landscape position.

The higher OC and TN in the treated site could be due decomposition of higher organic matter, atmospheric fixation of N through Tree Lucerne plant (Mekonnen et al., 2006), as these are dependent on organic matter accumulation and clay content of the soil (Ademe et al., 2017). There was higher plant biomass production, but less export of this biomass from the treated site by free grazing (author own data). Furthermore, higher OC in the lower section of the treated site (Table 5) can be explained by the transport of organic materials from upper landscape to the lower landscape through runoff. The relatively higher moisture availability in the lower landscape could also favored decomposition of organic materials and release of OC as mentioned by Alemayehu and Fisseha (2019). The soil moisture content was higher in the lower landscape compared to the upper section (author own data).

The higher available P in the treated site could be due to in situ deposition of residual P (from DAP fertilizer application) and released P from mineral rocks and decomposition of organic materials (Kwabiah et al., 2001; Jalali and Ranjbar, 2009); and preserved by the conservation structures. Furthermore, the higher K^+ in the lower landscape position of the treated site could be attributed to improved clay content of the soil and higher organic carbon as Potassium availability is highly correlated with clay content and OC of the soils (Zhang et al., 2009). On the other hand, the lower pH in the upper landscape position of the treated site and higher pH in the untreated site could be due to nitrification processes and fertilizer application. The soil reaction (pH) decreases when hydrogen ions are released from the organic anions through nitrification in an open system (Ritchie and Dolling, 1985). Besides, subsequent plant growing and the type of fertilizer applied affect soil pH (IBID); further, differences in organic materials (Wilke, 2005) could have affected the pH of the soil.

Although the soil in the study area is not sonic, the higher Na^+ in the untreated site compared to the treated site could be linked to the effect of erosion on the parent material. Due to the higher Na^+ the untreated site could be more vulnerable to erosion and surface crusting since as explained by Nadir and Schubert (2002). These authors reported as Na^+ is responsible for destabilization of soil structure, increase susceptibility of the soil for erosion, and deterioration of hydraulic properties of the soils. This was also observed by the relatively higher SCR in the untreated site.

The current finding is in agreement with Wolka et al. (2011) who reported lower pH at the treated watershed compared to the untreated one. However, Demelash and Karl (2010), Ademe et al. (2017), and Alemayehu and Fisseha (2019) found higher pH values on conserved plots than the non–conserved plots. This might be due to differences in organic materials, because pH is affected by the constituents of organic materials (Wilke, 2005). Generally, the soils in the current study area were slightly acidic; yet, it is in the preferred range for most of the agricultural practices (Alemayehu and Fisseha, 2019). Furthermore, Demelash and Karl (2010) and Ademe et al. (2017) reported higher organic matter, OC and TN in the treated watersheds than in the untreated ones, and in the lower landscape position than the upper landscape position. Furthermore, Ademe et al. (2017) found higher P and K^+ at conserved landscape than the non–conserved one and K^+ in the lower landscape.

4.1.4 Effects of land-use types and soil depths on selected soil chemical properties

Land-use didn’t affect most of the soil chemical properties in both sites except available P in the treated site which showed significantly ($p \leq 0.001$) higher mean value in crop land than the grazing land (Table 6). Regarding soil depths, statistically ($p \leq 0.01$) higher mean values were observed on the upper 0 −15 cm depth for available P in the treated site, for pH, OC, TN and K^+ in both sites, and for Na^+ in the untreated site.

Table 6. Effects of land-use types and soil depths on selected soil chemical properties

	pH	OC	TN	Av.P	Na^+	K^+
Land–use (Lu)						
Treated crop	6.10	1.042^{a}	0.118^{a}	12.98^{a}	0.374^{c}	0.549
Treated grazing	6.12	0.924^{a}	0.096^{a}	9.26^{b}	0.407^{bc}	0.532
Untreated crop	6.36	0.470^{b}	0.064^{b}	6.69^{c}	0.506^{a}	0.416
Untreated grazing	6.24	0.372^{b}	0.062^{b}	5.77^{c}	0.464^{ab}	0.466
Soil depth (Dp)						
Treated 0–15 cm	6.23^{b}	1.181^{a}	0.122^{a}	13.31^{a}	0.394^{b}	0.59^{a}
Treated 15–30 cm	5.99^{c}	0.785^{b}	0.092^{b}	8.93^{b}	0.388^{b}	0.49^{b}
Untreated 0–15 cm	6.44^{a}	0.514^{c}	0.082^{b}	6.99^{c}	0.522^{a}	0.53^{ab}
Untreated 15–30 cm	6.16^{bc}	0.323^{d}	0.045^{c}	5.47^{c}	0.448^{a}	0.36^{c}
SE	0.046	0.053	0.006	0.561	0.087	0.025
p-Lu	ns	***	**	***	***	ns
p-Dp	**	***	***	***	***	**

Means under each heading within columns followed by different letters are significantly different from each other at $p \leq 0.05$; ** = significant at $p \leq 0.01$; *** = significant at $p \leq 0.001$; ns = non-significant; pH = Soil reaction (pH meter); OC = Organic carbon; TN= Total nitrogen; Av.P = Available phosphorus; Na^+ = Exchangeable sodium; K^+ = Exchangeable potassium.

The higher P in crop land could be associated to fertilizer application as farmers apply DAP to improve the crop yield and decomposition of organic materials (Kwabiah et al., 2001; Jalali and Ranjbar, 2009) and presence of relatively adequate aeration facilitated by tillage as P release is faster in good aerated soils (Brdjanovic et al., 1998). The higher pH, OC, TN, Av.P and K^+ in the upper 0 −15 cm depth compared to the lower 15-30 cm depth for both the treated and untreated sites could be due to presence of relatively higher organic matter on the surface as explained by Ademe et al., (2017). The higher OC in the upper part of the soil could have influenced K^+ because, Potassium availability is highly correlated with OC of the soils (Zhang et al., 2009). This finding is in line with reports of other researchers. For instance, Aytenew and Kibret (2016) reported higher P on cropland compared to the adjacent grassland; Tufa et al. (2019) reported as land–use didn't affect pH but the surface 0–20 cm soil depth revealed higher P than the subsurface soil; but our finding differs from their report on K+. According to their report, K content was affected by land–use not by soil depth which could be due to their study area that they studied within the elevation of 1200-2600 masl where high soil depth can be found while the current study was within the altitude of 2947-3156 masl where severe erosion reduced the soil depth. When there is high soil depth 0-20 cm and 20-40cm may be of similar characteristics; which may not be true for shallow soils.

4.2 Effects of integrated land management on water discharge and irrigation practices

4.2.1 Effects of integrated land management on water discharge

Integrated land management statistically ($p \leq 0.001$) improved the water discharge at the bottom outlet of the catchment compared to the untreated site (Table 7). In the dry season (December to

June) the treated site exhibited higher mean value of 1.62±0.07 Ls^{-1} compared to the lower man value of 0.24+0.01 Ls^{-1} in the untreated site which is more than six time higher than the discharge in the untreated site.

Table 7. Dry period water discharge at the outlet of the sites showing significantly higher mean value in the treated site compared to the untreated site (N= number of weeks that measurements were taken)

Sites	N	Mean water discharge (Ls^{-1})	Std. Deviation	SE	p
Treated	25	1.6192	0.367	0.073	0.000
untreated	25	0.2352	0.066	0.013	

During the dry months, sufficient water storages and flows were visible in rivers in the treated site while the rivers in the untreated site were dry (Fig. 12) so that discharge in the treated out let came from springs and rivers; while, the source of discharge in the untreated site were only springs from the ground water. Due to the cumulative effects of surface water and subsurface water sources in the treated site, higher discharge volumes were recorded during the dry season (Table 7; Fig. 13).

The higher discharge in the treated site compared to the untreated could be attributed by the integrated land management measures that retain runoff, increase infiltration and storage of rain water in the underground. Thus, the underground stored water continuously discharged in the dry period.

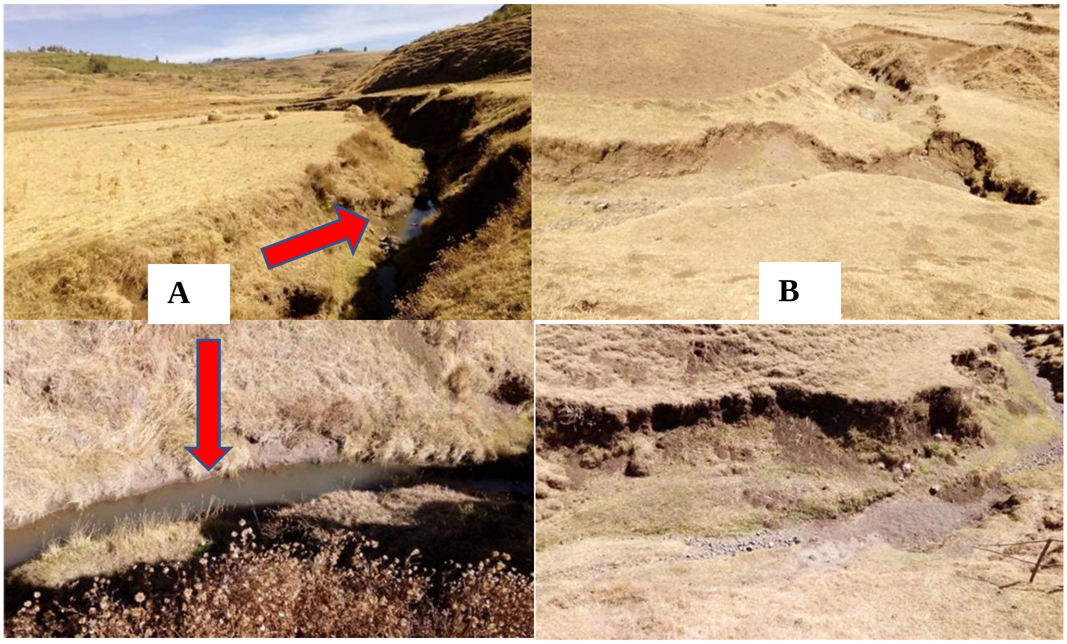

Figure 13. Partial view of rivers in the lower landscape position in Geda watershed during the mid-dry period (January); A: rivers in the treated site having surface water; B: rivers in the untreated site having no water at all

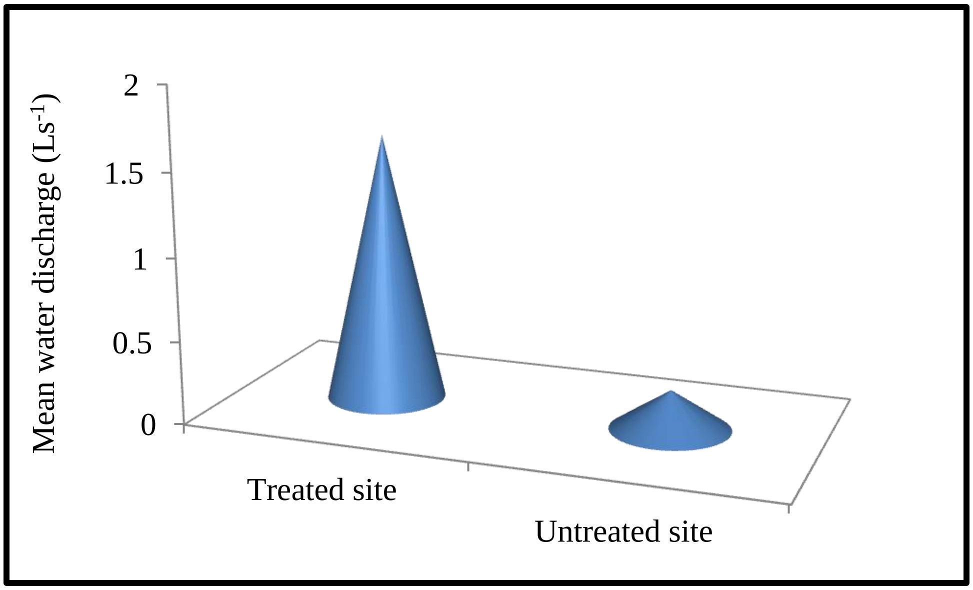

Figure 14. Amount of mean water discharge (Ls^{-1}) in the treated and untreated sites

The current result is in line with various researchers at different parts of the country. Nyssen et al. (2010) reported as catchment management results in higher infiltration rate and reduction of direct runoff volumes. Dabi et al (2017) also reported the positive impact of SWC structures in reducing runoff and increasing infiltration at various times and locations in Ethiopia. The average annual runoff reduction due to soil bunds at Galessa Watershed, central highlands of Ethiopia was 28% (Adimassu et al., 2012) and at Enabered watershed, northern Ethiopia was 27 % (Haregeweyn et al., 2012). Stone bunds with trenches were effective in reducing runoff in Tigray (Taye, et al., 2013).

In the finding of Sultan et al. (2017), combination of soil bunds with vegetation on cultivated lands reduced runoff by 49%, while the use of trenches across the landscape gradient of non-cultivated plots reduced runoff by 65%. According to Descheemaeker et al. (2006), area exclosure reduced runoff, increased soil moisture availability, promoted the development of new springs and more water discharged in rivers during longer periods and enhanced hydrology system. Dessalegn et al. (2015) also reported increased base flow as a response of terraces and infiltration furrows on hillsides that reduced run offs and increased infiltration of rain water. Since reducing surface runoff allows the water to stay at the spot and gives time for infiltration, conservation measures integrated with trees (root penetration enhances percolation) greatly contribute to ground water recharge and discharge improvements.

