Combining Rainwater harvesting and Agroforestry System for enhancing Crop Yield and Soil Nutrients: A holistic Approach towards improved Small-holder Farming

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Abstract

Water scarcity affects around 75% of global croplands, causing crop failure and substantial decrease in crop yield ultimately affecting global food security. Besides, the problem of food insecurity is likely to worsen due to climate change, land degradation, increasing population pressure, and the resulting demand for food production. The issues of water scarcity, food insecurity, and land degradation are closely interlinked and require a systematic and integrated holistic approach remedy. In this research, rainwater harvesting based small scale agroforestry system along with organic soil amendment was adopted as a holistic approach applied stepwise to simultaneously address these interrelated problems.

Before moving to the holistic approach, the study initially discusses on methods of rainwater harvesting site suitability assessment and run off estimation using GIS based geospatial datasets and soil conservation service curve number on chapter three and chapter four. The study further assesses the effect of existing rainwater harvesting and agroforestry systems on soil physical, chemical and biological properties on chapter five and six. Finally, chapter seven discusses field experiment carried out based on a holistic approach via the combination of in situ rainwater harvesting (stone bunds and RWH pond), agroforestry (*Zai maiz – vulgare Hordeum – eucalyptus globulus* intercropping), and soil organic amendments (poultry litter, poultry bio char and wood ash).

The results from RWH suitability assessment revealed that from a 1001 Km^2 catchment, four rainwater harvesting suitability classes were found with majority of the catchment falling under suitable area namely: 56% (550.75 Km^2) suitable area, 8.6% (85.27 Km^2) highly suitable areas and 30.8% (303.23Km^2) moderately suitable area whereas only 4.46% of the area was classified as poorly suitable area. The GIS based run off estimation was computed using spatial datasets and soil conservation service curve number method for 10 years rainfall data. Results from 2011 – 2019 indicated significant variation in runoff among the years. In general, the run off volume increased with the years with minimum run off rate (6.76Mm^3/year) obtained in year 2010 and maximum run off rate (54.26 Mm^3/year) obtained in 2018 followed by 49.26 Mm^3 /year in 2021. Based on the estimated run off, it could be possible to harvest up to 54 million cubic meters runoff from a 1001Km^2 catchment which necessitates more adoption and expansion of RWH structures which otherwise could lead to massive soil erosion and productivity decline.

Evaluation of existing in situ RWH techniques (stone bunds, terraced lands, and exclosure areas) indicated significant positive changes in selected soil physicochemical properties. This implies that adoption of in situ RWH is instrumental for enhancing soil quality and restoring degraded landscapes. Further research on the impact of in situ rainwater harvesting on soil microbial activity and socio economic aspects can support the design of sustainable soil – water - management practices.

Quantitative assessment of existing agroforestry legume trees (native and indigenous legumes) on soil biology (Arbuscular mycorrhiza fungi -soil AMF) and soil nutrients indicated significant differences in AMF root colonization among the tree species. *Faidherbia albida*, a native tree legume exhibited the highest hyphal root colonization (HC) and mycorrhizal hyphal colonization (MHC) percentages, followed by *Vachellia abyssinica.* Furthermore, spore density of AMF varied significantly among the trees, with *Faidherbia albida* showing the highest spore density, SOM, SOC compared to the exotic species *sesbania sesban.*

The RWH based small - scale agroforestry system combined in situ RWH (stone bunds & rwh pond), soil organic amendments (poultry litter, poultry biochar and wood ash) and *Zea mays* - *Hordeum vulgare* - *Eucalyptus globulu*s intercropping all in a holistic approach. The effect was evaluated on soil parameters, yield & biomass of *Zea mays & Hordeum vulgare* in a field experiment. The treatments were poultry litter &RWH (PWAFS), poultry litter biochar & RWH (BWAFS), wood ash & RWH (AWAFS), RWH alone (WAFS), and AFS (the control). The AFS in all the treatments refers to the conducted agroforestry system.

The result indicated that BWAFS increased the pH by 19.4% followed by AWAFS and PWAFS (9%). Maximum and minimum SOM (2.26%, 1.21%) were observed under BWAFS and AFS - the control respectively. Similarly, BWAFS significantly increased Av. P by 78.1% while WAFS increased by 40% compared to the control. BWAFS had significant effect on yield &biomass of *Zea mays & Hordeum vulgare followed by PWAFS, AWFS, and WAFS.* The study concluded that the combination of RWH, agroforestry and soil organic amendments through a holistic approach could significantly increase both soil nutrients and crop yield particularly in arid and semi-arid areas where rainfall is scarce, intermittent and where soil is degraded. Upscaling of this research could enhance dryland smallholder farming in reducing crop failure and runoff.

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List of Abbreviations

AMF	Arbuscular mycorrhizal fungi
AC	Arbuscular colonization
AFS	Agroforestry system
AMC	Antecedent moisture condition
AV.P	Available phosphorus
Av.K	Available potassium
DOY	Days of the Year
EC	Electrical conductivity
EXA	Exclosure area
FAO	Food and agriculture organization
GL	Grazed lands
GLASOD	Global assessment of human induced soil degradation
GIS	Geographic information system
HC	Hyphal colonization
HSG	Hydrologic soil group
ICP	Inductively coupled plasma
IWMI	International water management institute
MHC	Mycorrhizal hyphal colonization
NDMI	Normalized difference moisture index
PL	Poultry litter
PB	Poultry litter biochar
RS	Remote sensing
RWH	Rainwater harvesting
SCS - CN	Soil conservation service curve number
SDG	Sustainable development goals
SOM	Soil organic matter
SOC	Soil organic carbon
WA	Wood ash
WOA	Weighted overlay analysis

Chapter 1. Introduction

Over 80% of croplands worldwide rely solely on rainfed agriculture. These croplands cover an area of 1.5 billion hectares and contribute to nearly two-thirds of the world's food production (Teluguntla et al., 2015). The percentage increases to 95% in developing regions like sub-Saharan Africa (Mekdaschi Studer & Liniger, 2013). Nonetheless, 76% of croplands worldwide face water scarcity (moisture stress) leaving only 24% with the ability to utilize irrigation (Rosa et al., 2020). Even in situations where irrigation is feasible, the limited economic and institutional capabilities hinder efficient use of available water resources (Rosa et al., 2020). This challenge is particularly prominent on vulnerable and impoverished populations, such as those in sub-Saharan Africa, who bear severe consequences due to both economic and institutional constraints (Dell'Angelo et al., 2018).

One of the consequences of water scarcity is massive yield loss because of longer dry spells and frequent crop failure(Oweis et al., 2012). The crop failure in those areas coupled with increasing population pressure, limited arable land and intermittent rainfall has resulted in severe food insecurity, malnutrition and extreme poverty (Agada, 2016). The high temperature raise in arid/semi-arid agroecology particularly in sub- Saharan Africa has caused a loss of vast amount of rainfall (50 -70%) to the atmosphere without reaching the crops. Most of the rain directly evaporates from the soil surface before it generates run off ; part of the water which infiltrated in to a shallow depth also evaporates or produces limited run off (Rockstr & Falkenmark, 2015). As a result ,in drylands which comprises 40% of the global landmass, the yield of crops is reduced to up to 50% of their maximum potential due to water scarcity and the resulting crop failure (Oweis et al., 2007). The same Authors stated that drylands are the main hotspots for poverty and hunger due to multitude factors including intermittent rainfall, extended dry season and recurrent drought. Ethiopia, as a sub Saharan country has also faced similar challenge. With a surface area of 1.2 million Kilometres square, it is the largest country in the horn of Africa with economy mainly dependent on agriculture (Seleshi Bekele Awulachew & Merrey, 2007). The country has high population pressure estimated to reach 129 million by the year 2025 (Abdelkdair & Schultz, 2005) . The estimated runoff volume amounts to 110 billion cubic meters, with a significant portion transported by transboundary rivers (Ketsela, 2009) . Despite the water resource potential, the country has been adversely affected by erratic rainfall and desertification particularly in dry areas of northern Ethiopia (B. A. Abebe, 2014). Land deterioration has seriously affected the productivity of agricultural lands and water availability in the soil (Seleshi Bekele Awulachew & Merrey, 2007; Ciat et al., 2014; Vancampenhout et al., 2006). It prevents the infiltration of water and causes high amount of runoff (Esser & Haile, 2002a).

Rainwater harvesting has a multiple benefits to rural smallholder farmers such as securing water and increasing crop productivity in semi-arid regions, control of soil erosion and land degradation (Enfors, 2013; Mugerwa, 2007). Some water and soil conservation measures have been implemented in the region including terracing, earth embankment, and rainwater harvesting ponds in an attempt to reverse the degraded landscape (Tadesse, Gebrelibanos, & Gebrehiwet, 2016). However, due to the complex interaction of water deficit, soil erosion, and food insecurity, it is essential to develop a system beyond the conventional monoculture farming where the various problems could be addressed in a holistic approach, which is the main theme of this PhD study. Combining rainwater harvesting and agroforestry along with organic soil amendments can improve smallholder farmers livelihood in a cost effective and sustainable manner (Otterpohl, 2016). This PhD research focuses on combining rainwater harvesting and agroforestry as a potential remedy to water deficit, soil degradation and food insecurity taking the case of eastern Tigray, northern Ethiopia. Developing such a holistic agroforestry requires among others identification of suitable rainwater harvesting sites and estimation of surface run off in order to fully utilize the water resource potential and these are presented in chapter-three and chapter-four of the thesis. Chapter-five and chapter-six discuss on assessment of existing rainwater harvesting techniques and agroforestry systems on selected soil nutrients. Chapter- seven discuses onsite implementation of the designed holistic small scale agroforestry system and evaluates its effect on essential soil nutrients, yield and biomass of crops.

1.1 Problem statement

Poor distribution and spatiotemporal variability in rainfall is a major problem facing the agricultural sector in drylands across the globe (Ziadat et al., 2012). These areas continuously suffer from recurrent droughts and extended dry spells leading to food insecurity and soil nutrient depletion (Wudil et al., 2022). Particularly, Tigray region, a semi-arid region in northern Ethiopia has been prone to a stable climate change over a long period of time (30 years) and this is deemed to increase the magnitude and the frequency of natural disasters and extreme weather events- (G. Hadgu et al., 2013). Most of the semi-arid areas in Tigray are highly overused for cultivation and grazing of livestock that resulted in erosion of the fertile top soil (Abesha, 2014). In a rain fed agriculture, good management of rain water is of utmost importance because unmanaged rainfall results in high risks of yield losses, soil erosion and or unfavourable growth conditions which eventually leads to food insecurity (Wubetu, 2016).These all problems are highly affecting the small holder farming in the region. Hence, it is necessary to swiftly shift from conventional rainfed farming towards a holistic agroforestry practises supported with RWH systems and organic soil amendment. The holistic approach can provide valuable insight towards sustainable small scale farming.

1.2 Research Questions

- How can the conventional monoculture farming be transformed in to diversified farming in water-scarce areas?
- How can farmers in arid/semi-arid environment reduce the risks of crop failure?
- How can the competition for soil nutrients and water be minimized while simultaneously growing trees and crops in a single farming unit?

1.3. Objective

1.3.1 General Objective

The main objective of this PhD thesis is to develop a RWH based small-scale agroforestry system that contributes to the restoration of degraded soils and water cycles, ultimately leading to improved crop yields for smallholder farmers in eastern Tigray, Ethiopia.

1.3.1 Specific Objective

- To develop a GIS based methodology for selecting optimum rainwater harvesting areas
- To determine GIS based Runoff potential using SCS CN- curve number
- To evaluate the effect of existing rainwater harvesting techniques on soil properties
- To assess impact of existing agroforestry systems on soil fungi and soil nutrients
- To develop a drought resilient small scale agroforestry system and analyze its effect on crop yield and soil nutrients.

1.4 Significance of the Study

The main importance of this research is that it can reduce the risks of water scarcity, soil erosion and improve livelihood of farmers by employing an effective combination of rainwater harvesting (RWH) and agroforestry systems. It helps farmers to convert their degraded land in to a fertile and suitable farming land. This in turn can help farmers produce diversified products of food, fodder, and fuel wood from a single farm plot than in monoculture farming, which is often characterized by single output. In regions where rainfall is scarce and intermittent, such combination of RWH & agroforestry system can help many smallholder farmers in their effort to combat food insecurity.

Chapter 2. Literature Review

2.1 Rainwater Harvesting

Rainwater harvesting can be defined as the collection and concentration of rainfall to make it available for domestic or agricultural uses in areas where moisture deficit is severe (Mekdaschi Studer & Liniger, 2013) . Oweis et al. (2012) elucidated the concept of rainwater harvesting by highlighting that a 4-hectare cropping area receiving only 150 mm of annual rainfall may not produce economically valuable crops under usual circumstance. However, if half of the area (2ha) is used for rainwater harvesting collection and transferred to the other half-cropped area, we could potentially harvest a total of 300 mm of rainfall, assuming no water losses. This shows that more rainwater is harvested by compromising part of the land and use it for runoff collection in order to secure water for crops. The major advantages of rainwater harvesting is its simplicity and adaptability (Mzirai & Tumbo., 2010).

2.1.1 History of Rainwater harvesting

The history of RWH dates back to 9 000 years in southern Jordan where water was collected from mountainous catchments for domestic use(Oweis et al., 2012; D. Prinz, 1996). In China, run off farming water harvesting was practiced for millennia by directing rainfall to the soil profile (Yuan et al., 2003). In addition, in the semi-Arid of Loess plateau, china , they utilized ridges with compacted soil and plastic mulch (with sand or gravel) to harvest rainwater onsite (Tian et al., 2003). In semi-arid India, runoff water harvesting Ponds called ''*Khadin*'' and ''*Ahar*'' were used to accumulate rainwater since 15th century (Koul et al., 2012; Dieter Prinz & Malik, 2002). Israel's Negev desert is well known for its ancient runoff agricultural practices from 200 B.C- 630 A.D (D. Prinz, 1996). The hilly areas were treated to facilitate runoff during rainfall while the command area (farming area) was built on the adjacent bottomlands (Al-Seekh & Mohammad, 2009; Hilary Fuller Renner & Frasier, 1995). The farm plots were constructed with rock dikes across the watercourses, thus accumulating and conserving soil inside the plots while the cropping systems varied according to catchment size and its drainage channels (Komariah & Senge, 2013). Records show that a variety of crops were grown in the Negev desert including barley, wheat, legumes, grapes, figs and dates with the support of RWH (Dieter Prinz & Malik, 2002). Runoff farming or micro catchment water harvesting has regained more attention since 1980s due to the growing demand for agricultural water (Boers, 1994; Boers & Ben-Asher, 1982; H. F. Renner & Frasier, 1995).

In sub- Saharan Africa (SSA), micro catchment water harvesting is a dominant water harvesting techniques used by small holder farmers to irrigate their lands by channelling runoff from small catchments into farm ponds with 50 – 100 m^3 storage capacity (Komariah & Senge, 2013; Ngigi, 2003; Vohland & Barry, 2009). Micro-catchment water harvesting techniques including zai pits, Trenches, Soil bunds, Terracing, microbasins, and ponds are commonly practiced RWH techniques in SSA (Biazin et al., 2012) .

In Ethiopia, rainwater harvesting practice dates back to ancient Axum civilization - 560BC(Binyam & Desale, 2015). Rainwater was collected in ponds for both domestic, and religious purposes (Kassahun, 2007) . The konso people in southern Ethiopia had established a well builtup level terraces for growing of crops (Esser & Haile, 2002b). In the dry lands of northern Ethiopia, rainwater harvesting based conservation measures were introduced since 1971 to alleviate the problem of drought and food insecurity (Esser & Haile, 2002b). Since 2003, the Ethiopian government in collaboration with non-governmental organizations has introduced the development and expansion of rainwater harvesting for crop production, and domestic purposes (Bekele et al., 2012). Flood water harvesting, spring development, river diversion, and flood spreading were mainly used for irrigation in the region (Bekele et al., 2012). The Abraha atsbeha village in Tigray- northern Ethiopia is known for its successful soil-water management techniques such as the construction of stone bunds, Soil bund with deep trenches, percolation ponds, Bench terraces, RWH Ponds , area exclosure and check dams etc.(Tadesse, Gebrelibanos, & Geberehiwot, 2016). An effective participatory rainwater harvesting and watershed management at Abreha atsbeha has restored the degraded landscape, increased the groundwater table and brought socioeconomic impacts to the community and this enabled the village receive the international recognition of Rio+20 for innovative hunger solution (M. Haile & Gebregziabher, 2020).