4.2.2 Effects of integrated land management on irrigation practice

Integrated land management intervention significantly ($p = 0.05$) influenced irrigation practices in Geda watershed (Table 8). Although irrigation land didn’t significantly increase, land-use significantly ($p \leq 0.05$) shifted from pulse to vegetables in the treated site.

Table 8. Temporal changes of irrigated land and crop types in the treated site before 2012 and in 2018 (after the introduction of integrated land management in 2012)

Land size and crop type	Year	Total irrigated land size (ha)	Mean land size & crop type (ha)	Std. Deviation	SE	p
Irrigated land size (ha)						
Irrigated land	2012	22.5	1.500	4.012	0.732	0.064
	2018	26.0	1.733	4.627	0.845	
Planted crop types						
Lentil,	2012	19.5	1.300	3.472	0.634	0.050
Chickpea	2018	1.8	0.117	0.370	0.068	
Vegetable	2012	3.0	0.200	0.592	0.108	0.049
crops	2018	24.3	1.617	4.305	0.786	

The relatively higher water availability in the treated site increased irrigated land and beneficiary farmers at *Ashal-wuha* irrigation site which is found at the lower part of the treated site. Despite, the level of significant change, in the treated site, the irrigated land expanded by 4.5 ha and four additional beneficiary farmers accessed irrigation water after the intervention. Furthermore, farmers significantly shifted their crop type from less water demanding and low yielding field crops to high water demanding and productive vegetable crops. Before the integrated land management intervention they were growing lentil and little chickpea; whereas now they are producing carrot, cabbage and garlic. In addition, pulse production significantly decreased by 84.51% (17.7 ha) whereas, vegetable production significantly increased by 89.01% (21.3 ha) after the introduction of integrated land management practices.

Farmers at *Filwuha* irrigation site, the lower part of the untreated site, also practice irrigation during the off season (Table 9). Even though not significant, the size of irrigated land increased by 2.75 ha, and beneficiary farmers increased by four; yet, in contrast to the treated site, farmers couldn’t shift crops from low water demanding pulses to high water demanding vegetables.

Table 9. Temporal changes of irrigated land in the untreated site in 2012 (before integrated land management measures were introduced in the treated site) and at present (2018)

Years	Irrigated land size (ha)	Mean (land holding)	Std. Deviation	SE	p
2012	0.25	0.050	0.112	0.050	0.098
2018	3	1.200	1.0.4	0.583	

The increased in irrigated land without changing the crop types in the untreated site could be due to increased awareness of farmers about the benefits of irrigation works to improve their income during the off seasons. Thus, relatively more farmers could have utilized the available water from springs to grow water efficient crops such as lentil in this area. Increased irrigation water availability could have been motivated farmers in the treated site to shift the type of crops which was not observed in the untreated site that have similar situations for other factors.

4.3 Effects of integrated land management practices on plant species richness

Treatment and landscape position significantly ($p \leq 0.001$) influenced plant species richness in Geda watershed (Table 10). Higher numbers of plant species were observed in the treated site compared to the untreated one. The effect of landscape position was significant ($p \leq 0.001$) when supported with integrated land management measures; but its effect was insignificant if conservation measures are not practiced. Thus, the upper landscape position in the treated site showed significantly ($p \leq 0.001$) higher plant species.

Table 10. Effects of integrated land management and landscape position on plant species richness in Geda watershed.

	Mean
Site (S)	
Treated	29.500^a
Untreated	20.771^b
Landscape position (Lp)	
Treated upper	32.158^a
Treated lower	27.871^b
Untreated upper	19.444^c
Untreated lower	22.476^c
SE	0.806
p-S	***
p-Lp	***

Means under each heading within columns followed by different letters are significantly different from each other at $p \leq 0.05$; *** = significant at $p \leq 0.001$.

Both crop and grazing lands in the treated site showed significantly ($p \leq 0.001$) higher plant species richness compared to all land-use in the untreated site (Table 11). Crop land in the untreated site revealed significantly ($p \leq 0.001$) higher plant species richness compared to grazing land in the same site. Thus, the influence of land-use on plant species richness was not significant when supported by integrated land management measures; but this affected plant species richness in the untreated site. Furthermore, aspect and conservation types didn’t show significant differences in plant species richness.

Table 11. Effects of integrated land management, land-use, aspect and conservation types on plant species richness

		Mean
Land-use (Lu)		
Treated crop		29.417^a
Treated grazing		29.577^a
Untreated crop		23.636^b
Untreated Grazing		18.346^c
Aspect (As)		
Treated	North East	30.87a
	West	26.92ab
	South west	29.47a
Untreated	North East	20.71c
	West	22.29bc
	South west	20.24c
Conservation types* (Cs)		
Untreated	0	20.771^b
Treated	1	29.667^a
	2	28.000^a
	3	31.000^a
	4	31.500^a
SE		0.806
p-Lu		***
p-As		***
p-Cs		***

Means under each heading within columns followed by different letters are significantly different from each other at $p \leq 0.05$; *** = significant at $p \leq 0.001$.

[*] Conservation types: 0 = no conservation measure; 1= soil bund/trench with biological support (Tree Lucerne and or Phalaris); 2 = soil bund/trench without biological support; 3= Terrace without biological support; 4= terrace with biological support.

The treated site accounted an additional plant species richness of 18%, 10%, 70.59% and 66.67% total plant species, herbs, shrubs and trees respectively over the untreated one. Out of the total 150 plant species recorded, 138 with relatively more number of families were found in the treated site. In addition, families represented by two or more species and species frequencies were higher in the treated site than the untreated site (Table 12). However the dominant plant species (86.67%; N=128), recorded in the study area were herbaceous (grasses and weeds) followed by shrubs (11.33%; N=17). Trees covered only 2% (N=3) in the study area (Fig. 15).

Table 12. Numbers of plant species, their families and frequencies recorded in the study area

Variables	Treated site	Untreated site	Total*
Total no. of sampled plots	40	40	80
Total no. of species recorded	138	111	150
Total family (number)	41	36	41
Families represented by two or more species (number)	21	15	21
Families represented by one species (number)	20	20	20
Species frequency (total)	1,205	861	2,066

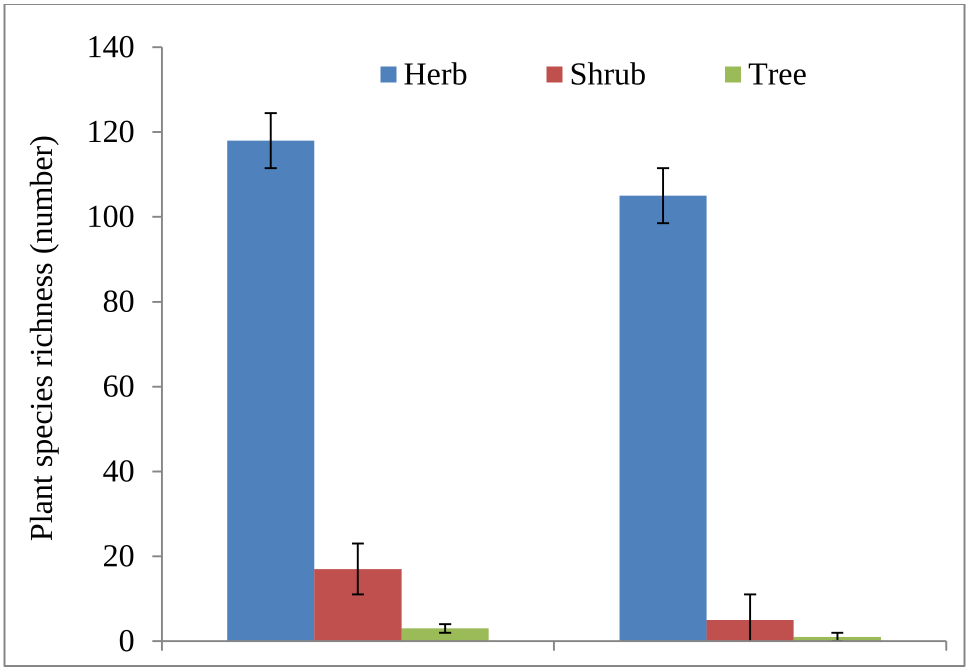

Figure 15. Number of plant species by growth habits recorded in the study area. Bars indicate standard errors of the means

Among the total 17 shrubs documented in the study area, only 5 (29.41%) were found in the untreated site while all of them were observed in the treated site. Furthermore, two more tree species, *Buddleja polystachya* and *Dovyalis abyssinica* were observed in addition to the common *Eucalyptus globulus* in the treated site while only Eucalyptus *globulus* was recorded in the untreated site.

The most dominant plant species in the treated site were *Andropogon abyssinicus*, *Bidens macroptera*, *Chamaecytisus proliferus*, *Eucalyptus globulus*, *Phalaris acqutica*, *Hyparrhenia hirta*, *Medicago polymorpha*. On the other hand, *Alchemilla pedata*, *Andropogon abyssinicus*, *Bidens macroptera*, *Digitaria abyssinica*, *Medicago polymorpha*, *Hyparrhenia hirta* and *Trifolium campestre* were the dominant species in the untreated site (Appendix 1).

The dominate plant species in the upper landscape position of the treated site were *Andropogon abyssinicus*, *Bidens macroptera*, *Chamaecytisus proliferus*, *Eucalyptus globulus*, *Phalaris acqutica;* while *Andropogon abyssinicus*, *Chamaecytisus proliferus*, *Hyparrhenia hirta*, *Medicago polymorpha* were the dominate species in the lower part of the treated site. In the upper landscape position of the untreated site *Alchemilla pedata*, *Andropogon abyssinicus*, *Bidens macroptera*, *Medicago polymorpha*, *Trifolium campestre* were dominate; while *Andropogon abyssinicus*, *Digitaria abyssinica*, *Hyparrhenia hirta*, *Sporobolus africanus* were the dominate species in the lower landscape positions of the untreated site.

Majority of the species (64%; N=73) recorded in the study area were found under eight families representing 62.32% richness in the treated site and 65.77% richness in the untreated site. Moreover, higher species richness was recorded under Asteraceae, Poaceae and Fabaceae in both sites (Table 13).

Table 13. Eight families representing major plant species in Geda watershed

Family	Treated site	Untreated site	Total[*]
Asteraceae	30 (278)	20 (187)[f]	32 (465)
Poaceae	23 (262)	23 (191)	26 (453)
Fabaceae	13 (145)	8 (89)	13 (234)
Lamiaceae	5 (33)	7 (19)	7 (52)
Polygonaceae	4 (73)	4 (71)	4 (144)
Plantaginaceae	4 (43)	3(14)	4 (57)
Cyperaceae	4(27)	4 (21)	6 (48)
Euphorbiaceae	3 (37)	4 (21)	4 (58)
Subtotal	86 (898)	73 (613)	96(1,511)
Percent of total (%)	62.32(74.52)	65.77(71.20)	64(73.14)

[*] Total is not necessarily the sum of the values across the rows due to overlapping presence.
[f] Values in brackets are the relative frequencies of species under each family.

Sorensen’s similarity index revealed higher similarities in species richness between the treated and untreated sites, and upper and lower landscape positions of each sites (Table 14). However, the observed differences were statistical for the treated and untreated sites, upper and lower landscape positions in the treated site and crop and grazing lands in the untreated site (Table 10).

Table 14. Sorensen’s similarity indices for species richness with regard to treatment and landscape positions

Sites and landscape positions	No. of species	Similarity and dissimilarity indices	
		Similarity Index ($Ss=2c/2c+a+b$)	Dissimilarity Index ($D = 1- Ss$)
Treated site	39	0.79	0.21
untreated site	13		
Common in both sites	98		
Treated upper	31	0.77	0.23
Treated lower	20		
Common in both landscapes	86		
Untreated upper	21	0.78	0.22
Untreated lower	19		
Common in both landscapes	69		

The higher plant species richness in the treated site compared to the untreated one could be due to the positive contributions of the conservation structures and the positive role of prohibited free grazing in the treated site. The support of different conservation measures such as soil bunds and terraces, introducing new species as biological support to the physical structures, as well as prohibition of free grazing is expected to significantly increase species richness in the treated site. Plant species richness is significantly affected by resource availability such as nutrients, water, temperature, light and the extent of disturbances (Pausas and Austin, 2001). Conservation structures in the treated site improved the soil fertility level (Terefe et al., 2020) and moisture contents of the soils which are basic for plants growth. Furthermore, the prohibited free grazing in the treated site has a critical role in reducing disturbance. Thus, integrated land management significantly improved plant species richness in the study area. This finding is in line with other researchers at different parts of Ethiopia. For example, Mekuria et al. (2009), Mekuria & Veldkamp (2012) and Hishe et al. (2017a) reported that conservation practices increased soil moisture availability and conditioned natural regeneration of plant species and enhanced vegetation regrowth. In addition, in the current study, Tree Lucerne and Phalaris were introduced in the treated site giving additional species compared to the untreated one to elevate species richness in the treated site.

Prohibiting free grazing was one of the integrated land management intervention measures in the treated site while free grazing mainly by cattle and sheep was a common practice in the untreated site. Livestock suppress plant species proliferation through grazing and browsing as well as damaging trees and shrubs by trampling and repeated physical contact. This was evidenced by the higher number of shrub and two indigenous tree species recorded in the treated site. However, shrub and tree species were expected to occur more frequently in the treated site, their lower number in contrast to the expected outcome could be due to severe exhaustion of the soil seed bank and high degradation of genetic materials prior to the conservation measures; so that only very limited plants above herbaceous ones regenerated after the conservation measures.

Furthermore, the age of the conservation measures could have contributed to the lower number of tree and shrub species. Mekuria & Veldkamp (2012) reported that plant species proliferation increases with age. Thus, in the current study, more plat species specially tree and shrub species would be enhanced as the age of the conservation structures increases. Nevertheless, the regenerated shrubs and these few tree species could play critical role in harboring birds for nesting which could help dispersal of tree seeds from elsewhere and improve the rehabilitation of plant genetic richness and diversity in the watershed.

Herbaceous plants were the dominant species in both sites; which could be due to low or absence of shading effects due to restricted tree plants in the watershed. The current finding is in agreement with other findings elsewhere. For example, Mekuria & Veldkamp (2012) reported higher plant species richness and diversity with large number of herbaceous and smaller number of shrubs at exclosure landscape than the adjacent communal grazing lands after restricting human and livestock interferences. Damtie (2017) also found improved forest coverage, bushes and shrubs in conserved landscapes than the un-conserved one in Debre Mewi Watershed, northwest Ethiopia. Further, Descheemaeker et al. (2006), Nyssen et al. (2008), and Hishe et al. (2017a) reported vegetation proliferation with an area exclosure in Tigray region, Ethiopia.

The influence of landscape position in the treated site could be due to the effectiveness of the integrated land management measures compared to the lower landscape position. The physical and biological structures were well installed in the upper part compared to the lower part; which could have relatively better conditioned the plant growth and survival. The finding is in line with Mekuria & Veldkamp (2012) who reported a higher species richness and diversity at the upper landscapes compared to the foot landscapes.

The higher plant species in crop land compared to the grazing land in the untreated site could be due to introduction of weeds with seeds in crop fields while the grazing pressure on the grazing land could have suppressed plant species. Plant species richness was not statistically affected by aspect and conservation types which could be due to less environmental gradient as a result of less elevation differences. The effect of environment is highly scale-dependent to create high niche diversity and thus significantly affect species richness (Pausas and Austin, 2001). The similarities in the main function of the physical structures and the low shading effect of Tree Lucerne, in the current condition, could be the reason for insignificant effects of the conservation types on species richness.

4.4 Effects of integrated land management on plant biomass production, biomass export and carbon stock

4.4.1 Effects of integrated land management and landscape positions on plant biomass production and biomass export

Integrated land management interventions significantly ($p \leq 0.01$) increased plant biomass production in the main season and retained higher plant biomass in the dry season compared to the conventional practice (Table 15). Exported plant biomass was significantly higher in the untreated site. In the treated site, a total of 8.89±0.84 and 5.3±1.01Mg ha^{-1} plant biomasses were recorded while the total plant biomasses recorded in the untreated site were 5.91±0.44 and 0.32±0.05 Mg ha^{-1} in the main cropping season and the dry months, respectively. In addition, the lower landscape position in the treated site revealed significantly ($p \leq 0.001$) higher plant biomass production in the main season and plant biomass retention in the dry season which was driven from Tree Lucerne as evident by the comparison of the land-use types (Table 16).

However, both plant biomass production in the main season and biomass retention in the dry season were not affected by landscape position in the untreated site.

Table 15. Effects of integrated land management and landscape positions on plant biomass production in the main season and biomass retention in the dry season

	N	Plant biomass (Mg ha^{-1})		Exported plant biomass (Mg ha^{-1})
		Main season	Dry season	
Site (S)				
Treated	50	8.89^{a}	5.30^{a}	3.62^{b}
Untreated	40	5.91^{b}	0.32^{b}	5.59^{a}
Landscape position (Lp)				
Treated Upper	20	5.77^{b}	2.21^{b}	3.56^{b}
Lower	30	10.97^{a}	7.36^{a}	3.65^{b}
Untreated Upper	20	5.38^{b}	0.33^{b}	5.05^{ab}
Lower	20	6.44^{b}	0.31^{b}	6.12^{a}
SE		0.525	0.617	0.325
p-S		**	***	**
p-Lp		***	***	*

Exported plant biomass was significantly higher ($p \leq 0.05$) in the untreated site both in the upper and lower landscape positions, compared to the treated site. About 94.59% of the biomass was exported from the untreated site through harvesting and transporting to homesteads and by free grazing. Free grazing removed nearly all crop residues and above ground herbaceous materials left from harvesting in the untreated site (Fig. 16). Whereas, the amount of plant biomass exported from the treated site was much lower (40.72%) compared to the untreated one; mostly done through crop harvesting and hay.

Figure 16. Plant biomass retention status of the sites following main season crop harvest. **Left**: treated site showing the presence of ample crop residues and other organic sources at the landscape; and **right:** untreated site showing severe plant biomass export from the landscape.

There was a strong positive correlation between the main season plant biomass production and the moisture contents of the soils both in the upper 0-20 cm and the lower 20-40 cm depths in the treated site (Table 16). Thus, the higher plant biomass recorded in the treated site could be attributed by the increased soil moisture, as well as due to the introduced Tree Lucerne plants and prohibition of free grazing.

Table 16. Correlation between plant biomass production, carbon stock and soil moisture conditions

	PB	MSCS	SM (20cm)	SM (40cm)
Plant biomass	1			
Main season C stock	0.999**	1		
C sequestered	0.851**	0.832**		
Soil moisture (20cm)	0.707**	0.694**	1	
Soil moisture (40cm)	0.694**	0.641**	0.932**	1

** Correlation is significant at the 0.01 level (2-tailed); PB = Plant biomass; MSCS = Main season carbon stock; SM (20 cm) = soil moisture at 20 cm depth; SM (40 cm) = soil moisture at 40 cm dept.

Availability of soil moisture is important to improve biodiversity and increase elasticity of plant growth; which further enhances the biomass production of plants (Nyssen et al. 2008; Wubet et al. 2013; Hishe et al. 2017b). Soil moisture protects plants from forced maturity and allows them to accumulate more biomass with in the available resources and climatic conditions.

Furthermore, prohibition of free grazing in the treated site could have contributed a lot to retain sizable amount of plant biomass in the landscape; while plant biomass export was comparatively higher in the untreated site, where free grazing is a common practice. This finding is in line with Tadesse and Penden (2002) who reported that grazing pressure decreases biomass production. Girmay et al. (2008) also reported as uncontrolled free grazing destroys vegetation cover, reduces up to 23% top soil carbon stock and exposes the soil for erosion in Ethiopia.

Other explanation regarding the higher plant biomass retained in the treated site could be the problem of weed infestation. Weeds become more common on crop lands in the treated site. This discourages farmers to harvest the whole biomass of the plot at the soil surface; they rather harvest the crop selectively high above the soil surface, leaving behind the weeds and considerable amount of the crop straw at the bottom part. The overall effect is that more plant biomass retained in the treated site during the dry season.

4.4.2 Effects of land-use types on plant biomass production and biomass export

The effect of land-use on plant biomass production, biomass retention and exported plant biomass was significant ($p \leq 0.001$) in the treated site while land-use significantly ($p \leq 0.001$) affected the main season biomass production and exported plant biomass in the untreated site (Table 17).

Table 17. Effects of land-use types on plant biomass production, biomass retention and exported plant biomass

	N	Plant biomass (Mg ha^{-1}) Main season	Plant biomass (Mg ha^{-1}) Dry season	Exported plant biomass (Mg ha^{-1})
Land-use types				
Treated Crop	20	8.09^{b}	1.95^{b}	6.14^{ab}
Grazing	20	4.49^{c}	1.69^{b}	2.80^{c}
Tree Lucerne	10	19.31^{a}	19.23^{a}	0.20^{d}
Untreated Crop	20	6.92^{b}	0.41^{c}	6.51^{a}
Grazing	20	4.90^{c}	0.24^{c}	4.66^{b}
SE		0.525	0.617	0.325
p-value		***	***	***

Means within columns under each topic followed by different letter(s) are significantly different from each other at $p \leq 0.05$; *** = significant at $p \leq 0.001$; ns = none significant.

Tree Lucerne plot revealed the highest plant biomass production (19.31±0.31 Mg ha^{-1}) and highest biomass retention (19.23±0.34 Mg ha^{-1}) compared to other land-uses in the treated and untreated sites (Table 17; Fig. 17). There was no significant difference between the treated and untreated sites for biomass production by crop and grazing lands in the main season; however, plant biomass retention in the dry season by these two land-use types were significantly different with higher mean values of both land-uses in the treated site compared to the conventional one. In addition, plant biomass export from the grazing land in the untreated site was significantly higher compared to the same land-use type in the treated site.

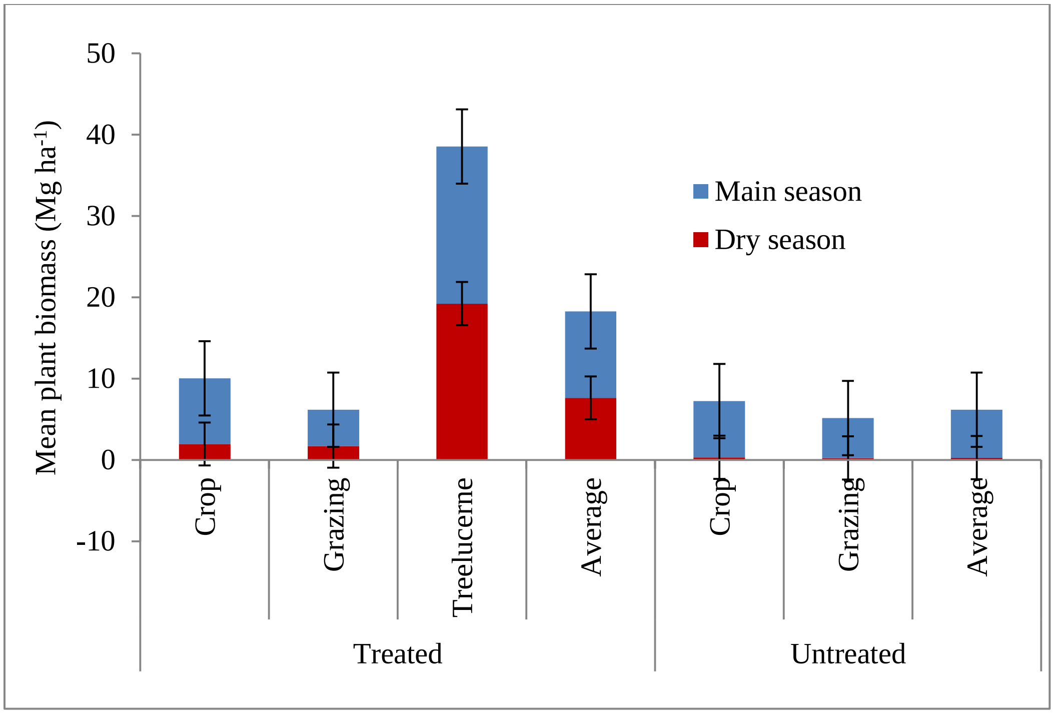

Figure 17. Mean plant biomass estimation by sites & land-use types, both in the main and dry seasons in Geda watershed. Error bars represent standard errors of the mean

Tree Lucerne is a perennial plant that adapts well in cool climate and slopped landscapes (vulnerable to soil erosion), provides protein rich fodder for livestock (Rajan et al. 2019) and enhances soil fertility and livestock productivity (Mekonnen et al. 2017). Thus, the plant is among the best elements of the integrated land management measure, both as a structural support and biomass production (Asmare and Gure 2019); however, the community seems not adopting the plant.

Farmers in the treated site are expanding eucalyptus tree in between the Tree Lucerne plots and on grazing lands more than in the untreated site, indicating low level of adapting the plant. From the total 27 new eucalyptus plots recorded in the study area, 20 plots (74.1%) were planted in the treated site while only 7 plots (25.9%) were planted in the untreated site (Table 18).

Table 18. The number of plots occupied by new eucalyptus plantation in the study area

Site	No. of plots planted by eucalyptus	Percent of total
Treated site	20	74.1%
Untreated site	7	25.9%
Total	27	100%

In addition, farmers were observed cutting Tree Lucerne from crop lands and exposing the plant to damage on grazing plots by selective entrance of livestock, while promoting eucalyptus plantation instead (Fig. 18).

Figure 18. Expansion of new eucalyptus plantation in the treated site substituting Tree Lucerne (upper two); and severe Tree Lucerne cutting (lower left) mismanaged and browsed Tree Lucerne (lower right) in the treated site

Tree Lucerne plantation at degraded landscapes in the study area might be an attractive component of land management option. Yet, the communities in the study area rather prefer eucalyptus. This could be due to the lower biomass production and lower timber production of Tree Lucerne compared to eucalyptus, the dominant plantation tree species in the area. In addition, its hindrance to farm operation, especially during plowing; low level of experience in the utilization of the foliage for livestock feed; and management of its shading effect on crops (personal communication with farmers) might be some of the reasons for low level of adopting Tree Lucerne in the study area.

Other deriving factors for expanding eucalyptus plantation in the treated site than the untreated one might be low crop productivity of the treated site due to: a) space competition by the conservation structures (Adimassu et al. 2017; Dabi et al. 2017); b) high weed infestation due to prohibited free grazing which could reduce weed seeds from subsequent germination; and c) rodent infestation due to hiding structures. Therefore, it is necessary to create strong awareness to the community regarding the management aspects of Tree Lucerne for its best performance and utilization (Mekonnen et al. 2017).