2.1.2 Types of Rainwater Harvesting

According to catchment area where the rain falls, catchment size and run off transfer distances, rainwater harvesting can be categorized as In situ RWH or ex situ RWH (Mekdaschi Studer & Liniger, 2013; Mzirai & Tumbo., 2010). In-situ RWH also called a micro-catchment runoff (*Fig 2.1*) refers to water harvesting by collecting surface runoff from a small catchment area and storing it in the root zone of an adjacent infiltration basin often planted with a tree, a bush or with annual crops (Biazin et al., 2012). This system is effective in soils where the soil water holding capacity is large enough and the rainfall is equal or more than the crop water requirement (Oweis et al., 2012). The ratio of catchment area to cropping area can range from 1: 1 to 25: 1 depending on the topography, aridity and soil type(Dieter Prinz & Malik, 2002). Due to the small size of the catchment, small-scale farmers can easily monitor it. This makes micro catchment runoff farming preferable by smallholder farmers. Examples of these systems are, Pitting, terracing, micro basins, contour bunds, contour ridges, and semi-circular bunds (Biazin et al., 2012; M. Falkenmark, 2001; Ibraimo & Munguambe, 2007; Dieter Prinz & Singh, 2000; H. F. Renner & Frasier, 1995).

ex situ RWH *(Fig 2. 1)* is a macro-catchment runoff water harvesting that comprises rainwater catchment, a conveyance system, a storage structure and a target area (Mekdaschi Studer & Liniger, 2013). Ex situ RWH, produce high runoff rate & predominance turbulent runoff flow. Here the runoff volume is collected external to the point of water storage and has relatively large catchment areas ranging from 1,000 m^2- 200 ha with a ratio of catchment area to cropping area ranging 10: 1- 100: 1 (Oweis et al., 2012) . Some of common examples include open ponds, cisterns, sand dams and spate irrigation (Biazin et al., 2012; Mzirai & Tumbo., 2010). Unlike in situ RWH, which are best practiced in gentle slopes, Macro catchment harvesting can be applicable for hilly areas with up to 50% slope but usually requires complex storage and conveyance structures until it reaches the target area (D prinz et al, 2002).

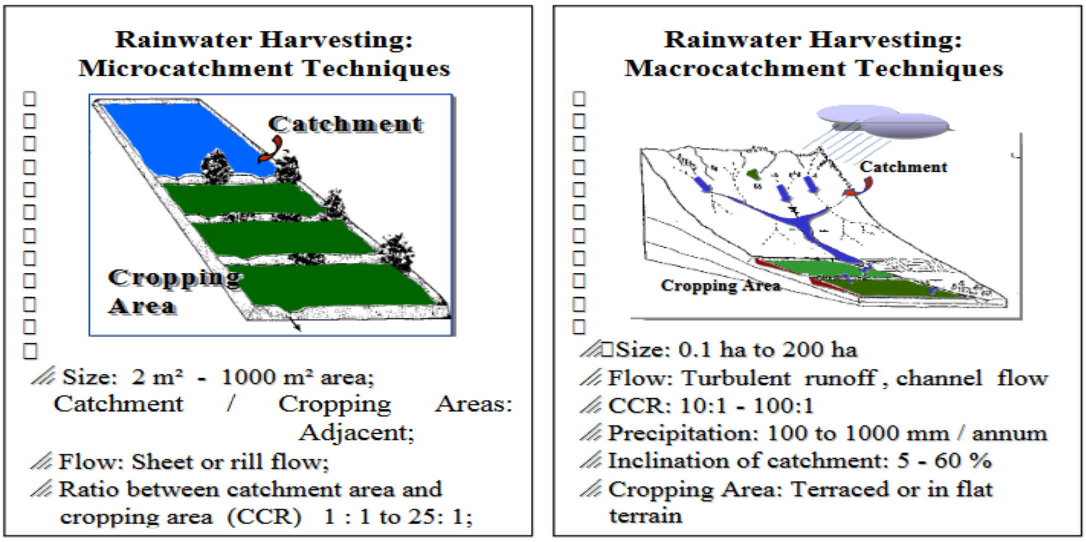


Figure 2.1 micro and macro catchment rainwater harvesting techniques with general features, (Dieter Prinz & Malik, 2002)

2.2 Global Agricultural water scarcity

Water is vital natural resource providing essential ecosystem services including food production, nutrient cycling, biodiversity conservation and over all life support system(Malin Falkenmark, 2020). Nowadays, however human driven factors including population pressure and unsustainable exploitation of water resource are causing it to decline. In addition, climate change is worsening water scarcity, leading to detrimental effects on crop productivity (X. Liu et al., 2022). Looking at the societal water consumption of fresh water withdrawals, agriculture (both food production and livestock) takes the lions share accounting to nearly 86% (*Fig 2.2*). Water scarcity occurs when there is an imbalance between crop water requirement and water present in rhizosphere as soil moisture (green water) or the available freshwater in surface and ground water referred to as blue water (Dell'Angelo et al., 2018). According to Rosa et al. (2020) , around 77% of global croplands are rainfed while the rest 23% croplands are irrigated. The same Author reported that three-fourths of the rainfed croplands (76%) experience green water scarcity (soil moisture) ranging from one month to 5 months a year. Similarly, up to sixty-eight percent of the current irrigated croplands experience blue water scarcity that occurs in two distinct forms. The initial scenario arises when the existing freshwater from surface and groundwater source is exhausted or inadequate for sustaining irrigation. Alternatively, it can occur when there is a possibility of freshwater withdrawal for irrigation, but it remains inaccessible due to economic and institutional limitations (Rosa et al., 2020). While rainfed agriculture is practised across various agro-ecological zones, the likelihood of water scarcity is lower in temperate to sub-humid regions, characterized by sufficient rainfall and fertile soil. Conversely, the impact is notably severe in dryland areas, constituting 40% of global croplands, due to unpredictable rainfall patterns and extremely high temperatures (Mekdaschi Studer & Liniger, 2013).

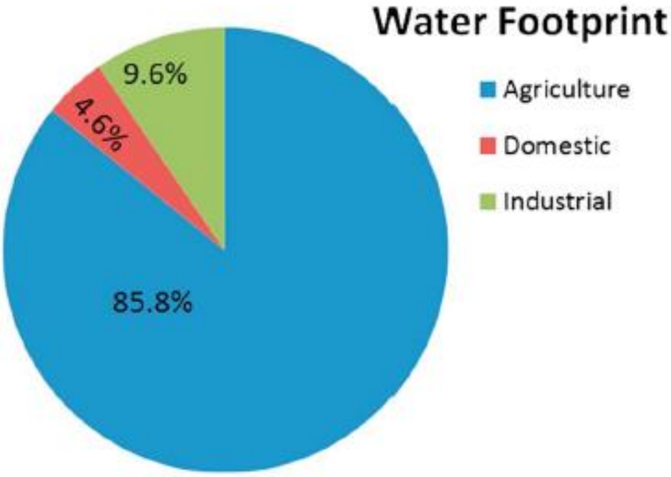


Figure 2.2: Global water foot print of human activities , modified (D'Odorico et al., 2018)*, CC BY 4.0*

Approximately 66% of the world's economically water-scarce croplands are found in sub-Saharan Africa, Eastern Europe, and central Asia where rainfall is not sufficient to support crop growth (Rosa et al., 2020). This means those regions have limited green water (water stored in the root zone) with a potential for blue water resource, which cannot be accessed due to economic, institutional, or technological limitations (Dell'Angelo et al., 2018). This is particularly true for sub Saharan Africa, where 50% of its population live under severe poverty, 25% are undernourished, and ninety-five percent of its agriculture is completely rainfed (*Table 2.1*) (Rockstr & Falkenmark, 2015). Based on the water balance for dry lands (*Fig 2.3*), up to fifty percent of rainfall that reaches the ground is lost directly from the soil surface as unproductive evaporation while up to one-quarter of the precipitation is lost via run off (Oweis et al., 2012). This implies that only fraction of the precipitation (>30%) is used as soil moisture and this is not enough to support crop growth and results in crop failure. The issue of water scarcity is not necessarily a lack of rainfall. Instead, it results from irregular rainfall patterns characterized by intense, short rainfall duration and extended periods of dry spells that can persist for months (De Boever et al., 2013).

Table 2.1 Approximate percentage of rain fed croplands (Mekdaschi Studer & Liniger, 2013)

Region	Percentage (%)
Latin America	90
Middle East and North Africa	75
East Asia	65
South Asia	60
Sub saharan Africa	95

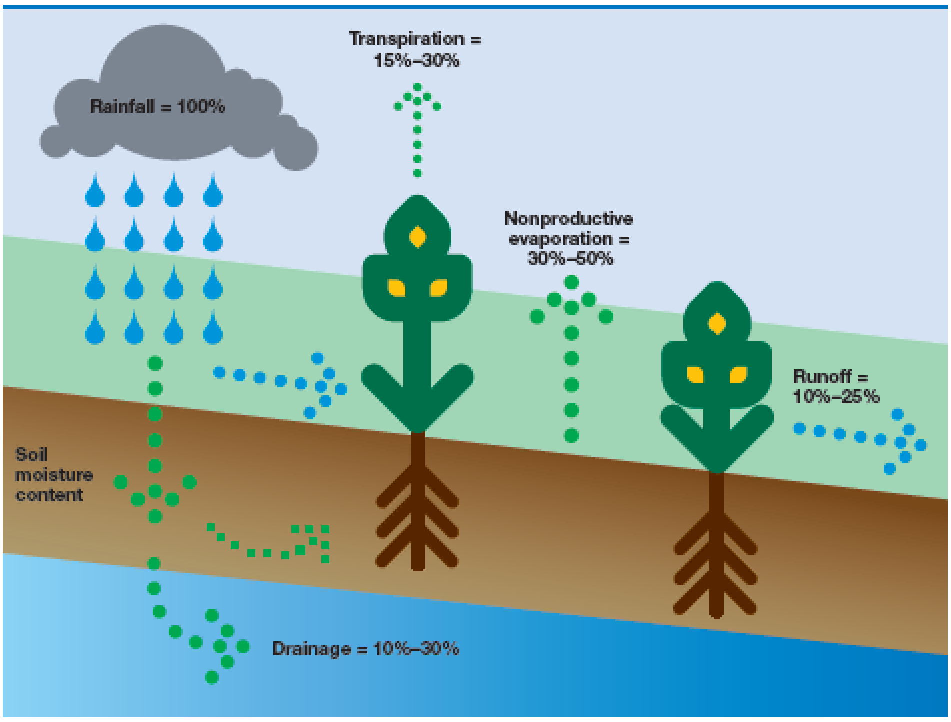


Figure 2.3 water balance of typical semi-arid tropics ,international water management institute -IWMI CC BY NC (Oweis et al., 2007)

2.3 Water scarcity - Food security - Land degradation Nexus

Food insecurity occurs when there is limitation in supply of sufficient and healthy nutritious food within a given household. Based on reports from world health organization (WHO), about 735 million people worldwide face food insecurity, while 600 million people are expected to be malnourished by 2030 (FAO et al., 2023). There are several factors contributing to today's food insecurity including water shortages, land/soil degradation, high population pressure, urbanization, and limited agricultural lands(Kousar et al., 2021). Water is a critical limiting factor in addressing the growing global demand for food production with the population expected to reach 9 billion by 2050 (Rockstr & Falkenmark, 2015). Ensuring food security by 2050 requires doubling of current agricultural water consumption (World Economic Forum, 2011). Hence, there is a strong nexus between water availability and food security. In addition, Crop productivity is determined by the availability and amount of moisture or irrigation water. nowadays however, the withdrawal of fresh water resources has exceeded the acceptable level, which resulted in unsustainable irrigation practices at the expense of the environment (Rosa et al., 2020).

The availability of adequate water resource is closely interlinked to UN Sustainable Development Goals such as SDG1 (No poverty), SDG2 (Zero Hunger), SDG3 (Good health & wellbeing), etc.(Taka et al., 2021). This suggests that ensuring water security can play a crucial role in realizing all the UN SDGs. Due to prolonged periods of drought lasting for months and subsequent crop failures, agricultural areas specifically in drylands frequently experience yields significantly below their potential, resulting in losses of up to fifty percent (Mekdaschi Studer & Liniger, 2013). According to Aridity index (*Fig 2.4*), a ratio of precipitation to evapotranspiration, the crop water requirement is directly proportional with the precipitation. The graph illustrates that in regions characterized by arid or semi-arid climates, with an aridity index ranging from 0 - 0.5, there was high crop water requirement. However, this decreased eventually as we move to the humid climate where rainfall is relatively reliable. Without a serious action in ensuring water security, future water scarcity is likely to be a key geopolitical tension that can influence the global economic system (Malin Falkenmark, 2013). When dealing with water security, it is critical to view water security together with water equity and its societal and ecological needs as well as its linkages with food, energy, climate and human security(Taka et al., 2021).

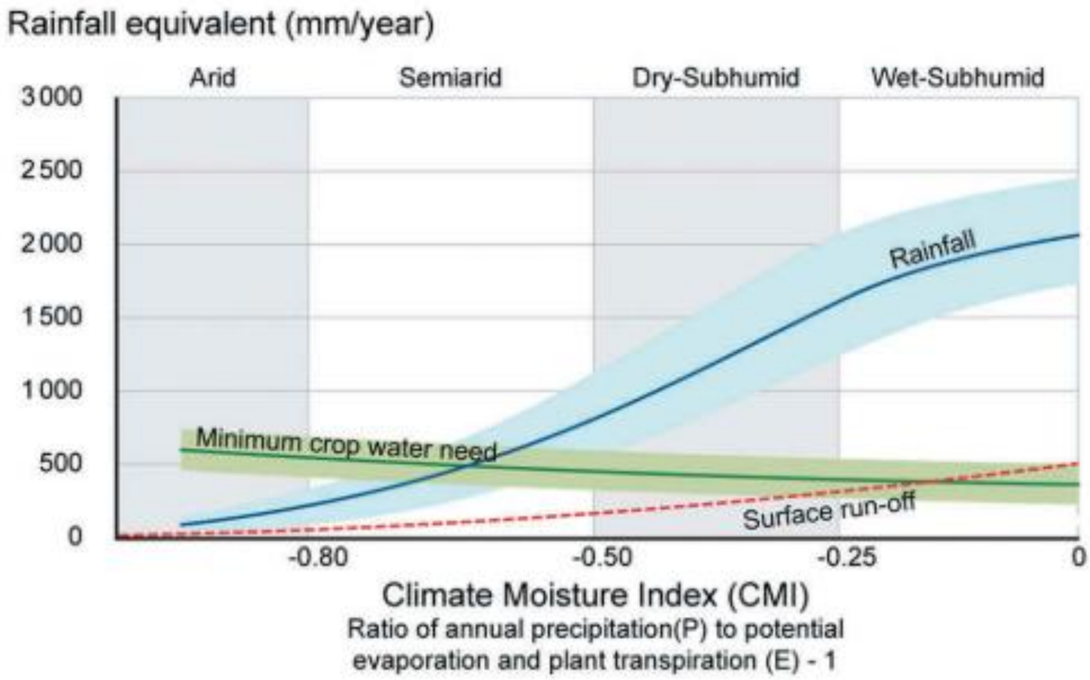
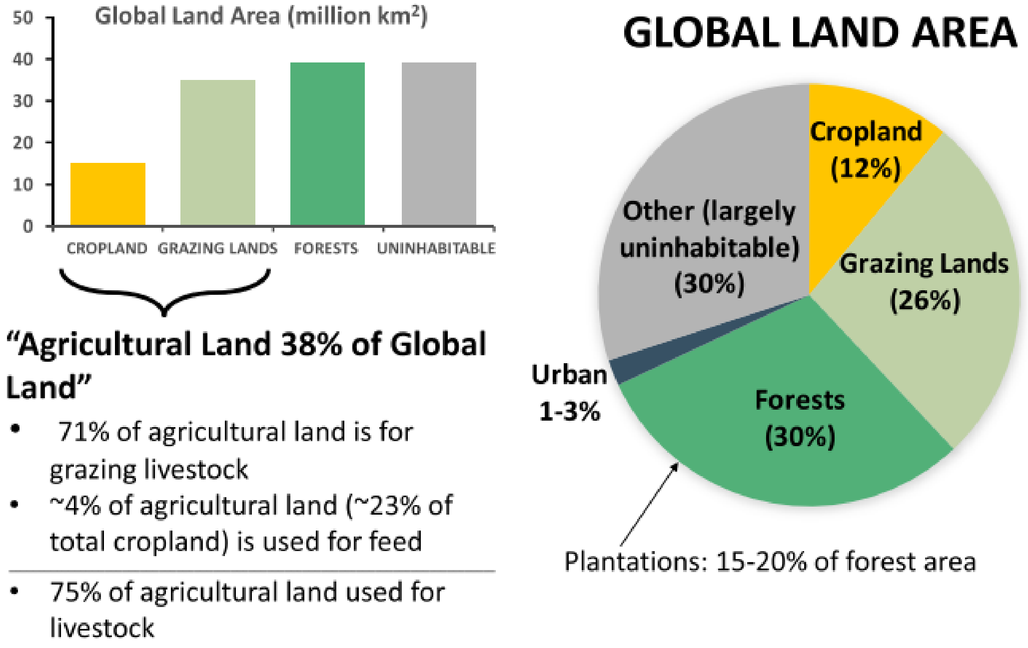


Figure 2.4 Aridity index- across hydro climatic zones (Malin Falkenmark, 2020), CC BY 4.0

Utilizing irrigation to address moisture deficit can be a mechanism to alleviate water scarcity. Nonetheless, this approach carries potential drawbacks, including adverse effects on river flow and groundwater depletion,(Malin Falkenmark, 2020). Another challenge with irrigation of freshwater resources is that approximately a quarter of world population lives under highly water stressed environment due to spatial and temporal variations in blue water distribution (Malin Falkenmark, 2020). Similarly, land degradation is becoming a threat to cropland agriculture. Global agricultural land constitute of 38% of global land area from which 12% are croplands while 26% are used for livestock grazing (*Fig 2.5*).