4.4.3 Effects of integrating land management on carbon stock through plant biomass

Integrated land management significantly ($p \leq 0.01$) improved carbon stock through the plant biomass compared with the conventional one (Table 19). The treated site retained 58.2% of the produced carbon stock through plant biomass while the untreated site retained 4.75% of the produced carbon stock.

Table 19. Effects of integrated land management, landscape position and land-use types on biomass carbon stock

		Mg ha^{-1}			
	N	MS^1 Carbon stock (1)	DS^2 Carbon Stock (2)	Exported carbon (1-2)	CO$_2$ Equiv.^{3} (DS × 3.67)
Site (S)					
Treated	50	4.33^a	2.52^a	1.82^b	9.24^a
Untreated	40	2.95^b	0.14^b	2.81^a	0.51^b
Landscape position (Lp)					
Treated Upper	20	2.86^b	1.09^b	1.77^b	3.98^b
Lower	30	5.32^a	3.47^a	1.84^b	12.75^a
Untreated Upper	20	2.69^b	0.12^b	2.57^{ab}	0.45^c
Lower	20	3.22^b	0.16^b	3.06^a	0.58^c
SE		0.248	0.289	0.161	1.061
p-S		**	***	**	***
p-Lp		***	***	*	***

Means within columns under each topic followed by different letter(s) are significantly different from each other at $p \leq 0.05$; * = significant at $p \leq 0.05$; ** = significant at $p \leq 0.01$;*** = significant at $p \leq 0.001$.

The higher mean value in the treated site was due to higher biomass production in the main season and higher biomass retention in the dry season. As a result, lower carbon export and higher CO$_2$ equivalent was observed in the treated site than the untreated one; because, higher plant biomass production consequently captures more carbon dioxide from the atmosphere (Tesfaye et al. 2019). On the other hand, significantly ($p \leq 0.01$) higher mean values were observed for exported carbon in the untreated site at both crop and grazing lands (Table 20).

Moreover, significantly higher carbon stocks and consequently higher CO_2 equivalent was observed in the lower landscape position in the treated site. This could be due to the presence of Tree Lucerne plantation in this part of the landscape; which showed the highest mean carbon stock than the mean values in crop and grazing lands (Table 20).

Table 20. Effects of land-use types on plant biomass carbon stock

		Mg ha^{-1}			
	N	MS^1 Carbon stock (1)	DS^2 Carbon Stock (2)	Exported carbon (1-2)	CO_2 Equiv.^{3} (DS × 3.67)
Land-use types					
Treated Crop	20	4.02^b	0.95^b	3.07^{ab}	3.48^b
Grazing	20	2.24^c	0.84^b	1.40^c	3.10^b
Tree Lucerne	10	9.15^a	9.01^a	0.14^d	33.05^a
Untreated Crop	20	3.46^b	0.16^c	3.30^a	0.58^c
Grazing	20	2.45^c	0.12^c	2.33^a	0.44^c
SE		0.248	0.289	0.161	1.061
p-value		***	***	***	***

Means within columns under each topic followed by different letter(s) are significantly different from each other at $p \leq 0.05$; *** = significant at $p \leq 0.001$.
$^{1-3}$MS = main cropping season; DS= dry season; Equiv. = Equivalent.

Next to Tree Lucerne, significantly higher carbon stock in the main cropping season was observed on crop land than the grazing land in both sites. However, there was no significant difference in the retained carbon stocks between crop land and grazing land in both sites. This could be due to fertilizer inputs for crop production and exporting higher carbon through the crop biomass.

This finding agrees with the findings of other scientists. For example, Mekuria et al. (2011) reported 83 to 87% above ground C stock following conversion of degraded grazing lands to exclosure. Further, they found a positive correlation between aboveground C stocks and moisture contents. Muluken et al. (2015), and Asmare and Gure (2019) noted higher plant biomass from the exclosure than the adjacent open grazing areas.

4.4.4 Effects of integrated land management on soil carbon stock

Integrated land management measure had significantly ($p \leq 0.001$) improved the soil carbon stock in Geda watershed (Table 21). The soils in the treated site exhibited significantly higher mean carbon stock of 24.40±0.675 Mg ha^{-1} than the mean value of 16.06±0.567 Mg ha^{-1} in the untreated site. The soil carbon stock in the treated site was higher by 8.34±0.675 Mg ha^{-1} (20.61%) over the untreated one.

Landscape position significantly affected the lower 15–30 cm depth carbon stock in the treated site with the upper landscape having higher mean value; but landscape didn’t significant influence the soil carbon in the untreated site. Further, the soil carbon stock was affected by the land-use type in the treated site but not in the conventional one. Tree Lucerne plot revealed significantly higher mean value in the upper 0–15 cm depth while crop land showed significantly higher mean value in the 15–30 cm soil depth (Table 21).

Table 21. Effects of integrated land management and landscape positions on soil carbon stock

	N	Surface and sub-surface soil carbon stocks (Mg ha^{-1})			
		0–15 cm	15–30 cm	Total (0–30 cm)	CO_2 Equiv.
Site (S)					
Treated	50	14.45^{a}	9.95^{a}	24.40^{a}	98.79^{a}
Untreated	40	8.70^{b}	7.36^{b}	16.06^{b}	59.43^{b}
Landscape position (Lp)					
Treated Upper	20	13.79^{a}	12.16^{a}	25.95^{a}	99.19^{a}
Lower	30	14.90^{a}	8.48^{b}	23.38^{b}	98.52^{a}
Untreated Upper	20	8.66^{b}	7.63^{b}	16.29^{c}	60.25^{b}
Lower	20	8.73^{b}	7.09^{b}	15.82^{c}	58.62^{b}
Land-use types (Lu)					
Treated Crop	20	14.65^{b}	12.78^{a}	27.43^{a}	100.67^{a}
Grazing	20	13.43^{b}	9.76^{b}	23.19^{b}	85.12^{b}
Tree Lucerne	10	16.10^{a}	4.66^{d}	20.76^{b}	76.18^{b}
Untreated Crop	20	8.34^{c}	7.62^{c}	15.97^{c}	58.59^{c}
Grazing	20	9.05^{c}	7.10^{c}	16.15^{c}	59.23^{c}
SE		0.380	0.363	0.629	2.307
p-S		***	***	***	***
p-Lp		***	***	***	***
p-Lu		***	***	***	***

Means within columns under each topic followed by different letter(s) are significantly different from each other at $P \leq 0.05$; *** = significant at $P \leq 0.001$; Equiv. = Equivalent.

Soil carbon stock increased with depth in crop land while it decreased in Tree Lucerne plot. This could be due to the decomposition of organic inputs on the surface soil which mixed down through pulverization of the soil by tillage in the crop land while it stays on the surface in the Tree Lucerne plots. Further, the lowest carbon stock observed in the lower 15-30 cm depth of the Tree Lucerne plot could be due to severe degradation of the plot before the intervention. Then, only the surface soil might have accumulated higher carbon stock due to the rapid accumulation and decomposition of the Tree Lucerne litters as explained by Muluken et al. (2015). Prohibition of free grazing could have contributed to the higher soil carbon stock in the treated site. According to Daniel (2015), plant biomass is the dominant source of soil carbon stock. The accumulated plant biomass in the study area could have been further decomposed and contributed to enrich the soil organic carbon as reported in the previous study (Terefe et al., 2020). This finding is in line with Ademe et al. (2017) who found higher organic matter accumulation at the treated sub-watershed than the untreated one. Further, Mekuria et al. (2011) reported an increase of 41 to 60% soil C stock on the exclosure than the communal grazing land.

4.4.5 Effects of integrated land management measures on total carbon stock

Integrated land management intervention significantly ($p \leq 0.001$) improved the total carbon stock compared to the conventional one (Table 22). Generally, the treated site exhibited significantly higher landscape carbon stock through the plant biomass and the soil compared to the untreated site. Unlikely, in the treated site, although considerable amount of carbon was captured by plant biomass in the main season, extremely lower carbon stock was observed from plant biomass (Fig. 19). Landscape positions and land-use types significantly influenced the total carbon stock while these didn’t affect in the untreated site.

Table 22. Effects of integrated land management, landscape positions and land-use types on total landscape carbon stocks

	N	Total landscape carbon stocks (Mg ha^{-1})		
		Plant biomass	Soil biomass	Total carbon stock
Site (S)				
Treated	50	2.52^a	24.40^a	26.92^a
Untreated	40	0.14^b	16.06^b	16.20^b
Landscape position (Lp)				
Treated Upper	20	1.09^b	25.94^a	27.03^a
Lower	30	3.47^a	23.37^b	26.84^a
Untreated Upper	20	0.12^b	16.29^c	16.41^b
Lower	20	0.16^b	15.82^c	15.98^b
Land-use (Lu)				
Treated Crop	20	0.95^b	27.43^a	28.38^a
Grazing	20	0.84^b	23.19^b	24.03^b
Tree Lucerne	10	9.01^a	20.75^b	29.76^a
Untreated Crop	20	0.16^c	15.97^c	16.13^c
Grazing	20	0.12^c	16.15^c	16.27^c
SE		0.289	0.629	0.672
p-S		***	***	***
p-Lp		***	***	***
p-Lu		***	***	***

Means within columns under each topic followed by different letter(s) are significantly different from each other at $p \leq 0.05$; *** = significant at $p \leq 0.001$.

The upper landscape position in the treated site showed statistically higher soil carbon stock while the lower landscape showed significantly higher carbon stock through the plant biomass. This could be due to fertilizer application to increase crop yield in the upper landscape and the Tree Lucerne plantation in the lower landscape. Tree Lucerne plantation demonstrated the higher carbon stock by the plant biomass.

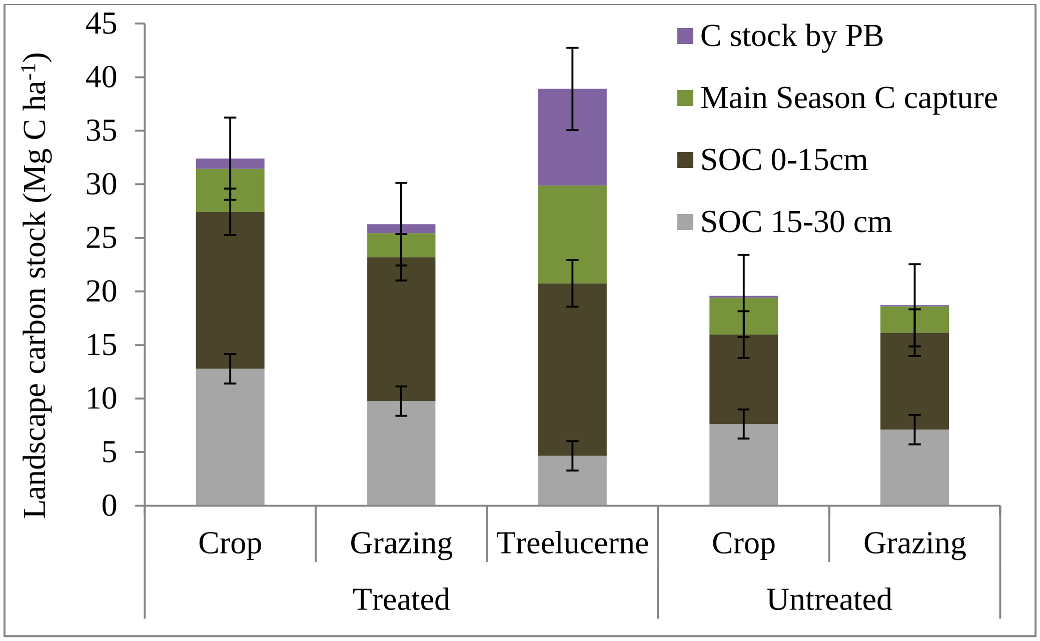

Figure 19. Landscape carbon stock in the study area: C = carbon, PB = plant biomass; SOC= soil organic carbon; C stock by PB = the dry season carbon stock by plant biomass; Main Season C capture was calculated from the main season plant biomass production, part of which later exported from the treated site while almost all of which was exported from the untreated site. Error bars represent standard errors of the mean.

The contribution of integrated land management interventions on total landscape carbon stock was appreciable. Due to the introduction of the integrated land management measures, an average of 10.72±0.84 Mg C ha^{-1} was stored in the treated site taking the conventional practice as a baseline (Fig. 18). The higher carbon stock by plant biomass and the soil in the treated site is attributed by the higher plant biomass production, which further decomposed and enriches the soil organic carbon. It can also be explained by the conservation structures through reduced soil erosion and increased plant inputs. In the untreated site, carbon stock from plant biomass was extremely low; this explains the higher biomass export from the system through free grazing and transporting the produced biomass to homesteads. This study illustrated that integrated land management interventions increased landscape carbon stocks under all land-use types when compared to the conventional practice (Fig. 20).

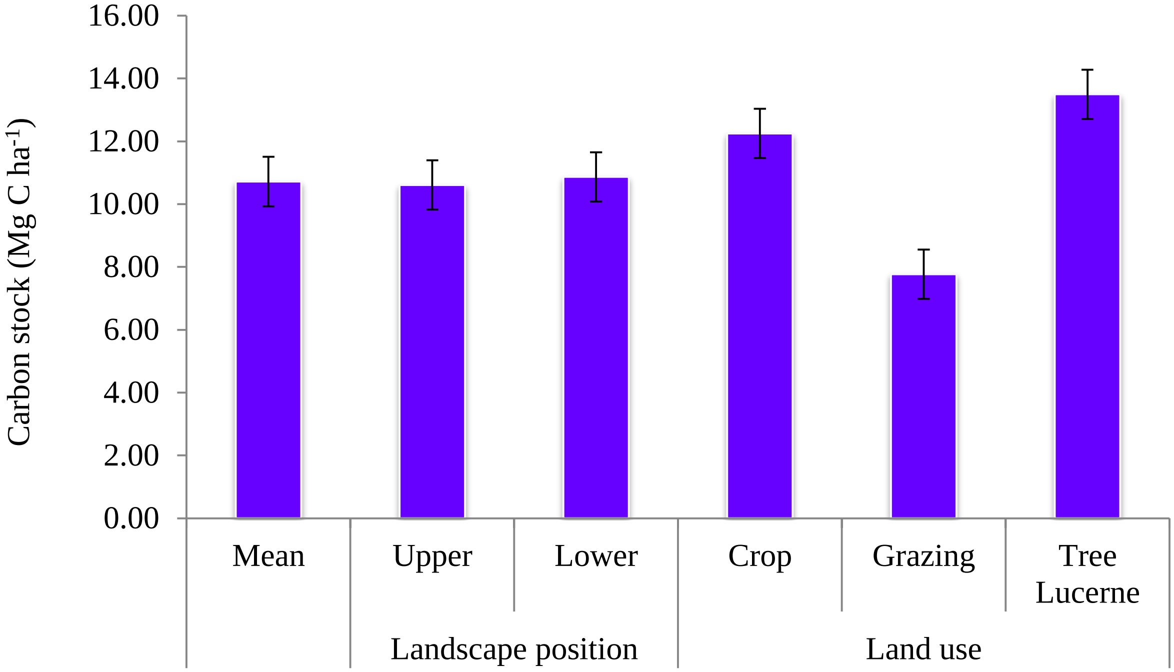

Figure 20. Integrated land management induced carbon stock calculated as a difference between carbon stock in the treated and untreated sites. Carbon stock by Tree Lucerne was compared with the grazing land in the untreated site. Error bars represent standard errors of the mean

Our finding agrees with the works of other scholars (E.g. Mekuria et al. 2011; Muluken et al. 2015; Manaye et al. 2019; Rajan et al. 2019). Mekuria et al. (2011) found higher soil carbon stock in the exclosure landscape that has better vegetation stock than the open grazing land; and soil carbon stock contributed the highest percentage (83−90%) of ecosystem carbon stock compared with aboveground carbon stock in the exclosure. Manaye et al. (2019) also reported significantly higher soil organic carbon stocks in the exclosure associated with higher plant biomass and species diversity than in the adjacent open grazing land; further, they reported that the surface soil (0-15 cm depth) of the exclosure contributed about 57% of the total carbon stock compared to 55% in the open grazing land. In addition, Rajan et al. (2019) reported that Tree Lucerne sequestered C at the rate of about 6 tons of CO_2 equivalent $ha^{-1}year^{-1}$ half which as soil organic carbon. Since Tree Lucerne is a nitrogen fixing plant, it can be used in combination with crop production and grass land management in contrast to the highly dominant eucalyptus tree. Thus, it needs careful selection of plots for Tree Lucerne and eucalyptus plantation looking the long term environmental impacts when deciding tree plantation in crop-livestock mixed system. Nevertheless, substituting Tree Lucerne by eucalyptus plantation might bring even higher biomass production and consequently higher carbon sequestration. This practice would change the land-use from crop production to plantation forestry which is in line with the land capability classification of these highly degraded landscapes. This could be an indirect positive influence of land management interventions towards restoring degraded landscapes. Still, promoting eucalyptus plantation might also negatively affect fertile crop lands; therefore, plot allocation for eucalyptus and Tree Lucerne should be carried out carefully in order to maximize the landscape productivity. Researchers and extension workers also need to consider farmers' preferences in selecting the type of tree they want to grow at degraded plots; and help farmers identify proper niches for the plants as per the concept of land capability classification.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This research provides evidences on the effects of integrated land management interventions introduced in Geda watershed. Since the farming practice in the study area is a mixed crop-livestock system, the land management intervention combined different technologies compatible to crop production and livestock husbandry. It introduced physical structures such as soil and or stone bunds, water collecting trenches, percolation pits, check dams, planting Tree Lucerne and Phalaris as a biological support to the physical structures, plantation of Tree Lucerne at highly degraded section of the landscape and prohibition of free grazing. The physical structures prevented soil erosion and runoff which otherwise could have removed the top fertile layer of the soil and diminished biomass productivity. Furthermore, the physical structures retained runoff and increased infiltration of rainfalls that further improved the soil moisture and the water flow. Prohibited free grazing reduced disturbances on plant species and thus improved floristic composition and reduced biomass export; and further increased the carbon stock of the landscape. Thus, the integrated land management intervention significantly improved the soil quality and productivity, the soil moisture, water discharge, species richness, plant biomass production and carbon accumulation in Geda watershed. The new knowledge identified through this research has been communicated to the scientific community through publications in peer reviewed journals; and the evidences generated would contribute to policy reforms in land management. Past conservation measures were ineffective due to simplistic rule of thumb, monolithic approach and lack of integrating technologies which intern showed low success stories. Whereas, the current rehabilitation approach which combined physical, biological, and management of livestock grazing showed appreciable improvements in ecosystem service indicators; and thus, would be one of the best conservation measures to curb land degradation, upscale to wider degraded areas to improve ecosystem services and benefit more farmers.

5.2 Recommendations

Different land management technologies may provide positive but very distinctive levels of effects when implemented in an integrated and well-connected manner than in a disaggregated and monolithic manner. This research proved that those physical structures combined and integrated with biological measures and management of the livestock grazing result in a more positive and highly productive effect than those without conservation measures and under free grazing practice. Hence, the following lessons and measures need to be considered when integrated land management technologies are implemented.

- It would be worthy to compile and make a package of the practices observed in the study area to scale the technologies and approaches to wider watersheds/ areas and benefit more farming communities;
- Prohibited free grazing was an important component of land management measure which reduced species disturbances, biomass export and protected the physical and biological structures from damage; but there should be alternative adequate feed availability for controlled feeding and sustain livestock production in the farming system;
- Alternative business options such as apiculture, fruit production, fattening etc. need to be given due attention to supplement the forgone benefits through free grazing by reducing livestock of individual farmer as a result of prohibited free grazing and to utilize resources installed for the conservation measures;

- As time goes, soil/stone bunds and water collecting ditches are filled by sediments which might affect the capacity of reducing runoff, soil erosion, trapping and infiltrating run offs. Thus, regular monitoring and maintenance of the physical structures should be part of the integrated land management intervention measure;
- The acceptance of Tree Lucerne by the local community is abating and farmers want to replace it by eucalyptus; thus, the effect of eucalyptus tree on the landscape carbon stock and livelihood of the farmers against the introduced land management technologies would be one of the future research interest;
- Long-term based studies should be initiated to generate evidences about the temporal effects of the land management interventions on the ecology and the community livelihood.

Limitation of the study

The data collection was done in one year (main and dry seasons); thus, the study didn't capture temporal changes in the soil properties, soil moisture content, water discharge, species proliferation and carbon stocks. The study considered only the integrated land management technologies for all the comparisons; plant biomass, carbon stock and soil properties didn't consider the eucalyptus plantation in the study area.

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Appendices

Appendix 1: List of plant species recorded in Geda Watershed

No.	Scientific name	Family	Growth Habit	Frequency			
				Treated site		Untreated site	
				Upper	Lower	Upper	Lower
1	*Ajuga integrifolia*	Lamiaceae	Herb	*2*	*1*	-	*1*
2	*Albuca abyssinica*	Asparagaceae	Herb	-	*2*	*2*	*2*
3	*Alchemilla pedata*	Rosaceae	Herb	*12*	*8*	*6*	*8*
4	*Aloe debrana*	Asphodelaceae	Herb	-	-	-	*2*
5	*Anagallis arvensis*	Primulaceae	Herb	*10*	*7*	*6*	*12*
6	*Andropogon abyssinicus*	Fabaceae	Herb	*17*	*19*	*13*	*17*
7	*Anthemis tigreensis*	Asteraceae	Herb	*1*	-	-	*2*
8	*Argyranthemum frutescens*	Asteraceae	Herb	*3*	*2*	*1*	*1*
9	*Argyrolobium ramosissimum*	Fabaceae	Herb	*1*	*1*	*1*	*1*
10	*Artemisia rehan*	Asteraceae	Herb	*5*	*6*	-	-
11	*Avena sativa*	Fabaceae	Herb	*4*	*6*	*8*	*7*
12	*Bidens macroptera*	Asteraceae	Herb	*18*	*16*	*11*	*12*
13	*Bromus catharticus*	Fabaceae	Herb	*8*	*10*	*3*	*3*
14	*Bromus madritensis*	Fabaceae	Herb	*9*	*9*	*7*	*5*
15	*Buddleja davidii*	Scrophulariaceae	Shrub	-	*2*	-	-
16	*Buddleja polystachya*	Scrophulariaceae	Tree	-	*1*	-	-
17	*Callitriche spp*	Callitrichaceae	Herb	*1*	-	-	-
18	*Campanula edulis*	Campanulaceae	Herb	-	*1*	*1*	-
19	*Capsella bursa pastoris*	Brassicaceae	Herb	*3*	*4*	*1*	*1*
20	*Carduus pycnocephalus*	Asteraceae	Shrub	*1*	-	*1*	-
21	*Carduus schimperi*	Asteraceae	Shrub	*10*	*6*	*2*	*7*
22	*Carex brunnea*	Cyperaceae	Herb	-	-	-	*1*
23	*Carex divisa*	Fabaceae	Herb	*2*	-	*4*	-
24	*Cerastium vulgatum*	Caryophyllaceae	Herb	*6*	-	*11*	*1*
25	*Cetaria verticillata*	Poaceae	Herb	*1*	*3*	*1*	*6*
26	*Chamaecytisus proliferus*	Fabaceae	Shrub	*13*	*9*	-	-
27	*Cichorium intybus*	Asteraceae	Herb	*3*	-	-	-
28	*Cirsium vulgare*	Asteraceae	Herb	*1*	*1*	-	-
29	*Commelina benghalensis*	Commelinaceae	Herb	*15*	*10*	*15*	*12*
30	*Commelina imberbis*	Commelinaceae	Herb	*6*	*2*	*5*	*2*

No.	Scientific name	Family	Growth Habit	Frequency			
				Treated site		Untreated site	
				Upper	Lower	Upper	Lower
31	*Convolvulus cneorum*	Convolvulaceae	Herb	-	*1*	-	-
32	*Conyza abyssinica*	Asteraceae	Herb	*1*	-	-	-
33	*Conyza stricta*	Asteraceae	Herb	*1*	-	-	-
34	*Conyza subscaposa*	Asteraceae	Shrub	*1*	-	-	-
35	*Conyza sumatrensis*	Asteraceae	Herb	*3*	-	-	-
36	*Cotula abyssinica*	Asteraceae	Herb	*6*	*12*	*11*	*11*
37	*Crassula alata*	Crassulaceae	Herb	*1*	*4*	-	*3*
38	*Craterostigma pumilum*	Scrophulariaceae	Herb	*1*	-	-	*1*
39	*Crepis acuminata*	Asteraceae	Herb	*2*	-	*1*	-
40	*Crepis capillaris*	Asteraceae	Herb	*1*	-	-	-
41	*Crepis foetida*	Asteraceae	Herb	*4*	-	*6*	-
42	*Crepis rueppellii*	Asteraceae	Herb	*1*	*6*	-	*5*
43	*Cymbalaria muralis*	Fabaceae	Herb	-	-	*1*	-
44	*Cynodon dactylon*	Fabaceae	Herb	*5*	*2*	*1*	*4*
45	*Cynoglossum amplifolium*	Boraginaceae	Herb	*10*	*6*	*1*	*8*
46	*Cynoglossum lanceolatum*	Boraginaceae	Herb	*1*	-	*1*	-
47	*Cyperus conglomeratus*	Cyperaceae	Herb	-	-	-	*2*
48	*Cyperus difformis*	Cyperaceae	Herb	*1*	-	-	-
49	*Cyperus longus*	Cyperaceae	Herb	*9*	*14*	*6*	*11*
50	*Cyperus rotundus*	Cyperaceae	Herb	*1*	*1*	-	-
51	*Cyperus sesquiflorus*	Cyperaceae	Herb	-	*1*	*1*	-
52	*Dactylorhiza elata*	Orchidaceae.	Herb	-	*2*	-	*2*
53	*Dichanthium annulatum*	Fabaceae	Herb	-	-	*2*	-
54	*Dichondra repens*	Convolvulaceae	Herb	*1*	-	*4*	*5*
55	*Dicliptera foetida*	Apiaceae	Herb	-	-	*1*	*1*
56	*Digitaria abyssinica*	Fabaceae	Herb	*7*	*12*	*3*	*9*
57	*Digitaria ciliaris*	Fabaceae	Herb	-	-	*1*	-
58	*Dovyalis abyssinica*	Flacourtiaceae	Tree	-	*1*	-	-
59	*Echinops Ellenbeckii*	Compositae	Shrub	*2*	*4*	-	-
60	*Eleusine indica*	Fabaceae	Herb	-	*1*	-	*1*
61	*Epilobium hirsutum*	Onagraceae	Herb	-	*1*	-	-
62	*Epilobium spp.*	Onagraceae	Herb	-	*1*	-	-
63	*Eragrostis aspera*	Fabaceae	Herb	*16*	*5*	*8*	*7*