"Agricultural Land 38% of Global Land"

- 71% of agricultural land is for grazing livestock
- ~4% of agricultural land (~23% of total cropland) is used for feed

- 75% of agricultural land used for livestock

Figure 2.5: Global land area estimates (Dell'Angelo et al., 2018) CC BY 4.0

Degraded lands are often characterized by soil erosion, loss of soil organic matter, loss of vegetation and nutrient depletion (Weeraratna, 2022). This aggravates soil physical degradation by negatively affecting soil infiltration and porosity thus disrupting the water cycle (Nachtergaele et al., 2007). The physical alteration of soil creates soil crust and soil compaction that accelerates run off. This leads to reduction in water holding capacity leaving minimal water left for crops. The negative relationship of soil degradation and water depletion is described in (*Fig 2.6*). The Global Assessment of Human-Induced Soil Degradation (GLASOD) stated soil degradation has affected 65% croplands in Africa, 51% in Latin America, and 38% in Asia (Nachtergaele et al., 2007). Therefore, when considering solutions to tackle future food insecurity, it is crucial to look for a holistic approach that simultaneously addresses water scarcity & soil degradation.

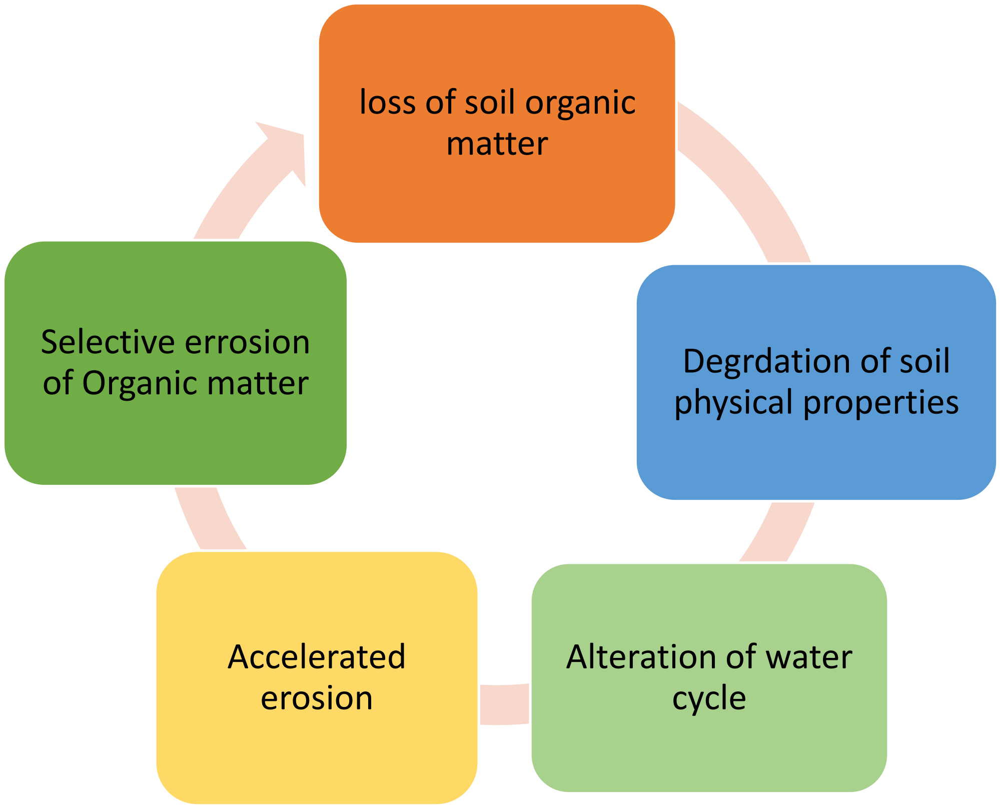


Fig.2.6 a negative relationship between soil degradation and water scarcity international water management institute –IWMI, modified from (Nachtergaele et al., 2007) CC BY 4.0

2.4 The Case of Sub Saharan Africa

Sub-Saharan Africa (SSA) encompasses nearly all African countries, excluding only six countries in Northern Africa. The region has a total landmass of 2.4 billion hectares, with just 10% of it under cultivation and constitutes 12.6% of the global cultivated land (Ahmed et al., 2022). Agriculture in SSA contributes to 20.5% and is dominated by smallholder farmers where farming takes place in fragmented farmlands usually less than 2 ha (Kim et al., 2021). SSA region has a population of 1.02 billion with sixty-two percent residing in countryside, and 80% of the people depend on agriculture. Approximately half of the population experiences extreme poverty, contributing to 40% of global poverty (Ahmed et al., 2022; Rockström & Falkenmark, 2015). About ninety- five percent of croplands in SSA are reliant on rainfed agriculture while 40% of its total area is considered arid and semi-arid climate (Malin Falkenmark, 2020). Because of the arid nature of the drylands in SSA, irrigation is very limited as half of the precipitation is evaporated directly from the soil surface without reaching the crops (Fig 2.3). Due to the harsh weather climates, SSA is prone to drought and extended dry spells that significantly reduces agricultural productivity (Agada, 2016). A crop yield reduction of up to 85% in the dry lands of SSA was reported due to the extreme hot climate that damages the root system and limits its ability to absorb moisture from the soil surface (Garg et al., 2012).The population in SSA is forecasted to double (2.17 billion) by 2050 and so will be the food demand (Kim et al., 2021). In line with this, 16% of the people in SSA will live under serious water scarce conditions while another 32% are expected to live under water stressed environments (Eludoyin & Olanrewaju, 2022). This will have unprecedented pressure on the limited available water resource. One mechanism to prevent extended dry spells in dry lands such as SSA is in situ RWH, which is harvesting rainwater water in field by modifying the landuse in order to concentrate majority of the rainfall. Other option would be supplemental irrigation where rainwater can be collected in RWH pond at the adjacent cropped area and are used to supplement moisture deficit. In addition to facing water scarcity, 65% of SSA's agricultural land is undergoing land degradation, marked by nutrient losses, and the decline of biological diversity (Kihara et al., 2020). These resulted in degrading soil biogeochemical characteristics with an estimate of 38Kg/ha average nutrient depletion while the associated cost of land degradation is estimated to be USD 68 billion each year. Multifaceted factors including traditional farming practices, soil tillage, excessive external inputs including chemical fertilizers, removal of soil cover, run off induced soil erosion, climate change etc. are all the root causes of land /soil degradation in SSA (Karlen & Rice, 2015). Some of the methods considered best practices for combating soil degradation are integrated soil fertility management and agroforestry systems(Bationo et al., 2011; Jama & Zeila, 2005; Kihara et al., 2020; Kim et al., 2021). However, most of these methods are applied separately in the literature and hardly looked at the holistic approaches where these interconnected problems could be addressed.

2.5 Agricultural water management

The extent of water scarcity is different across regions and depends largely on rainfall variability and distribution and availability of blue water resources (*Fig. 2.7*). While most of the water scarcity problems in arid areas are the result of limited rainfall usually a few 100 mm of annual precipitation, most of the water scarcity in semi-arid and sub humid climate are also the result of poor water management related issues on farm water balance (Oweis et al., 2007). Therefore, water scarcity in such cases can be mitigated by employing different rainwater harvesting techniques weather in situ or ex situ depending on the run off rate, slope, soil type, and topography of the catchment(Oweis et al., 2012). These RWH techniques are intended to bridge extended dry spells that can last from few weeks to few months even during the rainy season(Rockström, 2003). The first method has to do primarily with enhancing water productivity (*more crop per drop of water*). This method involves small-scale supplemental irrigation, which aim at upgrading rainfed agriculture and conservation agriculture (In-situ RWH) and it is easily applicable by smallholder farmers mainly in developing countries (Rockström & Falkenmark, 2015). The other method involves huge investment projects such as building large-scale reservoirs, dams, both above ground and underground storage mechanism with a potential to support full-scale irrigation precipitation (Mzirai & Tumbo., 2010). The higher investment costs of such macro catchment RWH, restricts its implementation to economically advanced countries. Application of macro catchment RWH techniques in developing countries requires the help of donors or government subsidy in developing countries. They are usually constructed through mass

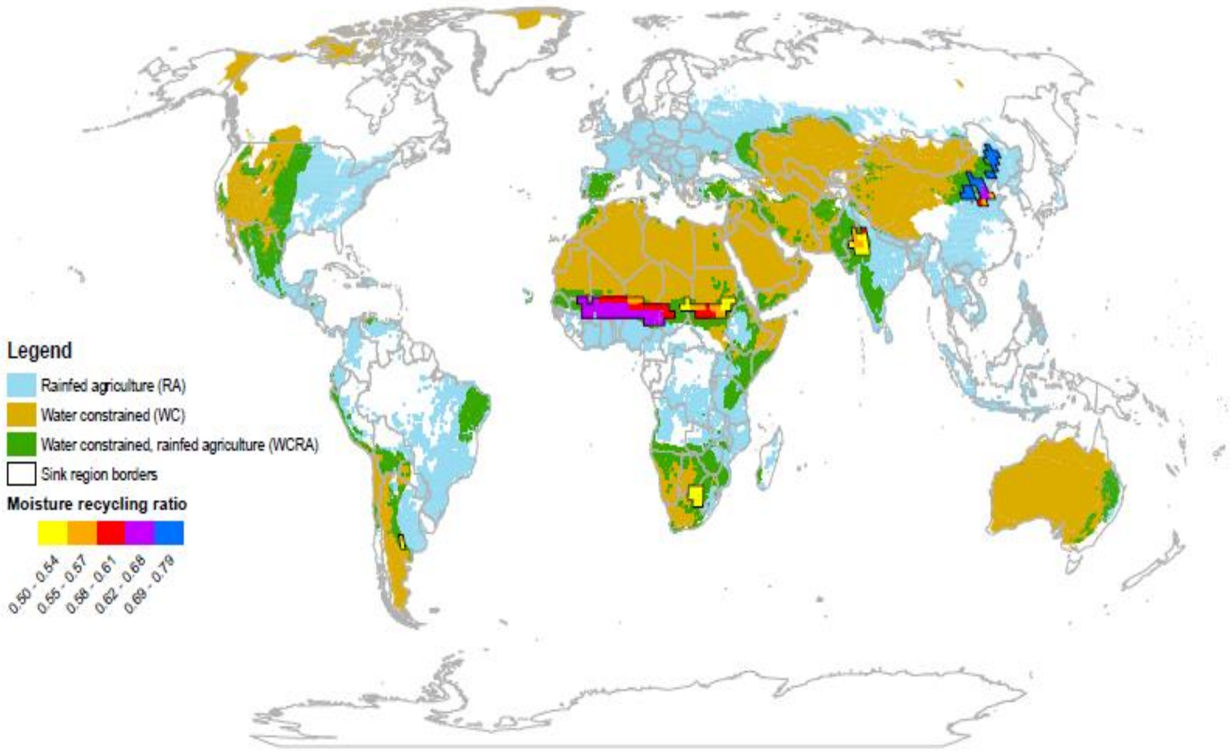
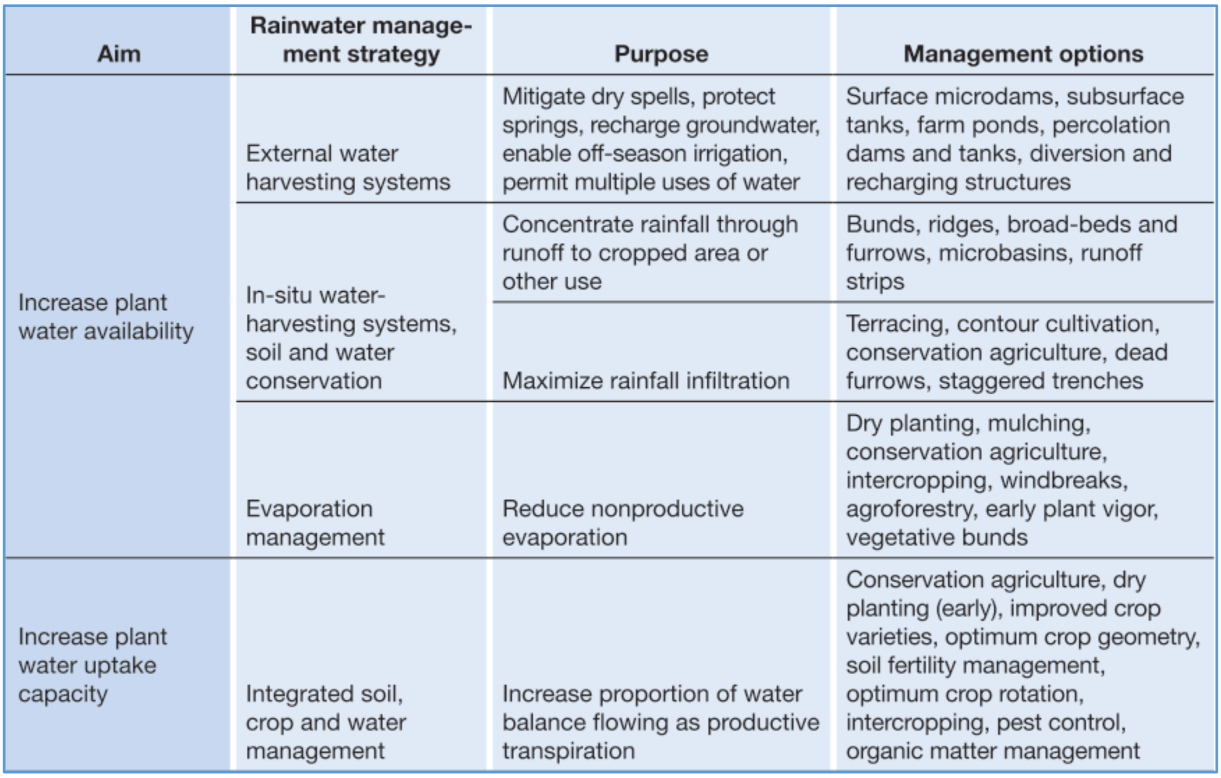


Figure 2.7 Global agricultural water scarcity extent (Keys et al., 2012) *CC BY 3.0*

community mobilization due to their labour intensive nature. These RWH techniques are detailed in (*Table 2.2*). Examples of macro catchment RWH are Surface or sub surface dams, subsurface tanks, farm ponds, percolation dams and tanks, diversion and recharging structures. In situ RWH on the other hand concentrate the rainfall where it falls and include Terracing, contour cultivation, conservation agriculture, bunds, Bunds, ridges, furrows, and microbasins. The choice of appropriate rainwater harvesting (RWH) method relies on various biophysical and socio-economic considerations, including factors such as topography, freshwater availability, expenses, climate, and more. The various agricultural management options in (*Fig 2.8*) gives us a continuum spectrum from purely rainfed to fully irrigated agriculture.

Table 2 .2 Rainwater management options- international water management institute - (Oweis et al., 2007)



Aim	Rainwater management strategy	Purpose	Management options
Increase plant water availability	External water harvesting systems	Mitigate dry spells, protect springs, recharge groundwater, enable off-season irrigation, permit multiple uses of water	Surface microdams, subsurface tanks, farm ponds, percolation dams and tanks, diversion and recharging structures
	In-situ water-harvesting systems, soil and water conservation	Concentrate rainfall through runoff to cropped area or other use	Bunds, ridges, broad-beds and furrows, microbasins, runoff strips
		Maximize rainfall infiltration	Terracing, contour cultivation, conservation agriculture, dead furrows, staggered trenches
	Evaporation management	Reduce nonproductive evaporation	Dry planting, mulching, conservation agriculture, intercropping, windbreaks, agroforestry, early plant vigor, vegetative bunds
Increase plant water uptake capacity	Integrated soil, crop and water management	Increase proportion of water balance flowing as productive transpiration	Conservation agriculture, dry planting (early), improved crop varieties, optimum crop geometry, soil fertility management, optimum crop rotation, intercropping, pest control, organic matter management

For instance, under purely rainfed agriculture, only in situ RWH (the green shed) techniques also known as field conservation techniques are feasible because, these areas have clear physical water scarcity as we move to the left, the blue colour shows us that there is both availability of moisture and fresh water resource . In such cases, supplemental irrigation is preferred RWH technique. These are common scenarios under semi-arid conditions. There is sufficient rainfall but it is spatial as well as temporal variable. So, the partial irrigation during an extended dry spell can save the crops and prevent crop failure- (Dell'Angelo et al., 2018; Oweis et al., 2007).

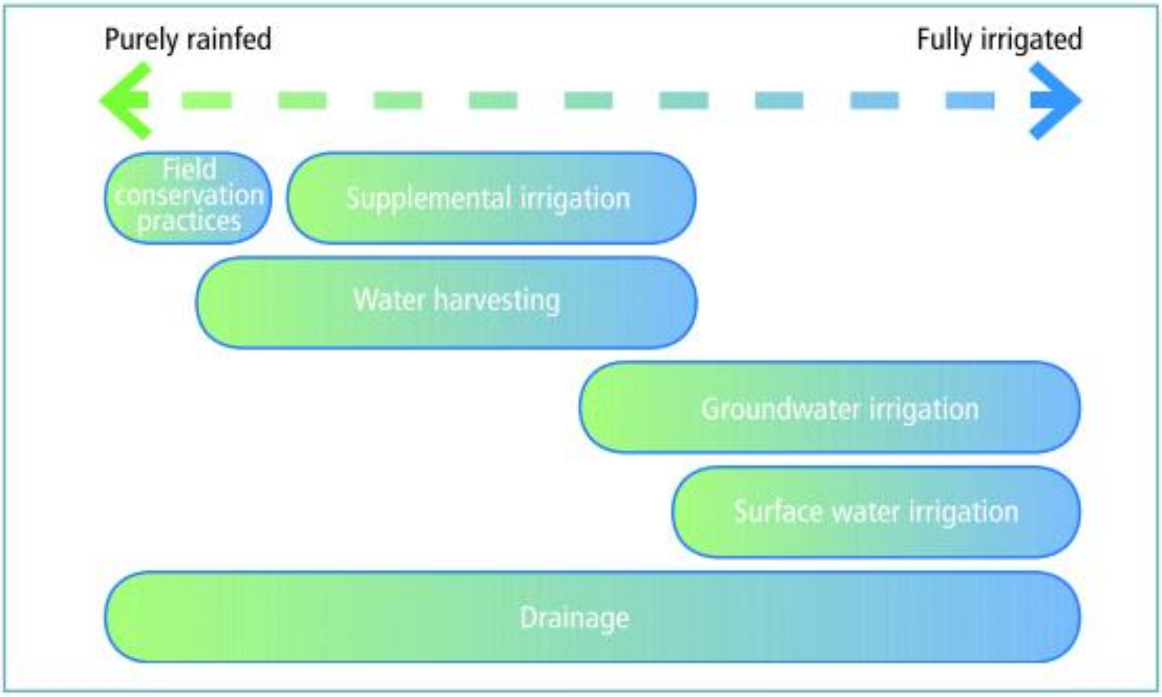


Figure 2.8 Diverse options of agricultural water management, a continuum spectrum from pure rainfed towards fully irrigated lands, Field conservation practices indicate in situ RWH practices,(Molden 2017) as cited in (Mekdaschi Studer & Liniger, 2013)

2.6 Agroforestry Practices

Agroforestry is a farming system of combining trees (woody species or shrubs) with the production of other crops or animals in a given landscape (T. Abebe, 2013; Zomer et al., 2014). The presence of wood perennials affects both biophysical and biochemical process which determine soil fertility of the substrate (Sobola & Amadi, 2015). Agroforestry plays a significant role in alleviating food scarcity for drought prone regions (Soni et al., 2016) Thus, it can be an economically and environmentally sustainable option for small-scale farmers(Zerssa et al., 2021). Agroforestry based rainwater harvesting is the combination of agroforestry and instu rainwater harvesting on farmlands -(Casanova et al., 2021). This combination will not only respond to the problem of water scarcity, it also reduces the occurrence of flooding by storing the incoming rain either on the soil profile or on external reservoirs, diversifies farmers income, and prevent soil erosion (Dev et al., 2018). It protects soil erosion during the increasing high rainfall intensity. One effective option for the sustainability of this system is to optimize the soil physical quality particularly its water holding capacity (Senge et al, 2013). Home garden agroforestry is commonly practiced in Ethiopia especially in southern Ethiopia and it is characterized by the unique combination of two native major perennials enset *(Ensete* *ventricosum*), and coffee (*Coffea arabica*) which grow in association with food crops and various multipurpose trees (Gebrehiwot, 2013) . Agroforestry systems along with RWH can facilitate crop growth and diversify income for small scale farmers (Smith & Mbow, 2014; Sobola & Amadi, 2015). Adding legumes, or so- called fertilizer trees with nitrogen- fixing roots, help crops take up nutrients (Dessalgn & Wolde, 2021). Intercropping indigenous fertilizer trees such as *Faidherbia Albida* in certain parklands systems can increase crop yields, such as barley (Al-Seekh & Mohammad, 2009; Droppelmann et al., 2000; K. M. Hadgu et al., 2009). Agroforestry can ensure food security at household level and create a job opportunity (Raj et al., 2017). Besides the direct benefits to farmers, agroforestry provides ecosystem services such as biodiversity conservation and climate change mitigation via carbon sequestration (Fungo et al., 2021).

Chapter 3. Developing a GIS based methodology for identifying suitable rainwater harvesting sites

3.1 Introduction

Ethiopia, as one of sub-Saharan countries in Africa has been severely hit by land degradation and recurrent drought(Megerssa & Bekere, 2019) . Drylands in Ethiopia comprise of around 66% percent of overall area and are known for their scarce water availability and lower agricultural productivity (Belay et al., 2015). The current available arable land is less than 40% and most soils have insufficient organic matter and poor water holding capacity (Seleshi Bekele Awulachew & Merrey, 2007) .This has brought a frequent drought and famine in those areas and food security remained as a serious challenge due to declining productivity of the soil (Seleshi B Awulachew, 2001) . (Tesfay, 2011) also emphasized moisture stress and soil fertility problems are challenges faced in Ethiopian drylands. The situation is extreme in highland areas such as Tigray where farming has been practiced for centuries (J. Nyssen et al., 2000).The reason behind this threat is rapid population growth, erratic rainfall distribution, steep topography, and runoff induced erosion (Hengsdijk et al., 2005). In order to reverse the recurrent drought, certain rainwater harvesting programs were introduced in the region (Belay et al., 2015). However, these RWH techniques focus on communal lands and are conducted through mass mobilization (Hishe et al., 2017).

RWH techniques conducted by individual smallholder farmers are very limited. As a result small holder farmers in Tigray are prone to crop failure and food insecurity (Blerk, 2017). Additionally, most of the conducted RWH structures have been carried out without proper site selection procedures and resulted in failure of the structures (Ketsela, 2009) . In order to adopt and replicate rainwater harvesting, the primary task should be identification of optimal rainwater harvesting areas (Debebe et al., 2023). This section discusses a GIS based approach to conduct RWH suitability assessment at a catchment level in eastern Tigray northern Ethiopia based on a published article by the author (Debebe et al., 2023).

Geographic information system is an essential tool to collect, store and analyze spatial datasets particularly in areas where data is scarce (de Winnaar et al., 2007; Debebe et al., 2023). They can be used for RWH suitability analysis due to their simplicity and flexibility. Acording to Ammar et al.,(2016), There are four main methodologies in the literature used for

RWH suitability assessment namely: GIS/RS, HM, GIS/RS, MCA, GIS/RS and MCA with GIS. HM refers to hydrological modelling and MCA for multi criterion analysis. The authors concluded that, combining GIS & MCA was most preferred method for optimum RWH site selection because of its flexibility and simplicity (Ammar et al., 2016; Wu et al., 2018). During criteria selection for RWH suitability assessment, considering physical, environmental, hydrological as well as socioeconomic parameters are of utmost importance for maximum accuracy. However, most literatures focus on biophysical factors with less emphasis on socio economic factors (Ammar et al., 2016; Ibrahim et al., 2019; Mahmoud & Alazba, 2015; Wu et al., 2018; Zheng et al., 2018; Ziadat et al., 2012). For instance, Tumbo et al., (2013) used topography, soil depth, soil texture, vegitation cover and drainage conditions as criteria (*Table 3.1*). For this case study, climate, bio physical and socioeconomic factors were considered.

3.2 Material and methods

3.2.1 Study area description

The study site (*Fig 3.1*) lies with in a typical semi-arid climate in eastern Tigray region (northern Ethiopia) with elevation ranging from 1500 -2000 meters above sea level. The site has short and intense rainfall in the summer and little or unprecedented rainfall in the winter usually experience long and extended dry spells. The geological formation of the site includes magmatic rocks and Mesozoic sedimentary rocks (Rabia et al., 2013) and dominant soil types were clay, clay loam, and sandy loam (Debebe et al., 2023).

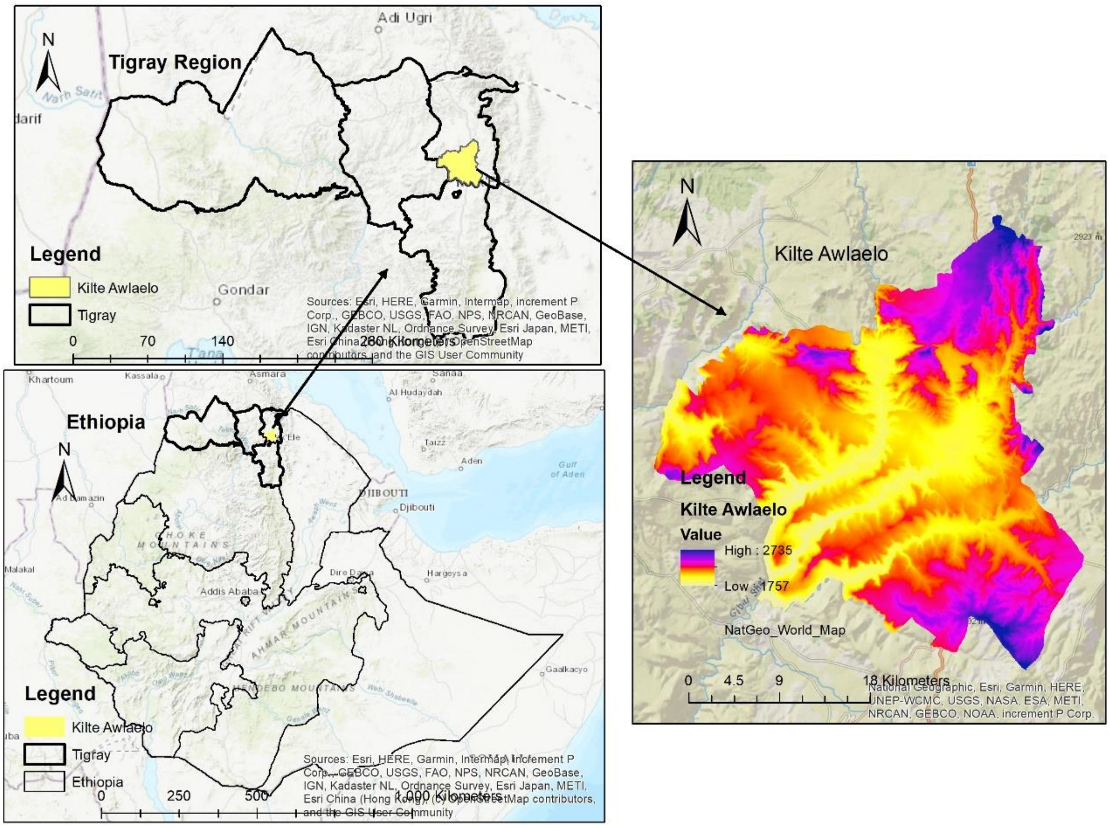


Figure 3.1. Study area map of, kilte Awlaelo eastern Tigray northern Ethiopia (Debebe et al., 2023)

3.2.2 Data collection

Digital elevation model and Landsat 8 images were acquired from United States geological survey (https://earthexplorer.usgs.gov) on 29.12.2021. Digital soil dataset was accessed from FAO soil data base https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/en/) on 23.01.2022. Climate data from *2011-2019* was obtained from climate research unit (https://crudata.uea.ac.uk/cru/data/hrg/) on 28.12.2021. Erdass imagine 2015 software was used for stack layering of land sat 8 images. Preparation, processing and generation of different map layers, supervised classification of land sat images as well as weighted over lay analysis was done using ArcGis 10.4.1. Google earth pro was used for ground truth and accuracy assessment of classified landuse land cover (LULC) images.

3.2.3 Selection and generation of criteria map

The criteria for the RWH suitability were chosen through an extensive literature review, aligning with FAO guidelines and expert inputs. They cover biophysical factors including soil texture, slope, land use, precipitation, aspect, soil moisture, and stream order, as well as socioeconomic factors like distance to road and river. The method employed higher number of criteria compared to similar studies for enhanced model accuracy (*Table 3.1*). These criteria highly influence rainwater harvesting (RWH), affecting factors such as runoff, soil properties, and terrain characteristics. In rural areas where RWH structures are commonly installed, socioeconomic considerations, such as proximity to roads and rivers for irrigation, are crucial due to limited farmer income and accessibility challenges (Debebe et al., 2023). Spatial datasets were processed in ArcGIS 10.4.1 to produce criteria map layers. Slope map and aspect maps were generated from a 90m spatial resolution DEM and land use/cover maps from Landsat 8 satellite imagery (de Winnaar et al., 2007). A supervised classification approach was applied for the land use/cover map while soil moisture index was computed using the normalized difference moisture index (Thakkar et al., 2015).The stream order map, indicating runoff potential, was derived from DEM (Rwanga & Ndambuki, 2017); soil texture map was derived from the FAO soil map and rainfall map was produced through inverse distance weighted spatial interpolation while distance from river and road map were computed using the Euclidean distance function (Zahedi, 2019). All Produced criteria maps (*Fig 3.3* $_{a\text{-}i}$) were categorized into sub-criteria according to the guidelines for agricultural rainwater harvesting in dry regions (Oweis et al., 2012). *Table 5* presents a detailed overview of the classified criteria and sub-criteria.

$$NDMI = \frac{(Band\ 5 - Band\ 6)}{Band\ 5 + Band\ 6} \text{……} \textit{equation 3.1}$$

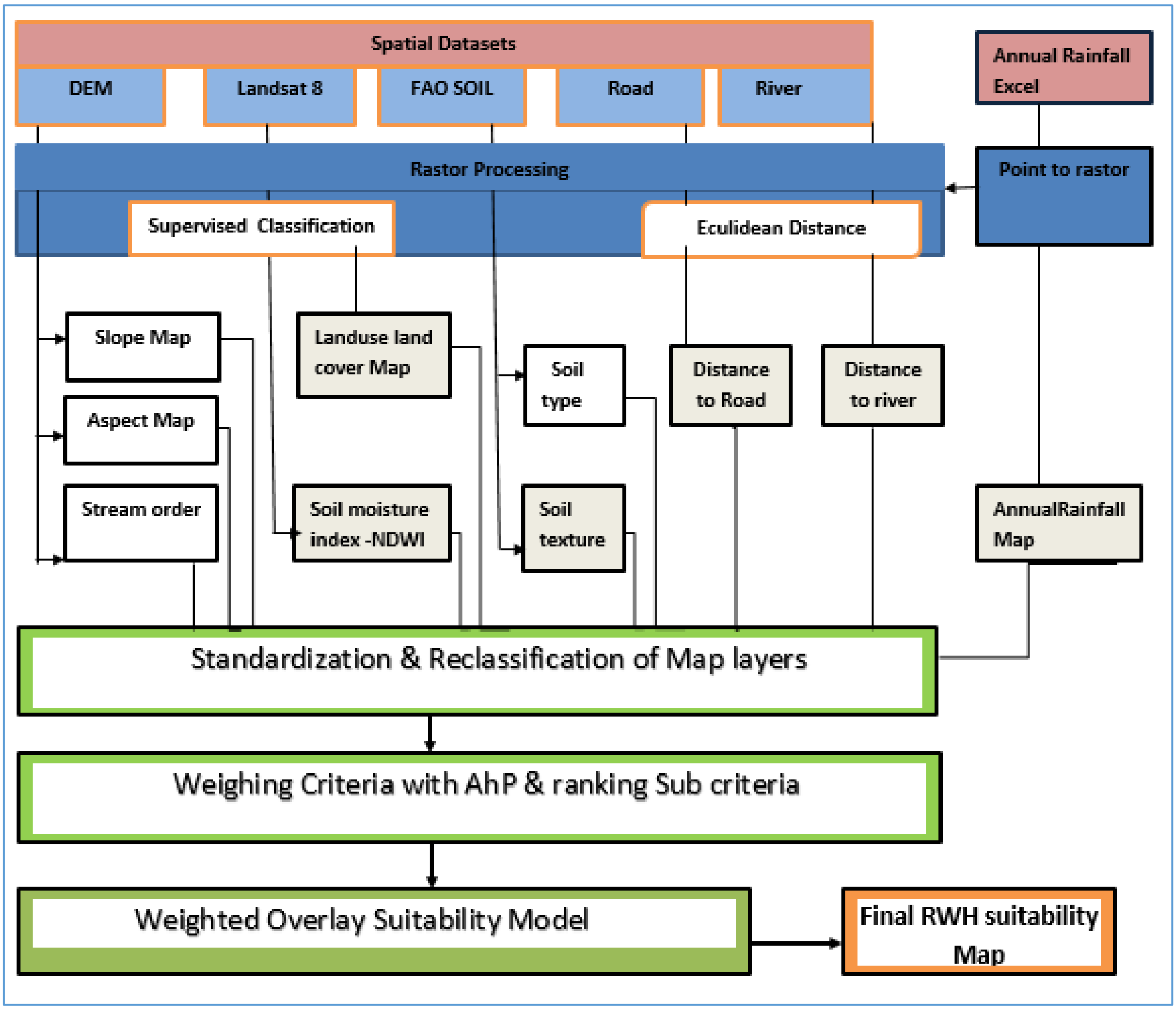


Figure 3.2. Methodology for producing suitable RWH site selection (Debebe et al., 2023)