No.	Scientific name	Family	Growth Habit	Frequency			
				Treated site		Untreated site	
				Upper	Lower	Upper	Lower
64	*Eragrostis biflora*	Fabaceae	Herb	*4*	-	*1*	-
65	*Eragrostis cilianensis*	Fabaceae	Herb	*3*	*8*	*3*	*2*
66	*Erodium moschatum*	Geraniaceae	Herb	*8*	*6*	*2*	*4*
67	*Eucalyptus globulus*	Myrtaceae	Tree	*8*	*6*	*3*	*1*
68	*Euphorbia peplus*	Euphorbiaceae	Herb	*10*	*3*	*3*	*9*
69	*Euphorbia prostrata*	Euphorbiaceae	Herb	*4*	*16*	-	*7*
70	*Euphorbia schimperiana*	Euphorbiaceae	Herb	-	-	-	*1*
71	*Galinsoga parviflora*	Compositae	Herb	*6*	*2*	*5*	*4*
72	*Galium aparine*	Rubiaceae	Herb	*11*	*4*	*11*	*5*
73	*Geranium dissectum*	Geraniaceae	Herb	*7*	-	*1*	-
74	*Geranium frigidum*	Geraniaceae	Shrub	*1*	-	-	-
75	*Gomphocarpus fruticosus*	Asclepiadaceae	Shrub	*1*	*2*	-	-
76	*Guizotia scabra*	Asteraceae	Herb	*10*	*11*	*12*	*11*
77	*Haplocarpha rueppellii*	Asteraceae	Herb	*13*	*4*	*7*	*10*
78	*Hebenstretia dentata*	Scrophulariaceae	Herb	-	*1*	-	-
79	*Helichrysum gerberifolium*	Asteraceae	Herb	*12*	*14*	*2*	*8*
80	*Helichrysum nudifolium*	Asteraceae	Herb	-	-	*1*	-
81	*Helichrysum schimperi*	Asteraceae	Shrub	*2*	-	-	-
82	*Helichrysum splendidum*	Asteraceae	Shrub	-	*4*	-	-
83	*Heracleum elgonense*	Apiaceae	Herb	*10*	*5*	*8*	*4*
84	*Holcus lanatus*	Fabaceae	Herb	*1*	*3*	-	*2*
85	*Hyparrhenia hirta*	Fabaceae	Herb	*2*	*10*	*2*	*6*
86	*Hypericum aethiopicum*	Hypericaceae	Herb	-	*1*	*1*	*2*
87	*Hypericum peplidifolium*	Hypericaceae	Herb	-	-	*1*	*1*
88	*Hypericum revolutum*	Hypericaceae	Shrub	*1*	*1*	*1*	-
89	*Impatiens rothii*	Balsaminaceae	Herb	-	*4*	-	-
90	*Indigofera arabica*	Euphorbiaceae	Herb	*1*	*3*	*1*	-
91	*Juncus bufonius*	Juncaceae	Herb	*7*	*4*	*2*	*2*
92	*Lactuca inermis*	Asteraceae	Herb	-	-	*2*	-
93	*Lactuca serriola*	Asteraceae	Herb	*4*	*2*	*2*	*4*
94	*Laggera tomentosa*	Asteraceae	Herb	*1*	-	-	-
95	*Lolium temulentum*	Fabaceae	Herb	*1*	*7*	*6*	*7*
96	*Malva verticillata*	Malvaceae	Shrub	*2*	-	*1*	-

No.	Scientific name	Family	Growth Habit	Frequency			
				Treated site		Untreated site	
				Upper	Lower	Upper	Lower
97	*Medicago polymorpha*	Fabaceae	Herb	*14*	*18*	*15*	*12*
98	*Misopates orontium*	Plantaginaceae	Herb	*1*	*4*	-	*1*
99	*Orobanche minor*	Orobanchaceae	Herb	*3*	*4*	*1*	*1*
100	*Oxalis obliquifolia*	Oxalidaceae	Herb	*6*	*1*	*5*	*8*
101	*Panicum repens*	Fabaceae	Herb	*10*	*7*	*4*	*7*
102	*Pennisetum sphacelatum*	Fabaceae	Herb	*1*	-	*3*	*2*
103	*Pennisetum thunbergii*	Fabaceae	Herb	*8*	*10*	*4*	*8*
104	*Pennisetum villosum*	Fabaceae	Herb	*1*	-	-	-
105	*Phagnalon nitidum*	Asteraceae	Herb	*3*	*9*	*2*	*2*
106	*Phalaris aquatica*	Fabaceae	Herb	*8*	*1*	-	-
107	*Phalaris arundinacea*	Fabaceae	Herb	*8*	*1*	-	-
108	*Plantago afra*	Plantaginaceae	Herb	*8*	*9*	*4*	*2*
109	*Plantago lanceolata*	Plantaginaceae	Herb	*11*	*9*	*1*	*6*
110	*Plantago major*	Plantaginaceae	Herb	*1*	-	-	-
111	*Polygonum aviculare*	Polygonaceae	Herb	*3*	*3*	-	*5*
112	*Polygonum nepalense*	Polygonaceae	Herb	*10*	*1*	*11*	*7*
113	*Romulea ramiflora*	Iridaceae	Herb	*2*	*2*	*2*	*8*
114	*Rumex abyssinicus*	Polygonaceae	Herb	*10*	*12*	*11*	*12*
115	*Rumex nepalensis*	Polygonaceae	Herb	*15*	*17*	*14*	*13*
116	*Salvia nilotica*	Lamiaceae	Herb	-	-	*2*	-
117	*Satureja condensata*	Lamiaceae	Herb	*1*	*3*	-	*1*
118	*Satureja paradoxa*	Lamiaceae	Herb	*2*	*8*	*1*	*2*
119	*Scabiosa columbaria*	Dipsacaceae	Herb	-	*1*	-	*1*
120	*Scleranthus annuus*	Asteraceae	Herb	*10*	*10*	*13*	*8*
121	*Scorpiurus muricatus*	Papilionaceae	Herb	*7*	*15*	*2*	*9*
122	*Silene burchellii*	Malvaceae	Herb	*1*	-	-	-
123	*Silene macrosolen*	Malvaceae	Herb	*1*	*5*	*2*	*1*
124	*Sisymbrium erysimoides*	Brassicaceae	Herb	*2*	*3*	*3*	*4*
125	*Snowdonia polystachya*	Fabaceae	Herb	*1*	*2*	-	*4*
126	*Solanum marginatum*	Solanaceae	Shrub	*1*	-	-	-
127	*Solanum nigrum*	Solanaceae	Shrub	-	*6*	*1*	-
128	*Soliva spp.*	Asteraceae	Herb	*9*	*6*	*8*	*11*
129	*Sonchus asper*	Asteraceae	Herb	*10*	*16*	*1*	*11*

No.	Scientific name	Family	Growth Habit	Frequency			
				Treated site		Untreated site	
				Upper	Lower	Upper	Lower
130	*Sonchus oleraceus*	Asteraceae	Herb	*7*	*8*	-	*2*
131	*Spergula arvensis*	Caryophyllaceae	Herb	*4*	*6*	*10*	*9*
132	*Sporobolus africanus*	Fabaceae	Herb	*14*	*15*	*10*	*10*
133	*Swertia abyssinica*	Gentianaceae	Herb	*1*	*3*	*1*	*2*
134	*Thymus schimperi*	Lamiaceae	Herb	*2*	*5*	*3*	*2*
135	*Thymus serpyllum*	Lamiaceae	Herb	*1*	-	*1*	-
136	*Thymus serrulatus*	Lamiaceae	Herb	*3*	*6*	*3*	*3*
137	*Tolpis virgata*	Asteraceae	Herb	*2*	-	-	-
138	*Torilis africana*	Apiaceae	Herb	*7*	*2*	-	*3*
139	*Torilis arvensis*	Apiaceae	Herb	*1*	-	-	-
140	*Trifolium campestre*	Fabaceae	Herb	*12*	*14*	*11*	*12*
141	*Trifolium lanceolatum*	Fabaceae	Herb	*1*	*9*	*1*	-
142	*Trifolium Pratense*	Fabaceae	Herb	*5*	*1*	*2*	-
143	*Trifolium repens*	Fabaceae	Herb	*5*	*2*	*2*	*7*
144	*Trifolium resupinatum*	Fabaceae	Herb	*2*	-	-	-
145	*Verbascum brevipedicellatum*	Scrophulariaceae	Herb	-	*1*	-	-
146	*Vernonia ambigua*	Fabaceae	Shrub	*1*	*3*	-	-
147	*Vernonia leopoldi*	Fabaceae	Shrub	-	*1*	-	-
148	*Veronica anagallis*	Fabaceae	Shrub	-	*1*	-	-
149	*Vicia hirsuta*	Fabaceae	Herb	*9*	*7*	*6*	*3*
150	*Vicia narbonensis*	Fabaceae	Herb	*5*	*9*	*5*	*9*

Appendix 2. Lab. analysis results of soil properties

Treatment	Landscape position	Land-use	Soil depth	Rep	BD (g/cm^3)	Sand %	Clay %	Silt %	E.C (dS/m)	pH (1:2.5)	Ex.Na	Ex.K	Av.P (ppm)	TN (%)	OC (%)	OM (%)
Treated	Upper	Crop	0-15	1	1.05	30	36	34	0.041	6.107	0.403	0.663	18.7	0.127	1.193	2.053
Treated	Upper	Crop	0-15	2	1.11	33	35	32	0.042	6.303	0.37	0.63	17.14	0.119	1.123	1.933
Treated	Upper	Crop	0-15	3	1.12	31	35	34	0.077	6.23	0.327	0.677	18.34	0.143	1.237	2.127
Treated	Upper	Crop	15-30	1	0.92	26	37	37	0.088	5.953	0.367	0.657	16.02	0.116	1.096	1.884
Treated	Upper	Crop	15-30	2	1.1	31	37	32	0.101	5.64	0.373	0.417	11.02	0.079	0.857	1.473
Treated	Upper	Crop	15-30	3	1.01	34	38	28	0.088	5.99	0.39	0.403	10.06	0.092	0.96	1.653
Treated	Upper	Grazing	0-15	1	1.19	33	35	32	0.064	6.05	0.35	0.4	9.12	0.106	0.885	1.52
Treated	Upper	Grazing	0-15	2	1.19	34	42	24	0.063	6.03	0.39	0.5	10.08	0.059	1.08	1.32
Treated	Upper	Grazing	0-15	3	1.19	32	36	32	0.055	5.94	0.35	0.335	8.52	0.091	0.77	1.86
Treated	Upper	Grazing	15-30	1	1.2	30	36	34	0.05	5.92	0.41	0.26	6.48	0.098	0.635	1.09
Treated	Upper	Grazing	15-30	2	1.15	31	44	25	0.043	5.98	0.3	0.31	8.22	0.053	0.69	1.19
Treated	Upper	Grazing	15-30	3	0.97	29	37	34	0.043	5.1	0.37	0.215	4.68	0.09	0.5	1.11
Treated	Lower	Crop	0-15	1	1.14	32	33	35	0.061	6.307	0.36	0.62	6.78	0.161	1.02	1.753
Treated	Lower	Crop	0-15	2	1.14	38	29	33	0.06	6.467	0.393	0.477	13.9	0.123	1.22	2.1
Treated	Lower	Crop	0-15	3	0.98	29	38	33	0.1	6.133	0.353	0.743	16.08	0.126	1.453	2.497
Treated	Lower	Crop	15-30	1	1.08	31	34	35	0.038	5.85	0.39	0.457	9.1	0.11	0.693	1.193
Treated	Lower	Crop	15-30	2	1.07	31	35	34	0.045	5.94	0.383	0.307	9.34	0.104	0.727	1.253
Treated	Lower	Crop	15-30	3	0.94	25	44	31	0.061	6.323	0.39	0.533	9.29	0.115	0.93	1.603
Treated	Lower	Grazing	0-15	1	0.97	35	34	31	0.062	6.28	0.48	0.96	16.2	0.165	1.59	2.73
Treated	Lower	Grazing	0-15	2	1.08	31	37	32	0.044	6.385	0.47	0.59	12	0.136	1.09	1.875
Treated	Lower	Grazing	0-15	3	1.19	36	38	26	0.025	6.49	0.48	0.46	12.9	0.106	1.51	2.6
Treated	Lower	Grazing	15-30	1	0.91	32	39	29	0.125	6.3	0.46	0.72	7.8	0.098	0.75	1.61
Treated	Lower	Grazing	15-30	2	0.99	29	39	32	0.087	6.375	0.435	0.865	5.76	0.084	0.935	1.29
Treated	Lower	Grazing	15-30	3	1.06	30	38	32	0.049	6.45	0.39	0.77	9.33	0.07	0.65	1.02
Untreated	Upper	Crop	0-15	1	1.39	58	24	18	0.037	6.38	0.39	0.46	7.14	0.052	0.95	0.95
Untreated	Upper	Crop	0-15	2	1.38	64	18	18	0.038	6.57	0.5	0.4	7.92	0.143	0.56	0.96
Untreated	Upper	Crop	0-15	3	1.35	52	20	28	0.037	6.48	0.43	0.31	7.2	0.108	0.55	0.94
Untreated	Upper	Crop	15-30	1	1.28	48	26	26	0.07	6.13	0.37	0.27	6.6	0.055	0.42	0.71
Untreated	Upper	Crop	15-30	2	1.36	53	25	22	0.043	6.4	0.61	0.24	6.72	0.036	0.4	0.74
Untreated	Upper	Crop	15-30	3	1.18	44	24	32	0.057	6.37	0.48	0.22	6.48	0.048	0.43	0.69
Untreated	Upper	Grazing	0-15	1	1.32	50	20	30	0.033	6.88	0.57	0.56	5.76	0.039	0.27	0.56
Untreated	Upper	Grazing	0-15	2	1.37	58	18	24	0.035	6.34	0.52	0.5	6.12	0.078	0.6	0.75
Untreated	Upper	Grazing	0-15	3	1.35	53	19	28	0.034	6.61	0.455	0.53	5.94	0.049	0.435	0.605
Untreated	Upper	Grazing	15-30	1	1.35	48	20	32	0.045	6.48	0.39	0.29	3.72	0.02	0.13	0.23
Untreated	Upper	Grazing	15-30	2	1.34	50	24	26	0.088	5.95	0.41	0.29	4.8	0.036	0.33	0.46