Table 3.1. Some previously applied biophysical and socio economic criteria's for RWH suitability assessment (Debebe et al., 2023)

Name of Authors	Selected criteria
(Mugo & Odera, 2019)	Slope and drainage, LuLc, Lineaments, soil texture
(Adham et al., 2018)	Runoff depth, slope, soil texture, LuLc, Stream order
(Rana & Suryanarayana, 2020)	Slope, LuLc, Soil texture, Curve number, Stream order, drainage
(Ibrahim et al., 2019)	Slope map, Stream order, LuLc, Soil types,
(Suryabhagavan, 2019)	Soil texture, LuLc, Lineaments, elevation, slope, drainage density , geology, Fault, Distance to Settlement, Distance to road

(Alwan et al., 2020)	Stream order, slope, rainfall, evaporation, land cover , soil type, Dist. to road
(Saha et al., 2018)	Rainfall, soil type, LuLc, Slope, runoff potential, drainage density, Lithology and design peak discharge
(Mahmood et al., 2020)	Soil group, Rainfall, Slope, drainage density, Land cover
(Mugo & Odera, 2019)	Texture, Runoff depth, drainage density, LuLc, Lineament Density
(Wu et al., 2018)	Soil texture, land cover, slope, distance from agricultural land, distance from road, Runoff
(Rajasekhar et al., 2020)	Slope, Contour, LuLc, soil type, geology, drainage density
(Mahmoud & Alazba, 2015)	Soil texture, rainfall surplus, Slope, runoff coefficient, vegitation cover
(Tumbo et al., 2013)	Soil texture/depth, topography , Rivers, Rainfall, LuLc
(Tiwari et al., 2018)	Drainage network, depth of depression, Soil map , rainfall, runoff
(Adham et al., 2016)	Rainfall, drainage length, storage capacity, storage dimentions, soil texture/depth, slope, distance to settlements
(Aghaloo & Chiu, 2020)	Slope, Rainfall, soil texture, drainage network, river, constraints (road and railway)

3.2.4 Relative weights of criteria maps

Criteria weight of the WOA model was calculated through expert judgment. The Criteria are ranked based on their significance and priority relative to a specified objective. AhP facilitates quantitative comparisons through a pairwise technique (Table 3.2). Initially, pairwise comparison was conducted for all criteria, assigning continuous scale values from 1 to 9 (Table 3.3) followed by a 9 × 9 normalized matrix (Table 3.4). λ, a maximum eigenvalue, was calculated following (Saaty et al., 1980). Finally, a consistency Ratio (CR) was computed using equations 2 and 3, where CI represents the consistency index, RI is the random index, and n is the number of criteria. A $CR < 0.1$ is deemed acceptable, indicating that factors are evaluated with minimal inconsistency.

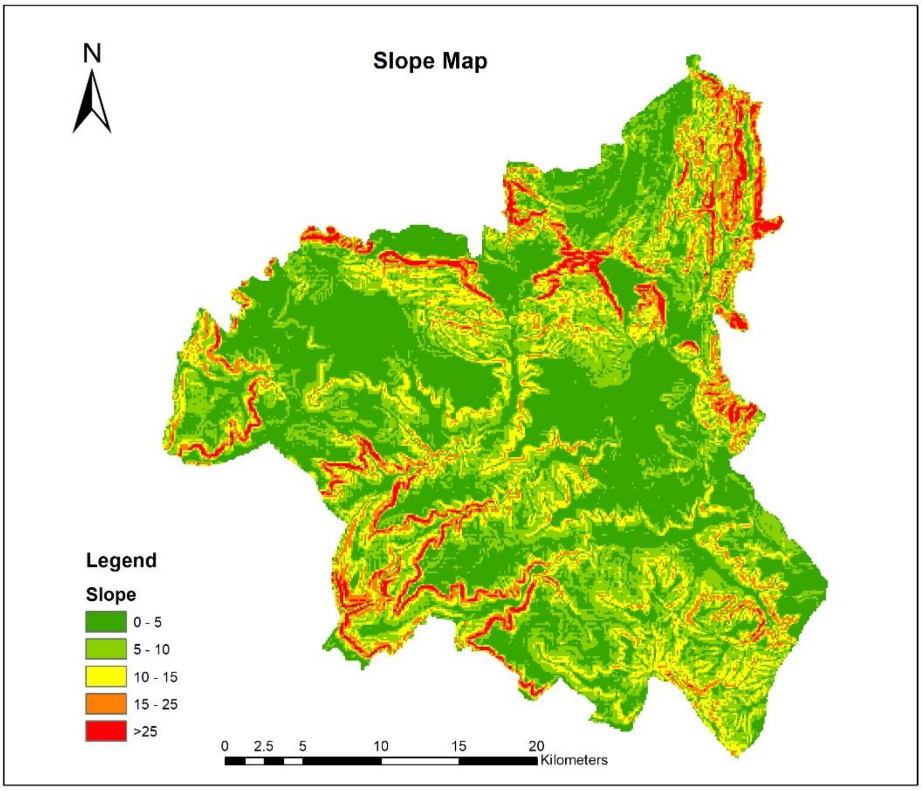


Figure 3.3a Slope map of Kilte Awlaelo

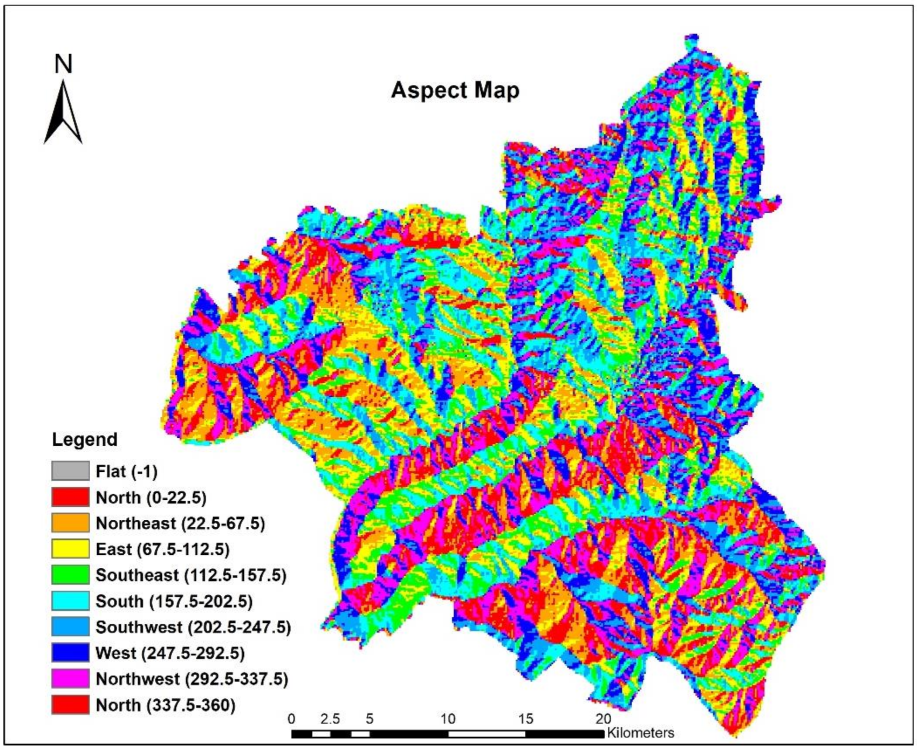


Figure 3.3b. Aspect map of Kilte Awlaelo

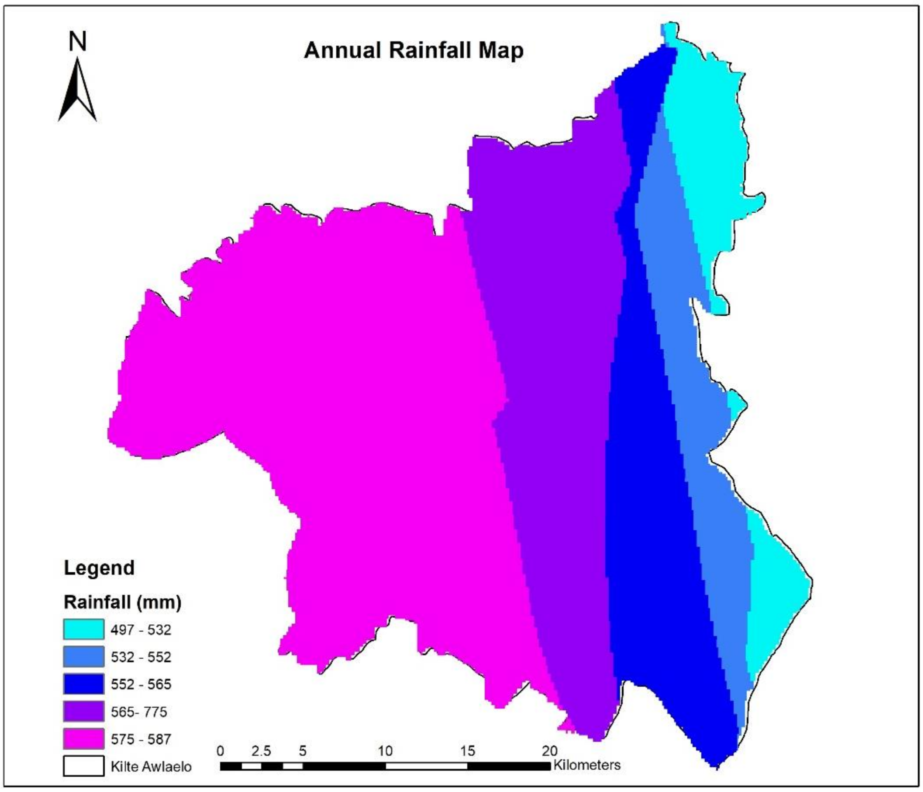


Figure 3.3c Annual rainfall map of klte Awlaelo

$CI = \frac{\lambda - n}{n-1}$……*equation 3. 2*

$CR = \frac{CI}{RI}$ …equation *3.3*

Table 3.2. Ranking relative importance of criteria (Saaty et al., 1980)

Imp. Rank	Definition	Explanation
1	Equal importance	Two criteria enhance similarly the stated goal
3	Slightly significance	Judgments slightly favour one criteria over another
5	Strong or essential importance	Judgments highly affect one against the other
7	Established importance	A criteria established a dominance
9	Absolute or high importance	The evidence favouring one criteria is very likely
2,4,6,8	Intermediate values	
Reciprocals	If criteria i is assigned a number relative to j, criteria j will then be assigned the reciprocal	

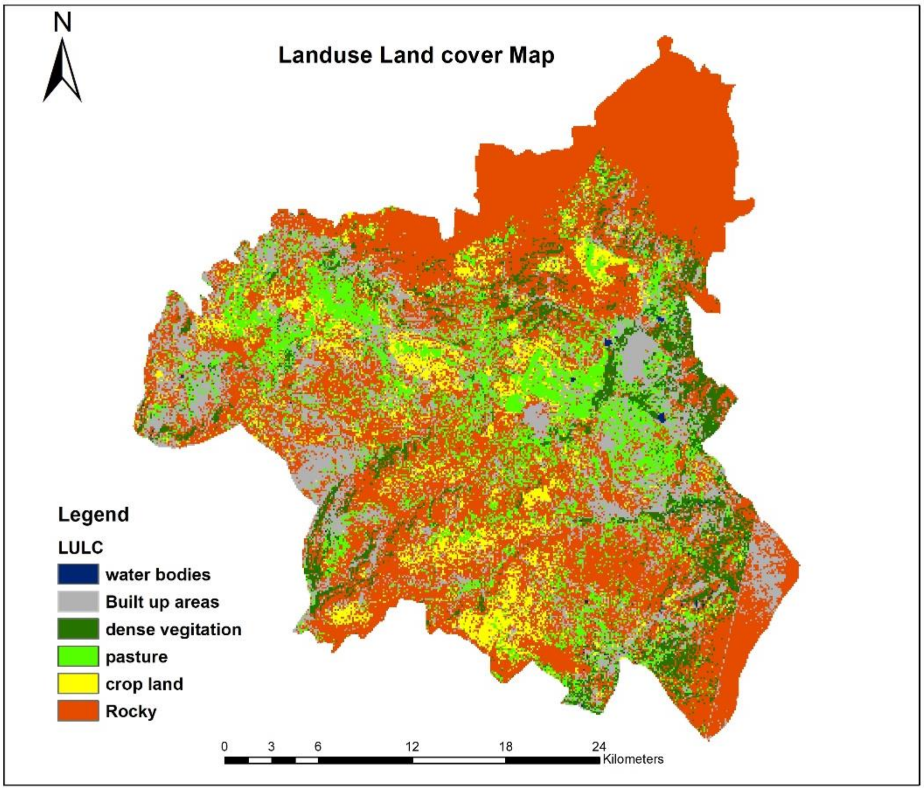


Figure 3.3d. Landuse/land cover map of Kilte Awlaelo

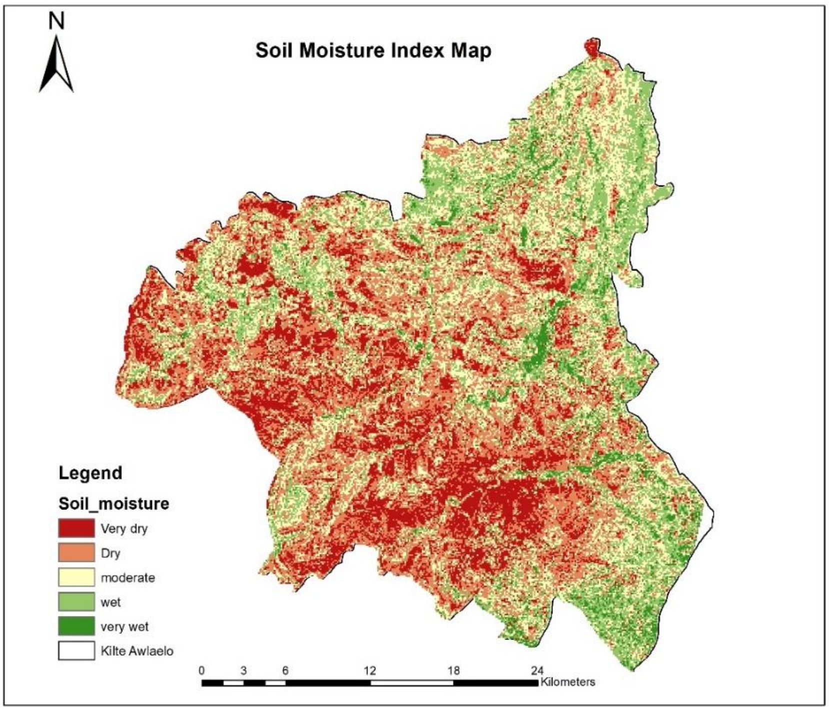


Figure3.3e.Soil moisture map of Kilte Awlaelo

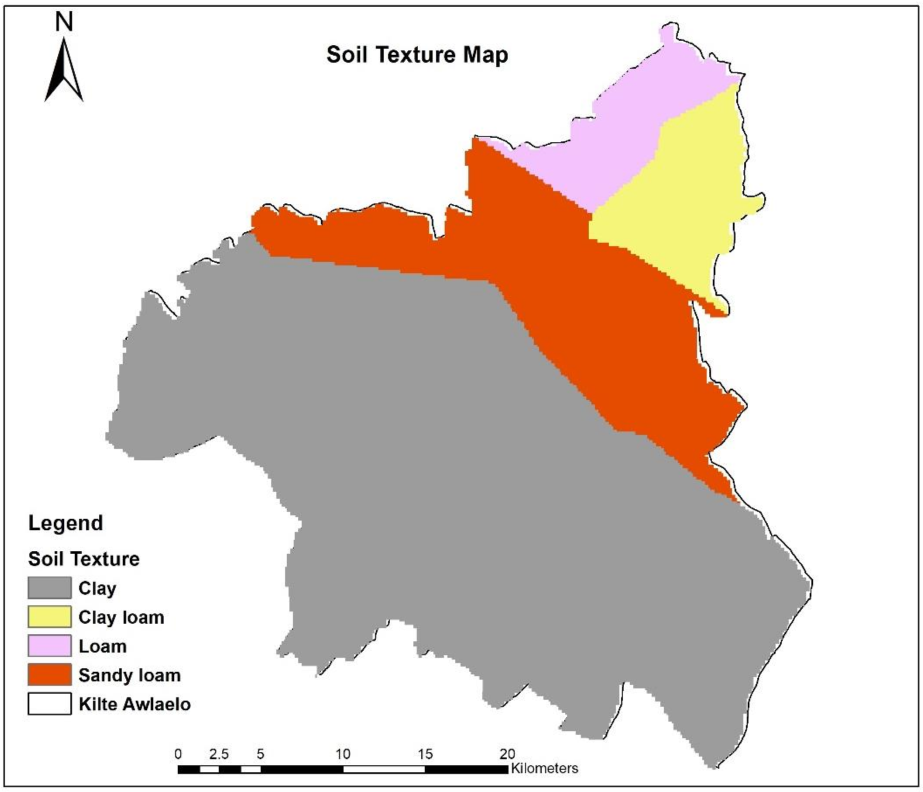


Figure3.3f. Soil texture map of Kilte Awlaelo

3.2.6 Site suitability Analysis

Weighted overlay analysis was applied for the RWH suitability analysis in ArcGIS 10.4.1 (Figure 3.2). It is a widely used technique for site suitability modelling across various domains (Ibrahim et al., 2019; Mahmoud & Alazba, 2015). All criteria were standardized to same cell size and coordinate system after inserted to WOA along with their % influence calculated from AHP. criteria were incorporated into WOA, along with their respective weights derived from Analytic Hierarchy Process (AhP). Additionally, sub-criteria or attribute classes in each criterion map were assigned score values ranging from 1 to 9 based on their significance for rainwater harvesting (Table 3.5). Ranking of the criteria was done considering their suitability for micro catchment RWH and macro catchment RWH respectively. Following the ranking of all sub-criteria accordingly (refer to Table 3.6), the WOA model was executed, resulting in the generation of a rainwater harvesting suitability map (Debebe et al., 2023).

$$S = \sum_{i}^{n} WiXi \dots . eqation\ 3.4$$

Where *S= suitability,* W_i*, =weight of each criterion,* X_i *= weight of sub criterion, n = number of criteria*

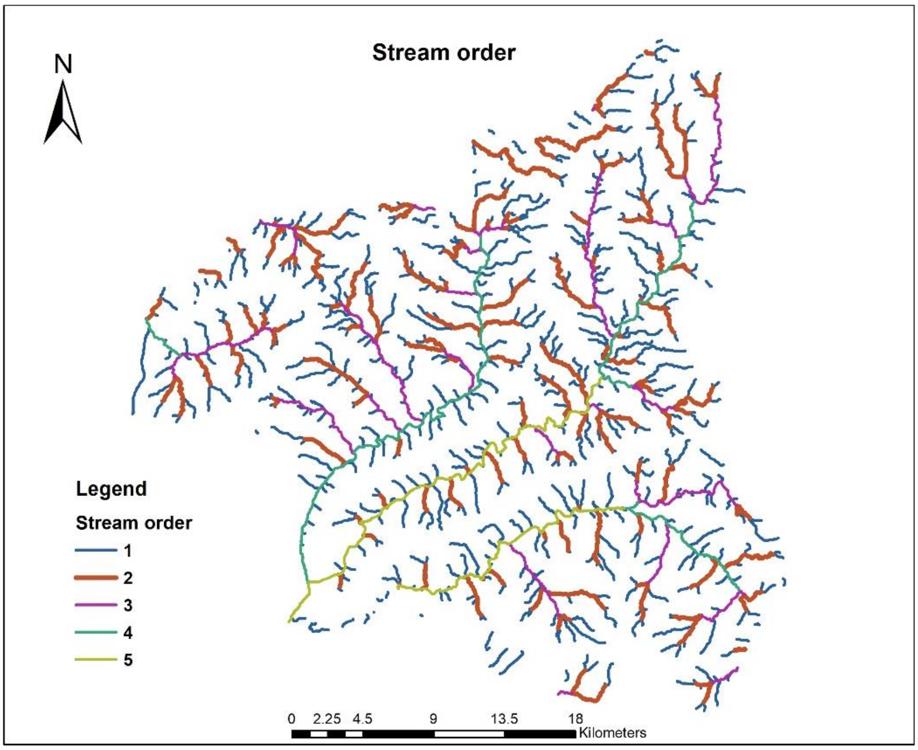


Figure 3.3g. Stream order map of Kilte Awlaelo

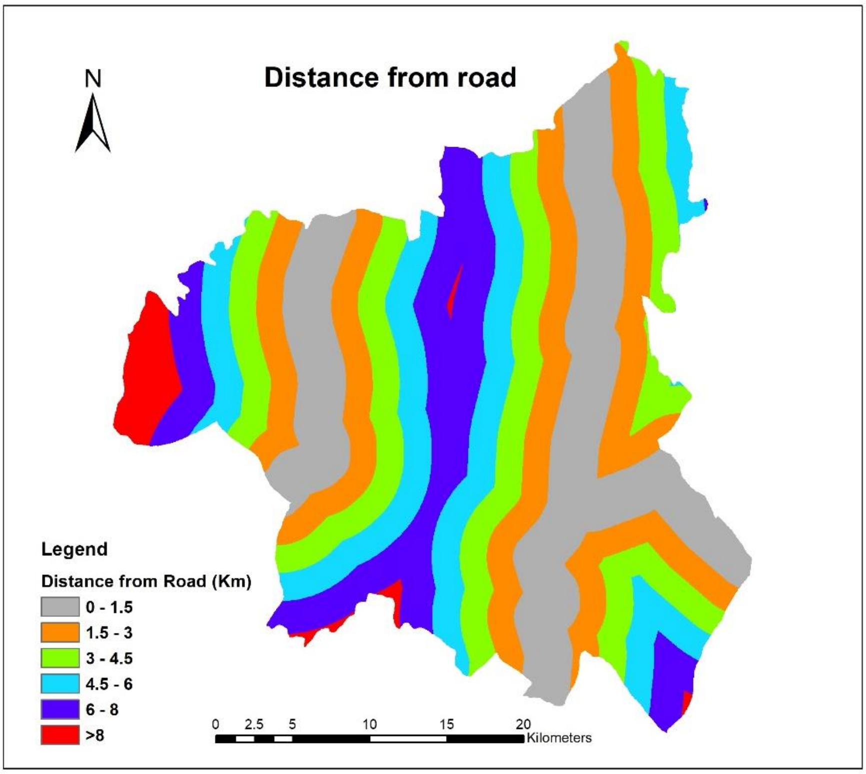


Figure 3.3h.Distance from road Map of kilte Awlaelo

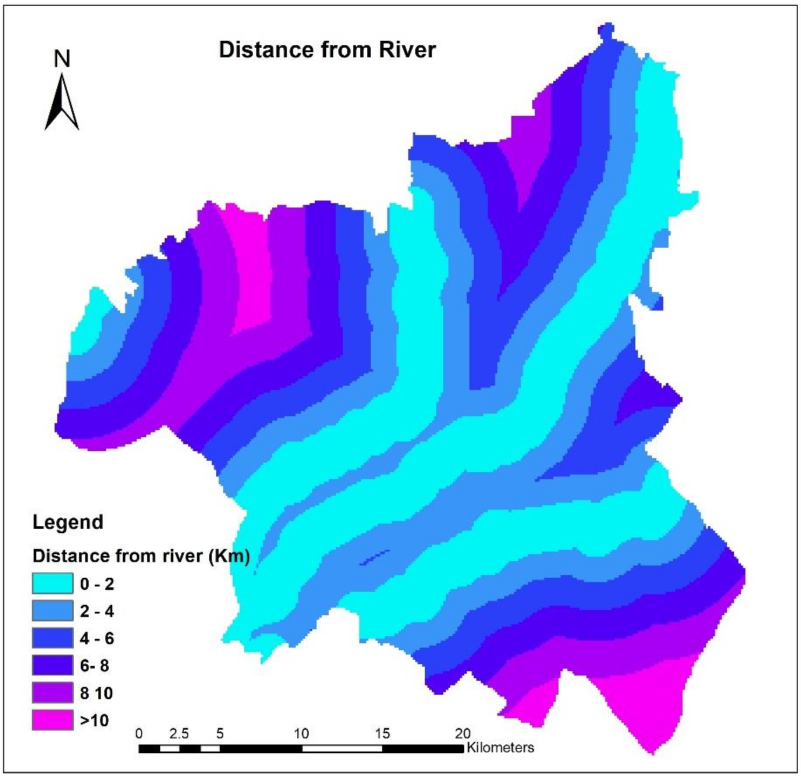


Figure 3.3i.Distance from river map of Kilte Awlaelo

3.2.7 Sensitivity analysis

For sensitivity analysis, two cases were considered. In the first case, the weights computed from AHP were used as % influence which give more weight to the bio physical factors than the socio economic factors. In case 2, all the 9 criteria received equal weights assigned automatically by the WOA. RWH suitability maps from the two cases were compared to see the influence of criteria weight on suitability assessment.

Table 3.3 Pair- wise comparison matrix

Criteria	**Rainfall**	**Soil texture**	**Soil moisture**	**Slop**	**Aspect**	**Stream order**	**LU LC**	**Dis_road**	**Dis_river**
Rainfall	1	3	3	5	4	5	5	7	7
Soil texture	1/3	1	3	3	4	7	3	3	3
moisture	1/3	1/3	1	2	3	5	3	3	5
Slope	1/5	1/3	½	1	2	2	2	3	3
Aspect	¼	¼	1/3	1/2	1	3	2	3	3
Stre.ordr	1/5	1/7	1/3	1/2	1/3	1	1	3	1
LULC	1/5	1/3	1/3	1/2	1/3	1	1	5	5
Dist. road	1/7	1/3	1/3	1/2	1/3	1/5	1/5	1	1
Dist. River	1/7	1/3	1/3	1/3	1/3	1/5	1/5	1	1

Table 3.4 Normalized matrix for weighing criteria

Criteria	**Rainfall**	**Texture**	**moisture**	**Slope**	**Aspect**	**St.order**	**LULC**	**Dis_road**	**Dis_river**	**Weight (%)**
Rainfall	0.357	0.496	0.334	0.379	0.261	0.204	0.287	0.241	0.241	31
Soil.texture	0.118	0.165	0.334	0.227	0.261	0.286	0.172	0.103	0.103	20
moisture	0.118	0.054	0.1115	0.151	0.195	0.204	0.172	0.103	0.172	14
Slope	0.071	0.054	0.057	0.075	0.130	0.081	0.114	0.103	0.103	9
Aspect	0.089	0.041	0.036	0.037	0.065	0.122	0.114	0.103	0.103	8
Str. order	0.071	0.023	0.036	0.037	0.021	0.041	0.057	0.103	0.034	5
LULC	0.071	0.054	0.036	0.037	0.021	0.041	0.057	0.172	0.172	7
Dist. Road	0.051	0.054	0.036	0.025	0.021	0.008	0.011	0.034	0.034	3
Dist. River	0.051	0.054	0.015	0.025	0.021	0.008	0.011	0.034	0.034	3

$\lambda = 9.87$, $CI = 0.108$ $RI, = 1.45$ $CR = 0.074$

Table 3.5 Areal coverage of criteria and sub criteria for input to weighted overlay suitability model

Criteria	Sub criteria	Area _Km^2	Area (%)
Slope-0^0	0-5	432.1	43
	5-10	288.5	29
	10-15	163.68	16
	15-25	81.92	8
	>25	3.21	3
Aspect- 0^0	Flat,North	206	21
	East	194	19
	SE,SW	204	20
	West	187	18
	N.West	210	21
Annual Rainfall(mm)	497-532	460.2	46
	532-552	233.9	23
	552-565	147.9	15
	565-775	89	9
	575-587	70.15	7
LULC	built-up area	178	18
	Dense vegitation	78.16	8
	Pasture	146.95	15
	Crop land	74.23	7
	Mountainous	521.7	52
Soil texture	Loam	55.6	5.5
	Sandy loam	189.51	19
	Clay loam	66.4	6.6
	Clay	690	69
Moisture Index	Very dry	193.66	19
	Dry	317.84	32
	Moderate	267.93	27
	Wet	174.36	17
	Very wet	45.59	6

Stream order	1st	338	33
	2nd	142	14
	3rd	63.5	6.3
	4th	439	43.3
	5th	30.5	5
Dist to Road (Km)	0-2	354.2	35
	2-4	291.3	29
	4-6	228.2	23
	6-8	110.9	11
	>8	16.16	1.6
Dist to River(Km)	0-1.5	331	33
	1.5-3	265	27
	3-4.5	196	19
	4.5-6	147	15
	>6	61	6

3.2.8 Model validation

Ones the RWH map was generated, its accuracy was checked through field visits and ground truth on google earth pro and ARC map (Fig 3.5). Due to the large size of the catchment (1000 square kilometres), one sample village (Abraha Atsbeha), was chosen as a representative to assess the model accuracy selected due to the presence of multiple soil water management structures (M. Haile & Gebregziabher, 2020)

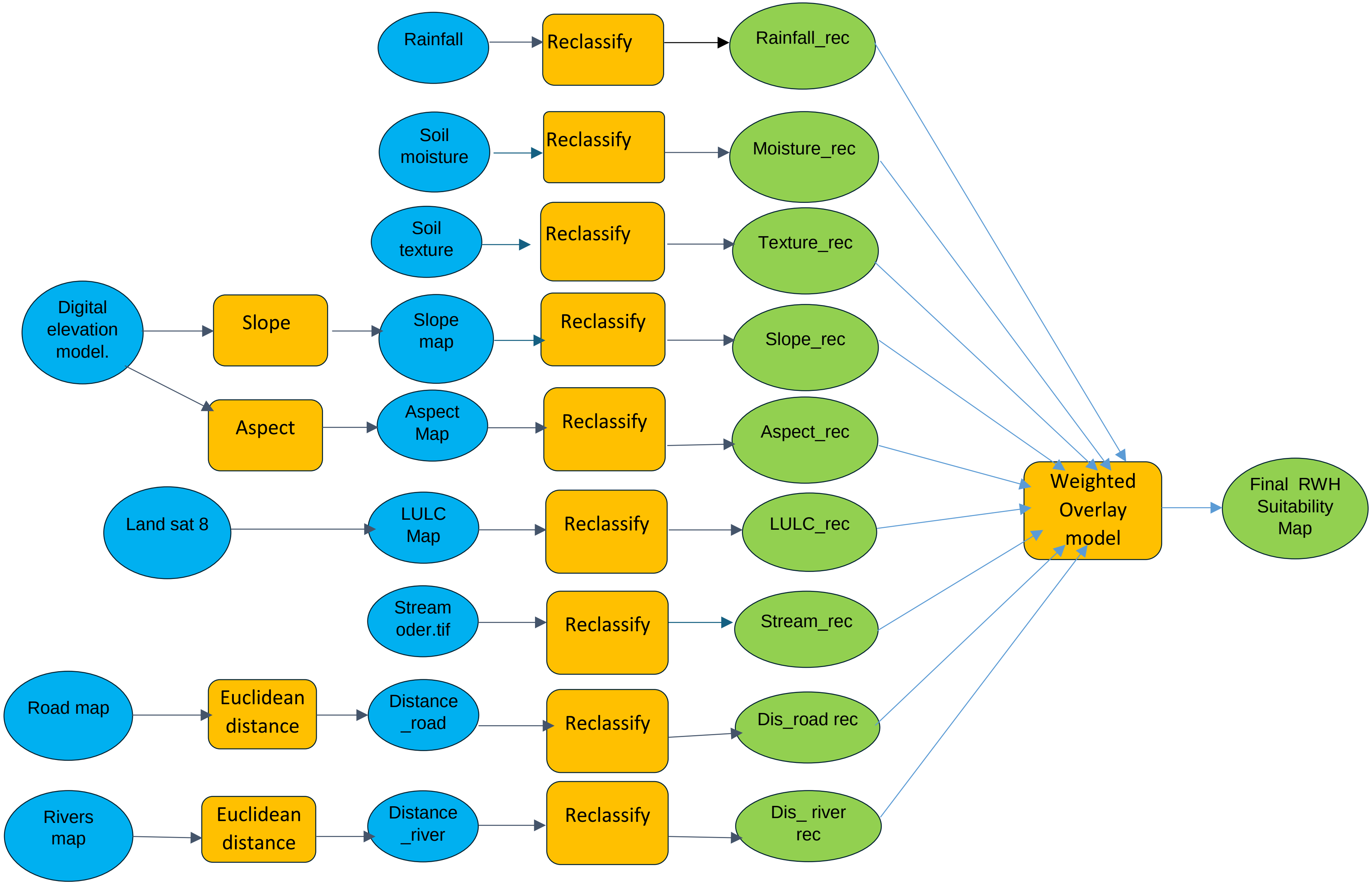


Figure 3.4 Developed Weighted over lay model for identifying optimal rwh areas(Debebe et al., 2023)

3.3 Result

Based on the computed analytical Hierarchy Process (AHP), highest weight was assigned for precipitation (31%), followed by soil texture, soil moisture, slope, aspect, stream order, and land use/land cover. Distances to road and river received lower weights (3%). The consistency ratio (CR) of 0.074 (<0.1) indicated the weighting criteria was unbiased. In the catchment, six land cover types were identified, aligning with a prior study. Accuracy assessment using the Kappa coefficient method yielded 72%. Dominant soil textures were clay (68%) and sandy loam (19%). The topography was mostly rocky, with 3.23% gentle slopes and 43.23% steep slopes (Tadesse, Gebrelibanos, & Geberehiwot, 2016). The aspect map indicated slopes facing south to southwest were gentle slopes and get steeper toward northeast to east. Stream order showed a decline, indicating fewer branched streams. Rainfall ranged from 581mm (46%) to 497mm (7%). The moisture index revealed 50% dry, 27% moderate, and 23% wet areas. Accessibility varied, with 35% within 0-2 km, 29% within 2-4 km, 23% within 4-6 km, and 12.6% over 6 km, indicating less RWH suitability. River accessibility was mainly within 0-4.5 km, with 20% at more than 4.5 km. The WOA suitability model for Case I yielded four Suitability classes with 56% suitable, 8.6% highly suitable, and 30.8% moderately suitable areas for RWH I (Fig 3.6). For Case II, similarly 37.6% suitable, 50.5% moderately suitable, and 8.6% less suitable areas were produced (Fig 3.7).