Untreated	Upper	Grazing	15-30	3	1.35	50	21	29	0.067	6.215	0.49	0.29	4.26	0.038	0.23	0.395
Untreated	Lower	Crop	0-15	1	1.27	46	22	32	0.029	7.03	0.52	0.56	6.72	0.032	0.36	0.75
Untreated	Lower	Crop	0-15	2	1	39	20	41	0.033	6.37	0.76	0.56	8.22	0.095	0.44	0.62
Untreated	Lower	Crop	0-15	3	1.29	46	26	28	0.024	6.2	0.68	0.62	6.42	0.046	0.43	0.75
Untreated	Lower	Crop	15-30	1	1.28	44	26	30	0.036	6.38	0.48	0.43	5.58	0.03	0.35	0.59
Untreated	Lower	Crop	15-30	2	1.04	34	24	42	0.036	6.08	0.48	0.41	5.46	0.034	0.39	0.88
Untreated	Lower	Crop	15-30	3	1.07	38	22	40	0.055	5.89	0.37	0.51	5.82	0.09	0.36	0.62
Untreated	Lower	Grazing	0-15	1	1.04	44	24	32	0.044	6.41	0.5	0.64	6.48	0.213	0.59	0.85
Untreated	Lower	Grazing	0-15	2	1.26	42	24	34	0.039	5.83	0.46	0.58	8.94	0.073	0.475	0.815
Untreated	Lower	Grazing	0-15	3	1.27	43	24	33	0.044	6.12	0.48	0.61	6.99	0.053	0.51	0.68
Untreated	Lower	Grazing	15-30	1	1.28	41	24	35	0.056	6.25	0.43	0.51	5.28	0.052	0.29	0.49
Untreated	Lower	Grazing	15-30	2	1.27	38	23	39	0.048	5.78	0.43	0.36	5.88	0.053	0.4	0.685
Untreated	Lower	Grazing	15-30	3	1.16	36	24	40	0.067	6.015	0.43	0.435	5.04	0.042	0.2	0.34

Appendix 3. Lab. analysis results and calculations of plant biomass and carbon stocks

Site	Lspos.	Lu	Rep	PB1 (t/ha)	PB2 (t/ha)	Exp. BM	C stock PB1 (t/ha)	C-Exported pb (t/ha)	Bd (0-15cm) g/cm^3	%C	SOC 0-0.15m(t/ha)	Bd (15-30cm) g/cm^3	%C	SOC 0.15-0.3m (t/ha)	TSOC 0-0.3m(t/ha)	SCO$_2$ equiv. (t/ha)	TCO$_2$eq.
1	11	3	1	7.088	3.381	3.707	3.502	1.853	0.94	0.95	13.395	0.95	0.92	13.110	26.505	97.273	103.324
1	11	3	2	7.023	3.131	3.892	3.441	1.938	0.98	1.05	15.435	1.08	0.79	12.798	28.233	103.615	109.131
1	11	3	3	12.774	3.518	9.256	6.355	4.627	1.03	1.18	18.231	1.02	1.01	15.453	33.684	123.620	129.961
1	11	3	4	10.490	2.424	8.066	5.184	3.995	1.18	0.69	12.213	1.21	0.57	10.346	22.559	82.790	87.155
1	11	3	5	8.286	2.717	5.569	4.095	2.784	0.98	1.15	16.905	1.08	0.96	15.552	32.457	119.117	123.930
1	11	3	6	3.509	1.090	2.419	1.753	1.210	0.97	0.83	12.077	0.91	0.85	11.603	23.679	86.902	88.895
1	11	3	7	3.419	1.491	1.928	1.696	0.964	0.96	0.85	12.240	0.98	0.76	11.172	23.412	85.922	88.608
1	11	3	8	9.300	1.958	7.342	4.614	3.669	0.99	1.12	16.632	0.82	1.07	13.161	29.793	109.340	112.807
1	11	3	9	1.684	0.679	1.005	0.822	0.501	1.17	0.68	11.934	1.01	0.65	9.848	21.782	79.938	81.114
1	11	3	10	7.500	5.701	1.799	3.601	0.895	1.19	0.64	11.424	1.24	0.63	11.718	23.142	84.931	94.862
1	11	4	1	2.570	0.996	1.574	1.280	0.787	0.92	1.25	17.250	0.94	1.12	15.792	33.042	121.264	123.075
1	11	4	2	2.389	1.182	1.206	1.194	0.602	1.24	0.51	9.486	1.28	0.31	5.952	15.438	56.657	58.827
1	11	4	3	7.720	3.360	4.360	3.860	2.180	1.01	0.91	13.787	0.95	0.82	11.685	25.472	93.480	99.646
1	11	4	4	2.980	1.341	1.639	1.490	0.820	1.18	0.85	15.045	1.08	0.7	11.340	26.385	96.833	99.294
1	11	4	5	6.110	3.055	3.055	3.055	1.528	1.18	0.77	13.629	1.04	0.81	12.636	26.265	96.393	101.998
1	11	4	6	6.756	1.180	5.576	3.378	2.788	1.15	0.77	13.283	1.19	0.69	12.317	25.599	93.948	96.114
1	11	4	7	4.762	2.494	2.268	2.333	1.086	0.98	1.07	15.729	0.97	1.02	14.841	30.570	112.192	116.768
1	11	4	8	4.960	2.232	2.728	2.480	1.364	1.18	0.79	13.983	1.12	0.75	12.600	26.583	97.560	101.655
1	11	4	9	2.631	1.114	1.517	1.306	0.759	1.24	0.52	9.672	1.48	0.42	9.324	18.996	69.715	71.726
1	11	4	10	3.525	1.234	2.291	1.763	1.146	1.19	0.75	13.388	1.18	0.67	11.859	25.247	92.655	94.919

1	12	3	1	12.000	1.200	10.800	6.000	5.400	1.09	1.04	17.004	1.24	0.88	16.368	33.372	122.475	124.677
1	12	3	2	10.300	0.515	9.785	5.150	4.893	0.98	0.88	12.936	1.17	0.57	10.004	22.940	84.188	85.133
1	12	3	3	6.651	2.672	3.978	3.301	2.027	1.25	0.68	12.750	1.15	0.69	11.903	24.668	90.532	95.205
1	12	3	4	10.672	4.032	6.640	5.332	3.320	1.09	0.98	16.023	1.06	0.85	13.515	29.538	108.404	115.787
1	12	3	5	5.500	0.825	4.675	2.750	2.338	1.22	0.75	13.725	1.08	0.74	11.988	25.713	94.367	95.881
1	12	3	6	8.200	0.362	7.839	4.100	3.919	1.07	0.98	15.729	1.04	0.92	14.352	30.081	110.397	111.061
1	12	3	7	7.230	0.656	6.574	3.615	3.287	1.17	0.95	16.673	1.06	0.89	14.151	30.824	113.122	114.326
1	12	3	8	9.700	0.485	9.215	4.850	4.608	1.16	0.97	16.878	1.04	0.92	14.352	31.230	114.614	115.504
1	12	3	9	9.800	1.600	8.200	4.900	4.100	0.96	0.94	13.536	0.93	0.8	11.160	24.696	90.634	93.570
1	12	3	10	10.600	0.490	10.110	5.300	5.055	0.96	1.2	17.280	0.9	0.96	12.960	30.240	110.981	111.880
1	12	4	1	4.750	0.713	4.038	2.375	2.019	1.06	0.59	9.381	1.19	0.36	6.426	15.807	58.012	59.319
1	12	4	2	3.563	0.641	2.922	1.778	1.461	1.18	0.56	9.912	1.03	0.43	6.644	16.556	60.759	61.921
1	12	4	3	2.963	0.296	2.667	1.482	1.333	1.06	0.59	9.381	1.19	0.36	6.426	15.807	58.012	58.555
1	12	4	4	4.584	1.769	2.815	2.284	1.407	1.04	0.89	13.884	1.08	0.86	13.932	27.816	102.085	105.303
1	12	4	5	2.851	0.912	1.939	1.418	0.970	1.03	0.83	12.824	1.18	0.66	11.682	24.506	89.935	91.579
1	12	4	6	3.653	1.094	2.559	1.827	1.279	0.92	0.89	12.207	0.95	0.754	10.745	22.959	84.260	86.268
1	12	4	7	4.577	3.975	0.602	2.280	0.301	0.96	1.17	16.848	0.73	0.56	6.132	22.871	83.937	91.200
1	12	4	8	6.850	2.813	4.038	3.425	2.019	1.16	0.94	16.356	0.72	0.5	5.400	21.707	79.665	84.826
1	12	4	9	5.380	1.028	4.353	2.690	2.176	1.25	0.92	17.250	0.89	0.4	5.340	22.640	83.089	84.974
1	12	4	10	6.250	2.421	3.829	3.125	1.915	1.2	0.85	15.300	0.69	0.41	4.244	19.585	71.877	76.319
1	12	5	1	20.425	20.677	-0.252	9.452	-0.182	0.89	1.24	16.554	0.54	0.51	4.131	20.640	75.748	111.104
1	12	5	2	19.746	19.017	0.729	9.354	0.382	0.79	1.35	15.998	0.73	0.36	3.942	19.898	73.026	105.953
1	12	5	3	17.635	18.931	0.061	8.354	0.063	0.92	1.23	16.974	0.61	0.62	5.673	22.628	83.045	113.473
1	12	5	4	19.953	17.758	-0.719	9.676	-0.077	0.91	1.23	16.790	0.73	0.39	4.271	21.086	77.386	113.177
1	12	5	5	17.933	20.569	-1.021	8.495	-0.447	0.76	1.27	14.478	0.82	0.34	4.182	18.747	68.801	101.619
1	12	5	6	19.965	19.019	-0.096	9.458	-0.007	0.78	1.29	15.093	0.57	0.61	5.216	20.311	74.541	109.278
1	12	5	7	20.413	20.057	0.440	9.670	0.247	0.9	1.25	16.875	0.72	0.38	4.104	20.831	76.450	111.032
1	12	5	8	18.845	19.814	1.544	8.927	0.765	0.87	1.23	16.052	0.55	0.64	5.280	21.275	78.079	108.034
1	12	5	9	19.345	17.409	0.224	9.164	0.143	0.86	1.25	16.125	0.83	0.39	4.856	20.969	76.956	110.063
1	12	5	10	18.885	19.042	1.091	8.946	0.551	0.86	1.24	15.996	0.83	0.42	5.229	21.193	77.778	108.588
2	21	3	1	3.800	1.946	1.854	1.900	1.881	1.35	0.42	8.505	1.18	0.43	7.611	16.116	59.146	59.215
2	21	3	2	5.580	0.038	5.542	2.790	2.576	1.08	0.62	10.044	1.05	0.58	9.135	19.179	70.387	71.174
2	21	3	3	4.886	0.429	4.457	2.443	2.248	1.16	0.57	9.918	1.18	0.54	9.558	19.476	71.477	72.194
2	21	3	4	6.920	0.391	6.529	3.460	3.356	1.32	0.5	9.900	1.28	0.45	8.640	18.540	68.042	68.423
2	21	3	5	5.810	0.208	5.602	2.905	2.760	1.37	0.26	5.343	1.34	0.23	4.623	9.966	36.575	37.108
2	21	3	6	2.030	0.291	1.740	1.015	0.995	1.18	0.43	7.611	1.25	0.37	6.938	14.549	53.393	53.467
2	21	3	7	8.350	0.041	8.309	4.175	3.916	1.38	0.45	9.315	1.36	0.42	8.568	17.883	65.631	66.580
2	21	3	8	5.860	0.518	5.343	2.930	2.813	1.37	0.26	5.343	1.34	0.23	4.623	9.966	36.575	37.005
2	21	3	9	5.770	0.234	5.536	2.885	2.846	1.36	0.48	9.792	1.34	0.45	9.045	18.837	69.132	69.274
2	21	3	10	6.230	0.078	6.152	3.115	3.007	1.4	0.45	9.450	1.48	0.39	8.658	18.108	66.456	66.854
2	21	4	1	5.230	0.523	4.707	2.615	2.354	1.15	0.54	9.315	1.08	0.49	7.938	17.253	63.319	64.278