Table 3.7. Identified suitable rwh sites for case I & Case II with their Area coverage (Debebe et al., 2023)

RWH site suitability	(**Km^2**) **Case (I)**	**% Case(I)**	Area (**Km^2**) **Case (II)**	**% Case(II)**
Highly Suitable	85.27	8.6	22.4	2.27
Suitable	550.75	56	372.5	37.6
Moderately suitable	303.23	30.8	504.7	50.5
Less suitable	43.87	4.46	85.9	8.6

The results from model validation revealed 17 bench terraces, 6 shallow hand-dug wells, and 3 exclosure areas (protected zones used for soil and water conservation) Fig 3.8.Up on cross checking their specific locations on the suitability map, 8 bench terraces were on moderate areas, 6 on suitable areas, and the remaining 3 on less suitable areas. Two of the shallow wells were found in moderate areas, and four on suitable classes. All exclosure areas were under the suitable class, established through community-based water harvesting and watershed management programs (Tadesse, Gebrelibanos, & Geberehiwot, 2016).

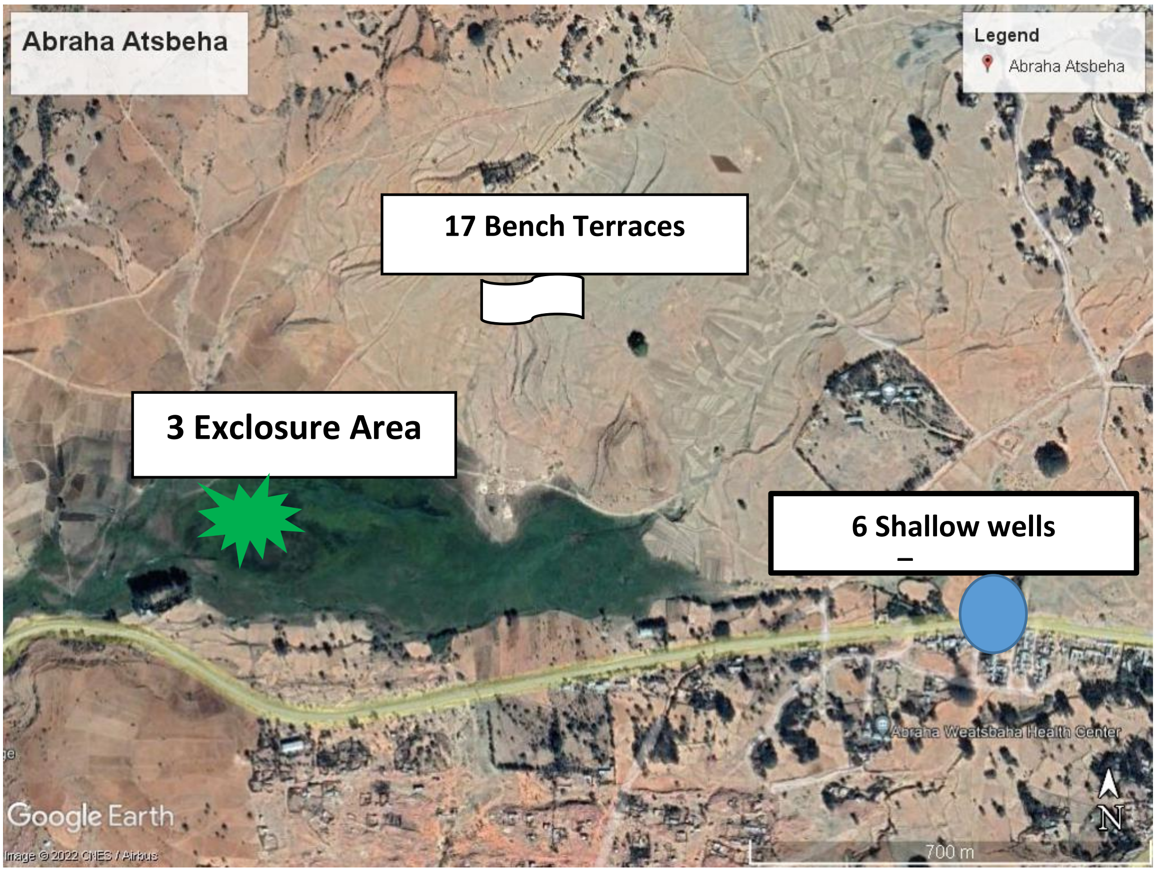


Figure 3.5.Visualization of the suitability model using high-resolution google earth images at Abreha Atsbeha sample site

3.4 Discussion

In analysing the attributes of each criteria map and sub-criteria, the area can be categorized a typical semiarid climate, mountainous topography with limited arable land and water resources, which aligns with (Ahmed Harb Rabia, 2012; B. M. Haile & Merga, 2002). Biophysical and socioeconomic factors were crucial in RWH suitability analysis. The assigned weights indicated varying significance levels among selected criteria, with biophysical factors proving more influence than socioeconomic. RWH suitability map in Case I, (with AhP), revealed significant changes in suitability classes compared to Case II (without AHP).

According to the suitability map, more suitable areas were present downstream similar to the study by (Adham et al., 2018) . Highly suitable areas are most convenient for RWH ponds and shallow wells because they are situated on the lower slope ranging from flat to gentle and concentrate sufficient water during rainy season. RWH Ponds (usual size 200 – 500 m^3) collect runoff water from sloppy areas can serve as alternative water resource (Mati, 2020). Ponds can be used for irrigation, livestock and for domestic purposes.

Suitable areas comprised around 50% of catchment with croplands, pastures and mountains being major landuse types. In situ /micro catchment RWH techniques use the soil profile as storage and are suitable for areas with low to medium slopes (Oweis et al., 2012). Examples included RWH pits, stone bunds, and terracing. These techniques are cost-effective, easily replicable, and allow farmers full control over installed systems. In situ RWH prevent runoff, promote slow infiltration, and are relevant in areas where irrigation is challenging. Moderate suitable areas, characterized by densely vegetated and build-up areas, favors macro catchment/Ex situ RWH such as check dams and sand dams (Mati, 2020). These structures can prevent water scarcity and soil erosion but are both labour and resource intensive. Expanding community-based RWH could address these challenges and bring communal benefits.

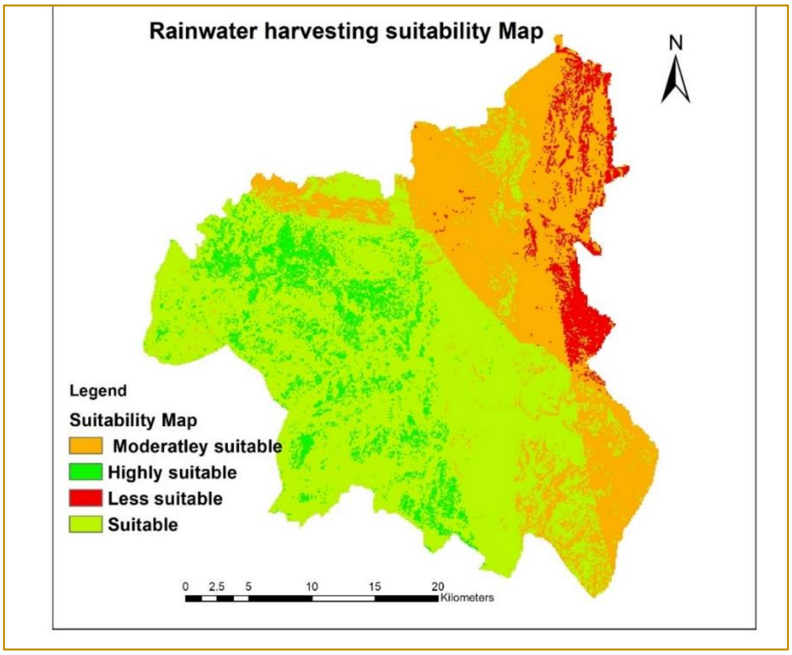


Fig 3. 6. Final rainwater harvesting suitability Map for case I

Moderate rainwater harvesting (RWH) suitability was observed in areas with significant vegetation (shrubs) and limited built-up regions. Various soil textural classes were present, with sandy loam being the dominant soil type, likely resulting from the weathering of parent material rocks. This dominance of soil types enhances infiltration rates due to their high permeability (Haregeweyn et al., 2012). These areas extend from undulating to rolling slopes upstream and the Siluh River downstream (Tadesse et al., 2017). Excessive runoff from steep slopes descends to flat areas. Macro catchment RWH techniques, such check dams(Djuma et al., 2017), underground storage, subsurface dams, and sand dams can be installed in such areas to address water scarcity and soil erosion (Mati, 2020). Sand dams offer an alternative underground water storage. They involve constructing reinforced concrete walls across a sandy riverbed, with the goal of allowing water to infiltrate and be stored underground during periods of seasonal water flow (Mati, 2020). The stored water can be extracted through the construction of shallow wells, boreholes, or a collector drain along the dam (Debebe et al., 2023).

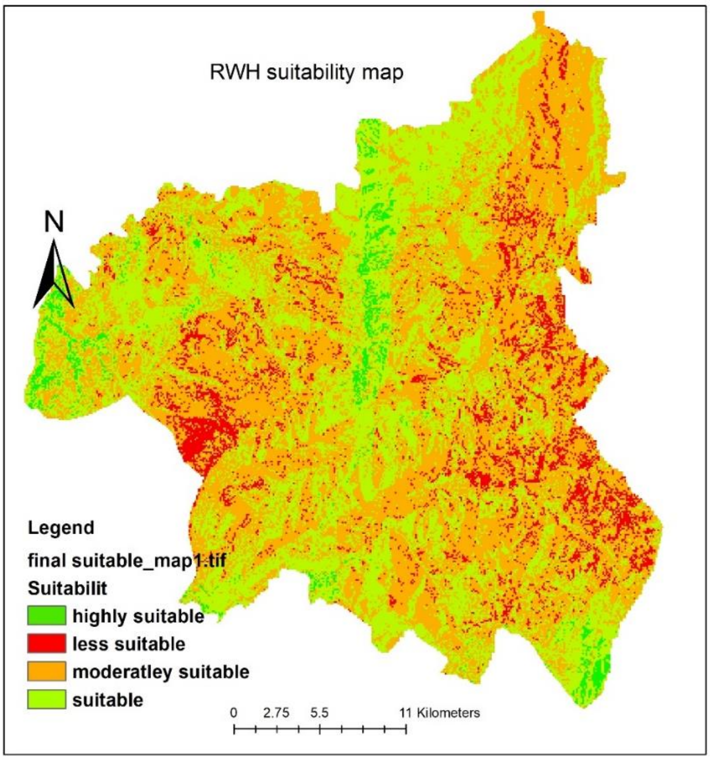


Fig.3.7 Final rainwater harvesting suitability map for Case II

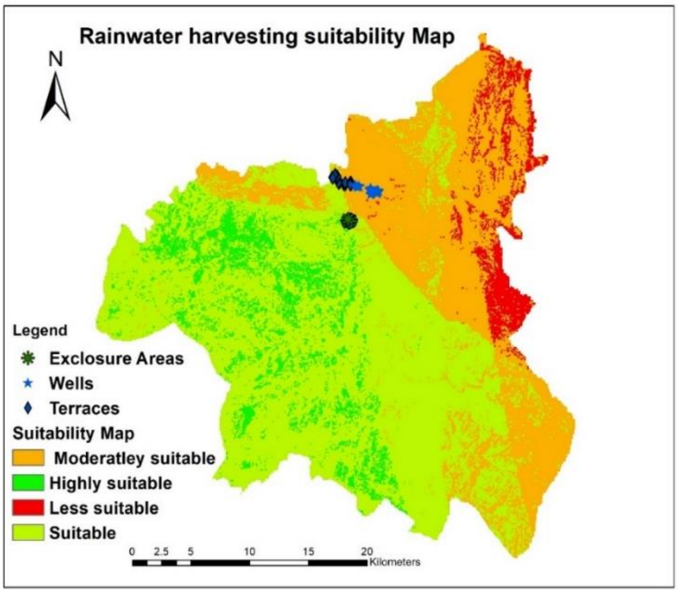


Figure. 3.8 validated suitability map (Debebe et al., 2023)

3.5 Conclusion and Recommendation

The WOA suitability model categorized the catchment into four suitability classes: highly suitable (8.6%), suitable (56%), moderately suitable (30.8%), and less/poorly suitable (4.46%). Model validation was conducted through field surveys and ground truth verification using Google Earth imagery and topographic maps in ArcGIS. The locations of RWH structures, such as bench terraces, shallow wells, and exclosure areas, were identified in the suitable areas. The RWH suitable site analysis model included a wide range of biophysical and socioeconomic criteria compared to existing literature. The study emphasized the significance of geographic information systems and remote sensing data in RWH suitability analysis, presenting them as valuable decision-making tools for large-scale assessments. The findings suggest the potential for applying this approach to expand RWH techniques, both in-situ and ex-situ, to areas with similar agroecology. Further RWH site suitability assessment should include more socioeconomic criteria and should compare the various available RWH site suitability models in terms of cost, simplicity and model accuracy in order to select the optimum suitability model for subsequent use.

Chapter 4. Gis Based Runoff Estimation using Soil Conservation Service Curve Number- SCS CN method

4.1 Introduction

Most of the rain in semi-arid areas is lost through surface evaporation (60%) and runoff with only little left to recharge rivers and ground water (Rockström & Falkenmark, 2015). Small scale farmers often with income and resource constraints cannot easily access irrigation because of the undulating topography and the associated pumping costs (Rockström & Falkenmark, 2015). One mechanism for the way forward is harvesting runoff water which retains green water where it falls through structuring and modifying farmlands (Dieter Prinz & Malik, 2002). Runoff estimation is thus important to facilitate water harvesting programs. Water availability assessment at catchment level is determined by quantifying runoff generated in the catchment (Welderufael et al., 2012). A catchment is defined as a combination of hydrologic and ecological unit comprising interrelated parts and functions (Luxon & Pius, 2013).

Prior to conducting soil and water conservation structures, runoff estimation should be the primary step as it is useful for assessing water potential of a basin or catchment. Once the generated runoff is estimated, it becomes simple to design and adopt the number and type of RWH techniques (Welderufael et al., 2012). The amount of runoff generated depends mainly on rainfall characteristics including intensity, distribution, duration, frequency of rainfall and catchment characteristics such as soil type, elevation, slope, catchment type, land use land cover and soil moisture (A. R. Buda, 2013; Gajbhiye & Mishra, 2012). Runoff is on one hand a good source for stream recharge and on the other hand is the main source of soil erosion. In this case conserving runoff through in situ water harvesting becomes a viable option. It has a multiple benefits including reducing soil erosion, reducing sedimentation and the effect of flooding downstream (Wubetu, 2016).