2	21	4	2	1.550	0.155	1.395	0.775	0.698	1.13	0.55	9.323	1.12	0.53	8.904	18.227	66.891	67.176
2	21	4	3	5.260	0.125	5.135	2.630	2.567	1.05	0.58	9.135	1.32	0.36	7.128	16.263	59.685	59.915
2	21	4	4	6.870	0.394	6.477	3.435	3.238	1.07	0.58	9.309	1.02	0.57	8.721	18.030	66.170	66.892
2	21	4	5	5.430	0.322	5.109	2.715	2.554	1.35	0.4	8.100	1.18	0.43	7.611	15.711	57.659	58.249
2	21	4	6	4.496	0.110	4.386	2.248	2.193	1.32	0.38	7.524	1.31	0.35	6.878	14.402	52.854	53.055
2	21	4	7	4.580	0.016	4.564	2.290	2.282	1.47	0.31	6.836	1.34	0.23	4.623	11.459	42.053	42.083
2	21	4	8	10.030	0.602	9.429	5.015	4.714	1.02	0.86	13.158	1.36	0.55	11.220	24.378	89.467	90.571
2	21	4	9	5.900	0.118	5.782	2.950	2.891	1.28	0.51	9.792	1.04	0.48	7.488	17.280	63.418	63.634
2	21	4	10	3.030	0.091	2.939	1.515	1.470	1.26	0.29	5.481	1.27	0.25	4.763	10.244	37.594	37.760
2	22	3	1	7.870	0.079	7.791	3.935	3.896	1.38	0.44	9.108	1.39	0.36	7.506	16.614	60.973	61.118
2	22	3	2	11.200	0.426	10.774	5.600	5.387	1.27	0.36	6.858	1.28	0.35	6.720	13.578	49.831	50.613
2	22	3	3	3.020	0.091	2.929	1.510	1.465	1.38	0.29	6.003	1.36	0.24	4.896	10.899	39.999	40.166
2	22	3	4	5.700	0.285	5.415	2.850	2.708	1.4	0.35	7.371	1.42	0.32	6.816	14.187	52.066	52.589
2	22	3	5	11.370	0.569	10.802	5.685	5.401	1.07	0.56	8.988	1.28	0.45	8.640	17.628	64.695	65.738
2	22	3	6	9.800	0.784	9.016	4.900	4.508	1	0.44	6.600	0.97	0.39	5.675	12.275	45.047	46.486
2	22	3	7	6.810	0.204	6.606	3.405	3.303	1.28	0.52	9.984	1.04	0.51	7.956	17.940	65.840	66.215
2	22	3	8	11.270	0.584	10.687	5.635	5.343	1.29	0.43	8.321	0.98	0.51	7.497	15.818	58.050	59.121
2	22	3	9	7.230	0.362	6.869	3.615	3.434	1.25	0.52	9.750	1	0.63	9.450	19.200	70.464	71.127
2	22	3	10	8.870	0.544	8.327	4.435	4.163	1.28	0.45	8.640	0.97	0.68	9.894	18.534	68.020	69.017
2	22	4	1	4.670	0.3736	4.2964	2.335	2.148	1.3	0.51	9.945	1.42	0.38	8.094	18.039	66.203	66.889
2	22	4	2	3.340	0.167	3.173	1.670	1.587	1.29	0.32	6.192	1.28	0.28	5.376	11.568	42.455	42.761
2	22	4	3	3.750	0.188	3.563	1.875	1.781	1.29	0.3	5.805	1.3	0.28	5.460	11.265	41.343	41.687
2	22	4	4	7.180	0.459	6.721	3.590	3.361	1.28	0.51	9.792	1.05	0.43	6.773	16.565	60.792	61.634
2	22	4	5	2.810	0.056	2.754	1.405	1.377	1.02	0.61	9.333	1.07	0.32	5.136	14.469	53.101	53.204
2	22	4	6	2.220	0.200	2.020	1.110	1.010	1.05	0.62	9.765	1.07	0.31	4.976	14.741	54.098	54.464
2	22	4	7	4.090	0.327	3.763	2.045	1.881	1.28	0.51	9.792	1.06	0.45	7.155	16.947	62.195	62.796
2	22	4	8	1.050	0.053	0.998	0.525	0.499	1	0.63	9.450	1.1	0.34	5.610	15.060	55.270	55.367
2	22	4	9	11.460	0.115	11.345	5.730	5.673	0.98	0.92	13.524	0.96	0.92	13.248	26.772	98.253	98.464
2	22	4	10	4.997	0.400	4.597	2.499	2.299	1.12	0.56	9.408	1.04	0.31	4.836	14.244	52.275	53.009

Site: 1= treated, 2= untreated; Lspos.: 11= treated upper, 12= treated lower, 21= untreated upper, 22= untreated lower; Lu: 3=crop land, 4= grazing land, 5= Tree Lucerne; Rep: replication; PB1= plant biomass production in the main season (t ha^{-1}); PB2= plant biomass remained in the dry season (t ha^{-1}); Exp. BM = Exported plant biomass through harvesting and free grazing (t ha^{-1}); c stock PB1 = carbon stock by main season plant biomass (t ha^{-1}); C-Exported pb=carbon exported from plant biomass(t ha^{-1}); Bd=bulk density; SOC= soil organic carbon; %C= carbon percentage; TSOC= total Soil Organic carbon; CO_2 equiv. =carbon dioxide equivalent.

Appendix 4. ANOVA for soil physical properties

		BD			Sand			Clay			Silt		
Source	**DF**	**Mean Square**	**F Value**	**Pr > F**	**Mean Square**	**F Value**	**Pr > F**	**Mean Square**	**F Value**	**Pr > F**	**Mean Square**	**F Value**	**Pr > F**
T	1	0.4219	37.73	<.0001	2790.75	87.49	<.0001	2465.33	286.62	<.0001	10.08	0.37	0.5484
TS	3	0.5730	23.13	<.0001	3573.83	76.61	<.0001	2493.50	99.51	<.0001	543.17	10.83	<.0001
TLU	3	0.4388	12.94	<.0001	2802.83	28.25	<.0001	2495.33	100.09	<.0001	87.167	1.07	0.3705
TSLu	7	0.6136	10.87	<.0001	3588.33	30.62	<.0001	2537.00	44.74	<.0001	646.67	5.84	0.0001
Dp	3	0.4640	14.41	<.0001	3051.83	37.11	<.0001	2526.83	110.90	<.0001	103.17	1.29	0.2907
TSDP	7	0.6183	11.11	<.0001	3847.00	53.49	<.0001	2572.67	50.99	<.0001	637.33	5.68	0.0001
TLuDP	7	0.4969	6.46	<.0001	3077.00	14.89	<.0001	2563.67	49.27	<.0001	189.33	0.99	0.4504

Appendix 5. ANOVA for soil moisture analysis

		GV. 20 cm			Gv. 4o cm			HD2 20 cm			Water Discharge (at the bottom out let only)		
Source	DF	Mean Square	F Value	Pr > F	Mean Square	F Value	Pr > F	Mean Square	F Value	Pr > F	Mean Square	F Value	Pr > F
T	1	356.85	65.48	<.0001	250.29	24.41	<.0001	8.6402	10.79	0.0015	53.92	394.49	<.0001
TSp	3	392.82	13.29	<.0001	275.70	9.02	<.0001	9.1897	3.76	0.0142	-	-	-
TLU	3	380.02	12.64	<.0001	284.88	9.43	<.0001	9.4046	3.86	0.0125	-	-	-

Appendix 6. ANOVA for soil chemical properties

		pH			Na			TN			Av.P			K			OC		
Source	**DF**	**Mean Square**	**F Value**	**Pr > F**	**Mean Square**	**F Value**	**Pr > F**	**Mean Square**	**F Value**	**Pr > F**	**Mean Square**	**F Value**	**Pr > F**	**Mean Square**	**F Value**	**Pr > F**	**Mean Square**	**F Value**	**Pr > F**
T	1	0.441	4.7	0.0353	0.10662	19.23	<.0001	0.0232	17.62	0.0001	286.99	31.27	<.0001	0.1184	4.27	0.0444	3.7935	68.74	<.0001
T Ps	3	1.380	5.94	0.0017	0.1266	8.02	0.0002	0.0259	6.54	0.0009	291.80	10.25	<.0001	0.4359	6.67	0.0008	3.9034	23.55	<.0001
T LU	3	0.5259	1.81	0.1594	0.1224	7.62	0.0003	0.0260	6.61	0.0009	375.28	16.49	<.0001	0.1353	1.58	0.2085	3.9360	24.09	<.0001
T Dp	3	1.2430	5.14	0.0039	0.1391	9.32	<.0001	0.04	11.44	<.0001	416.36	20.86	<.0001	0.3521	4.96	0.0047	4.9419	52.14	<.0001

Appendix 7. ANOVA for plant species analysis

Source	DF	Mean Square	F Value	Pr > F
T	1	1866.08	41.61	<.0001
TPs	3	2191.11	17.25	<.0001
TLU	3	2199.91	17.36	<.0001
Cons. type	4	1976.42	10.95	<.0001
Aspect	5	2010.36	8.89	<.0001

Appendix 8. ANOVA for plant biomass, exported biomass and carbon stocks

		Plant biomass production in the main season			Retained plan biomass in the dry season			Exported plant biomass from the landscapes			C stock by plant biomass			C stock by soil		
Source	**DF**	**Mean Square**	**F Value**	**Pr > F**	**Mean Square**	**F Value**	**Pr > F**	**Mean Square**	**F Value**	**Pr > F**	**Mean Square**	**F Value**	**Pr > F**	**Mean Square**	**F Value**	**Pr > F**
T	1	198.13	8.68	0.0041	550.90	19.39	<.0001	86.27	10.00	0.0022	125.75	20.35	<.0001	1547.27	84.13	<.0001
TSPs	3	533.75	9.15	0.0001	868.65	11.41	<.0001	97.88	3.75	0.0138	194.22	11.71	<.0001	1628.86	30.38	<.0001
TLU	4	1725.61	76.38	<.0001	1976.64	844.98	<.0001	378.18	17.19	<.0001	651.95	786.87	<.0001	1892.75	31.59	<.0001

Appendix 9. Data collection sheet for plant species identification

Date: ________________________ Site ________________

Data Collector: ________________

S. No.	Plot no.	sub plot no.	Transect no.	Aspect	Geo reference			Land-use	Conservation measure	Plant Species Inventoried				Remark/Note
					Alt.	Long.	Lat.			Code	Latin name	Growth habit	Local name	
1														
2														
3														
4														
5														
6														
7														
8														
9														
10														
11														
12														
13														
14														
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16														
17														
18														
19														
20														

Appendix 10. Semi-structured interview questions employed in the irrigation sites

Greeting/Salutation

1. Name of the respondent __________; Sex _____________; Age _____________

2. Marital status of the respondent: Married/widowed/divorced/single (Underline)

3. Educational status of the respondent: Read and write/ Yes, No, formal education (______ grade)

4. Living site: treated site; untreated site (underline)

5. What is the size of irrigation land you have?

a) Before 5 years (2012) ______________ b) currently (2018) _____________

6. Please list the type of crops you grow using the irrigation practice before 5 years and now.

a) Before 5 years (2012) ______________, _________________, __________________,
________________, ____________, ____________

a) Currently (2018) ______________, _________________, __________________,
________________, ____________, ____________

7. Have you noticed an increase/decrease of the irrigation water during the dry months? (Yes, No).

Why do you think the reason for increasing/decreasing?

____
____

8. What are the advantages and disadvantages of the conservation practices to the community in the watershed?

Advantages: ____
____
____
____

Disadvantages: ____
____

Thank you so much for your kind cooperation in giving me the information.

Appendix 11. Partial views of the treated site during the main (top) and the dry seasons (bottom).

Appendix 12. Partial views of the untreated site during the main (top) and the dry seasons (bottom).

Appendix 13. Soil analysis in the laboratory

Appendix 14. Water collection ditches in Tree Lucerne plantation trapping runoff during the short rainy seasons

Appendix 15. List of Scientific Papers

This doctoral thesis is comprised of the following papers.

I. Effects of sustainable land management interventions on selected soil properties in Geda watershed, central highlands of Ethiopia

   Hailu Terefe, Mekuria Argaw, Lulseged Tamene, Kindu Mekonnen, John Recha, Dawit Solomon **(Published in the journal Ecological processes 9:14)**

II. Sustainable land management interventions lead to carbon sequestration in plant biomass and soil in a mixed crop-livestock system: the case of Geda watershed, central highlands of Ethiopia

   Hailu Terefe, Mekuria Argaw, Lulseged Tamene, Kindu Mekonnen **(Published in the journal Ecological processes 9: 34)**

III. Effects of integrated land management interventions on soil moisture content and water discharge at Geda Watershed, Central highlands of Ethiopia

   Hailu Terefe, Mekuria Argaw, Lulseged Tamene, Kindu Mekonnen (Manuscript on preparation)

IV. Effects of integrated land management interventions on plant species richness at Geda Watershed, Central highlands of Ethiopia

   Hailu Terefe, Mekuria Argaw, Lulseged Tamene, Kindu Mekonnen and Abiyou Tilahun (Manuscript ready to submit)