4.2 Factors affecting Runoff

Runoff is a part of the rainfall, which is discharged in to streams by surface and subsurface flow (Ramke, 2018). During precipitation, trees and plants intercept a portion of the rain; another part is stored on the ground surface, which eventually either infiltrates or evaporates to the atmosphere (David et al., 2005; G. Li et al., 2019). Depending on the type and moisture status of the soil, certain amount is absorbed by soil and later percolates to water table. When rainfall is beyond infiltration rate, water begin to concentrate as surface detention, later flows to nearby overland, and is called surface runoff (Hümann et al., 2011). Based on their type of flows, the USDA hydrology classifies run off as surface flow, Inter flow, and Base flow(Mishra & Singh, 2003; Weyman, 1975). Surface flow occurs when water that is held on a surface flows over land; Inter flow occurs as water penetrates the top soil layer and flows laterally downstream with the help of impermeable zones which blocks further percolation (A. R. Buda, 2013; Usda, 1986). Such flow is typical in vegetative mountainous areas where there exist impervious surface and the falling leaves and litter facilitate infiltration of water. Base flow occurs when water flows from a drenched ground water section downstream where the waterway elevation does not exceed ground water table (Mo et al., 2021). When estimating run off, it is essential to obtain data for as many years as possible due to temporal and spatial variability of runoff.

Runoff is influenced by multiple interrelated factors, including topography, soil type, soil moisture, land cover, rainfall characteristics, and Catchment features all contribute to spatial and seasonal runoff variation(Anthony R Buda et al., 2009). Intense rainfall at the beginning, favours infiltration until the soil layer gets saturated. After that, soil aggregates become scattered to eventually form a surface crust that let the water accumulate in puddles and spill over the soil surface (A. R. Buda, 2013). Run off formation can be caused by either saturation excess or Infiltration excess (Woyessa & Bennie, 2004). The former occurs if rainfall intensity exceeds infiltration capacity while the later happens once the soil become water logged and can no longer store additional rainfall. According to a research on small agricultural catchment, runoff generated by saturation excess were produced by frequent but less intense rainfall, while runoff generated by infiltration excess were produced by infrequent, high intense summer rainfall (Anthony R Buda et al., 2009).

Rainfall duration is also another variable that directly affects volume of runoff. The more the rainfall duration, the less infiltration and the higher runoff generation (Oweis et al., 2012). Catchment area , slope, topography, and vegitation cover are other factors affecting runoff formation (Wubetu, 2016). The smoother the surface, the more the runoff where as the more rugged the surface, the less runoff it becomes; similarly, higher slope results in more runoff because the flow of water from hill area forms vast amount of erosive energy(A. R. Buda, 2013). Land cover of the area mainly vegitation cover reduces runoff by intercepting the precipitation thus allowing sufficient time for infiltration (Shi et al., 2009). Soil moisture at the start of precipitation also influences the rate of infiltration and runoff (Del Giudice et al., 2012). According to soil conservation service (Usda, 1986), soil permeability is a function of hydrologic soil condition that categorizes soils in four groups: Hydrologic soil group A, B, C, and D corresponding to high, moderate, low, and very low infiltration respectively. Each HSG groups are a function of curve number, soils maximum retention capacity, and types of land use/land cover (Del Giudice et al., 2012).

The Soil Conservation Service Curve Number (SCS- CN) which is developed by the United States department of agriculture is widely accepted method for the estimation of direct runoff due to its low input data requirements and simplicity(Zheng et al., 2018) . Data needed for this are spatial data sets, rainfall data, Soil type; soil texture and land cover data. It is applied in many watershed models such as SWAT(Shi et al., 2009). The use of SCS CN curve number helps to accurately estimate runoff which is important for implementation of RWH structures(Zheng et al., 2018). This method is mostly used for small agricultural catchments and it is selected because it considers all factors affecting runoff such as hydrologic soil group, land use, hydrologic condition, and moisture condition. Therefore this section discusses a Gis based runoff estimation in eastern Tigray using soil conservation service curve number (SCS- CN) method.

4.3 Material and methods

4.3.1 Data acquisition and processing

Digital elevation model file was extracted from United States National Aeronautics and Space Administration (NASA) earth data portal (https://search.earthdata.nasa.gov) of ASTER Global digital elevation model, with a 30m spatial resolution. The landsat8 image was extracted from (https://earthexplorer.usgs.gov/). A national map shape file was extracted from a free Gis software www.diva-gis.org. The catchment boundary was extracted from the region Map. Topographic elevation was extracted by mask from digital elevation model in Arc Gis (*for details and sources see section 3.2.2*). The size of downloaded free spatial datasets such as Aster dem, landsat8 and soil map was reduced to fit to the sub catchment boundary layer through rastor processing in the Arc GIs data management tool. The schematic diagram of all the process steps for estimating runoff potential is illustrated in (*Fig. 4.1*).

4.3.2 SCS CN curve number Model

Soil conservation service curve number - SCS CN model was primarily originated in USA and later became a popular method to predict runoff in small catchments (0.25 ha – 10^3 km^2) (Jan Nyssen et al., 2010). It is a curve number method that determines the effect of land surface conditions/land treatment and land use types on run of generation. It is basically a function of land cover and soil types present in an area which tells the amount of rainfall that infiltrates in to soil and the amount that becomes a runoff (Shi et al., 2009). The amount of runoff is directly proportional to the amount of curve number; high curve number means a high runoff/ low infiltration and a low curve number shows a low runoff /high infiltration (Zhan & Huang, 2004). The SCS curve-number method assumes for a rainfall storm event, the ratio of actual retention of soil following rainfall to maximum retention capacity of soil is the same as the ratio of direct runoff to rainfall. The initial abstraction number (Ia) represents all losses before runoff starts. The losses are interception by vegetation, evaporation, infiltration and water retention in surface depression (Fig *4.1*). After many small agricultural watershed experiments, Initial abstraction (Ia) is assumed as twenty percent of the potential maximum retention after runoff (Ia = 0.2S) (Usda, 1986).This method is used for quick runoff estimation of small catchments (Lalitha Muthu & Helen Santhi, 2015). The equation for SCS- curve number is given in (*equation 4.4)*.It has been widely accepted and used as the method of choice for planning and design of soil and water conservation interventions. The popularity of this method is due to its simplicity, predictability, stability, and its responsiveness to watershed properties affecting runoff (Oweis et al., 2012).

$$\mathrm{Q} = \frac{(\mathrm{P}-\mathrm{Ia})^2}{P+S-Ia} \ldots\ldots\ldots\ldots\ldots \; eq\ldots 4.1$$

Where

Q= Runnoff depth (mm) ,

S = maximum retension after the begining of runoff and ,

Ia is initial abstraction of rainfall (mm)

P is precipitation, substituting Ia= 0.2S in to equation 4.1, we get equation 4.2

$$\mathrm{Q} = \frac{(\mathrm{P}-0.2\ \mathrm{S})^2}{(P+0.8S)} \ldots\ldots\ldots\ldots\ldots eq\ldots.\ 4.2$$

S is related to soil types and land cover condition of the catchment and it is related to CN (equation 4.3). The curve number is a dimension less parameter which is a function of soil texture and soil type based on the United States hydrologic soil group classification, antecedent moisture condition and land cover of the area. It is directly related with the surface runoff. A higher value of curve number implies a high amount of runoff (H Zheng et al, 2018). The Individual curve number is first calculated for every land cover types which are then summed up to obtain a final weighted curve number as in equation 4.4. Many Authors have used the SCS-CN method to estimate runoff in their research(Geena & Ballukraya, 2011; Lalitha Muthu & Helen Santhi, 2015; Luxon & Pius, 2013; Shi et al., 2009; Uwizeyimana et al., 2019; Welderufael et al., 2012; Zheng et al., 2018).

$$S = \frac{25400}{CN} - 254 \ldots\ldots\ldots.\ equation\ 4.3$$

$$\mathrm{CN}= \frac{\sum(CNi*Ai)}{A} \ldots equation\ 4.4$$

Where:

CN = weighted curve number

CNi = Individual curve number

Ai = area of sub catchment for each Land cover types

A = Total area of sub catchment

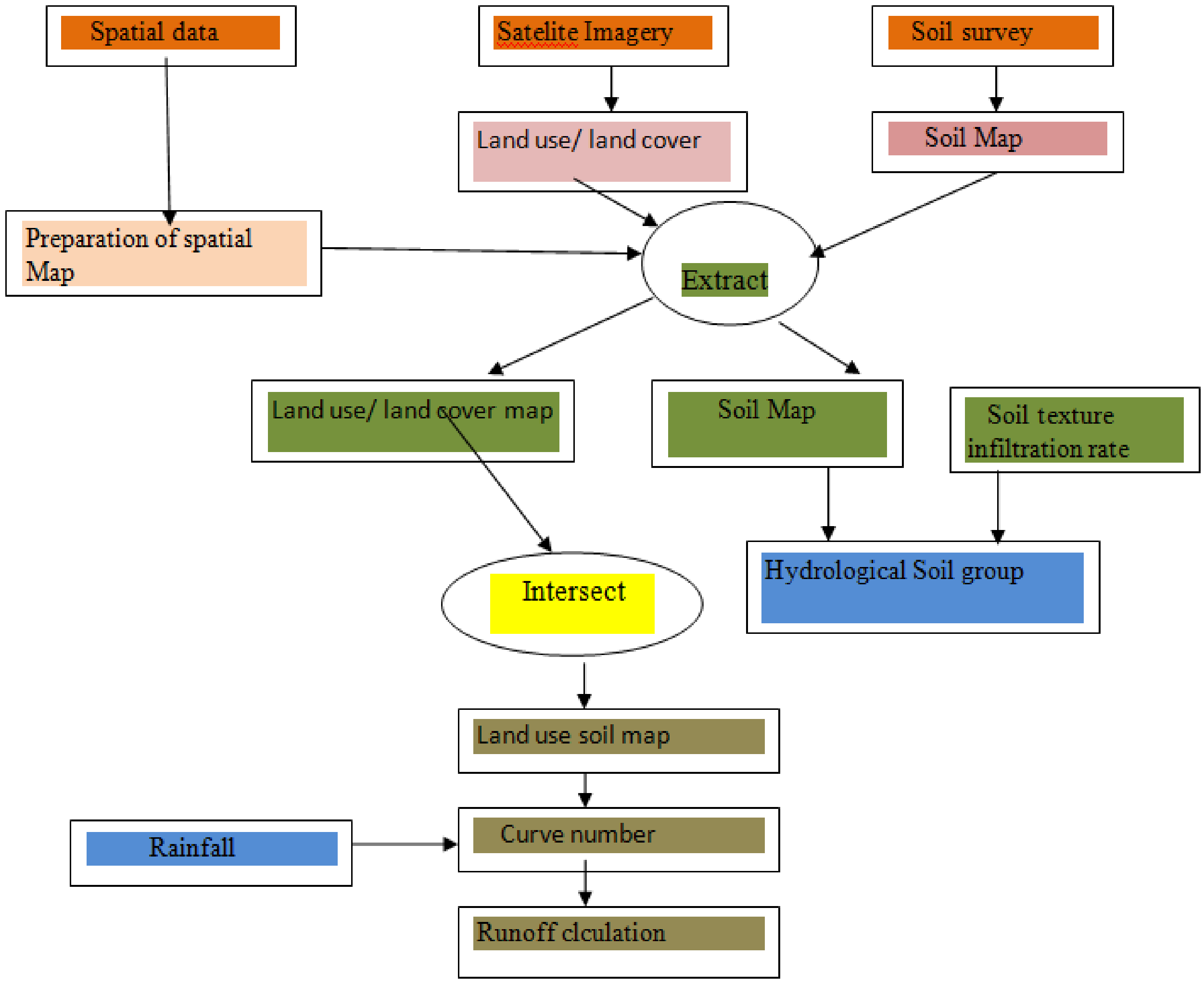


Figure 4.1 process steps for runoff estimation using SCS CN method

4.3.3 Hydrologic soil group

According to their soil texture and infiltration capacity, soils are classified in to four groups as Hydrologic soil groups (A, B C and D). Soil map was extracted from the food and agriculture organization -FAO global soil map for curve number-based Runoff modelling which is freely accessible on the FAO website. The study area had three major soil texture classes namely clay, clay loam, and sandy loam corresponding to soil hydrologic soil group D, C and B respectively.

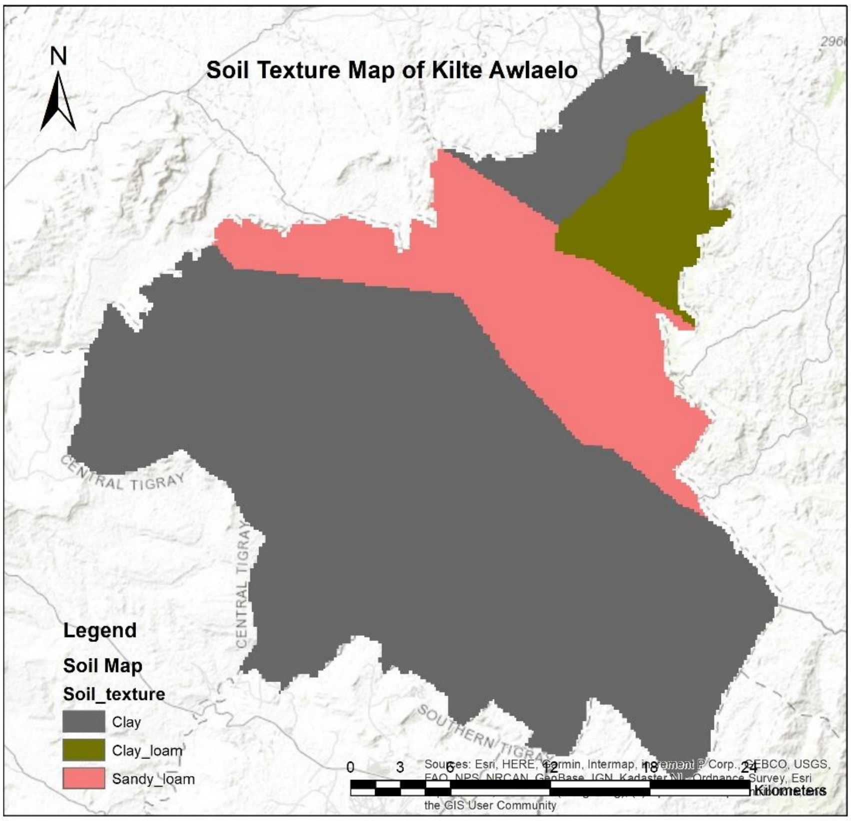


Figure 4.2 Hydrologic soil group classification of Kilte Awlaelo eastern Tigray -Ethiopia

Table 4.1. Hydrologic soil groups (HSGs) and their soil texture classification after (Usda, 1986)

HSG	Soil texture class	Run off potential
A	Sand	low
B	Sandy loam, Loamy sand	Moderately low
C	Clay loam, Silty clay loam, Sandy clay loam, Loam, Silty loam, Silt	Moderately high
D	Clay, Silty clay, Sandy clay	high

4.3.4 Land use Land cover

The study area catchment shape file was extracted from the regional map of Tigray and was georeferenced to the WG 84 reference system in Arc Gis software 10.4.1. The catchment had a total area of 1001Km square. Land use land cover (Fig 4.4) was prepared first by stack layering the different band compositions of Landsat 8 OLI/TIS images using Erdass imagine 2015 software (Tilahun, 2015). The classification was made using supervised maximum likelihood classification. This classification is where the analyst prepares samples of spectral signature of known categories (vegetation, rocky, etc) and the software assigns the pixel values in the image to its most resembling land cover type (Rwanga & Ndambuki, 2017).

Six major categories have been identified via supervised classification (Table 4.3) namely: Dense vegetation containing bush lands and trees (19.3 %), sparse vegetation mainly grazing land (16.5%), crop land , area of land ploughed for growing rain fed crops (20.7%), rocky (30.7%), and bare lands with devoid of plants (12.9%). The accuracy of classified land use land cover was conducted by the method described by (Tilahun, 2015) using ArcGIS and Google earth pro (Fig 4.3). 100 random sample points were created in ArcGIS and were exported in to Google earth pro for ground truth estimation. These were cross checked with the predicted value generated from supervised classified land sat image. An error matrix (Table 4.2) was then generated based on the frequency of class names. The diagonals in table 2 shows class names that are correctly matched with their reference values. An overall accuracy was obtained to be 83.78%.This justifies that supervised classification made was acceptable.

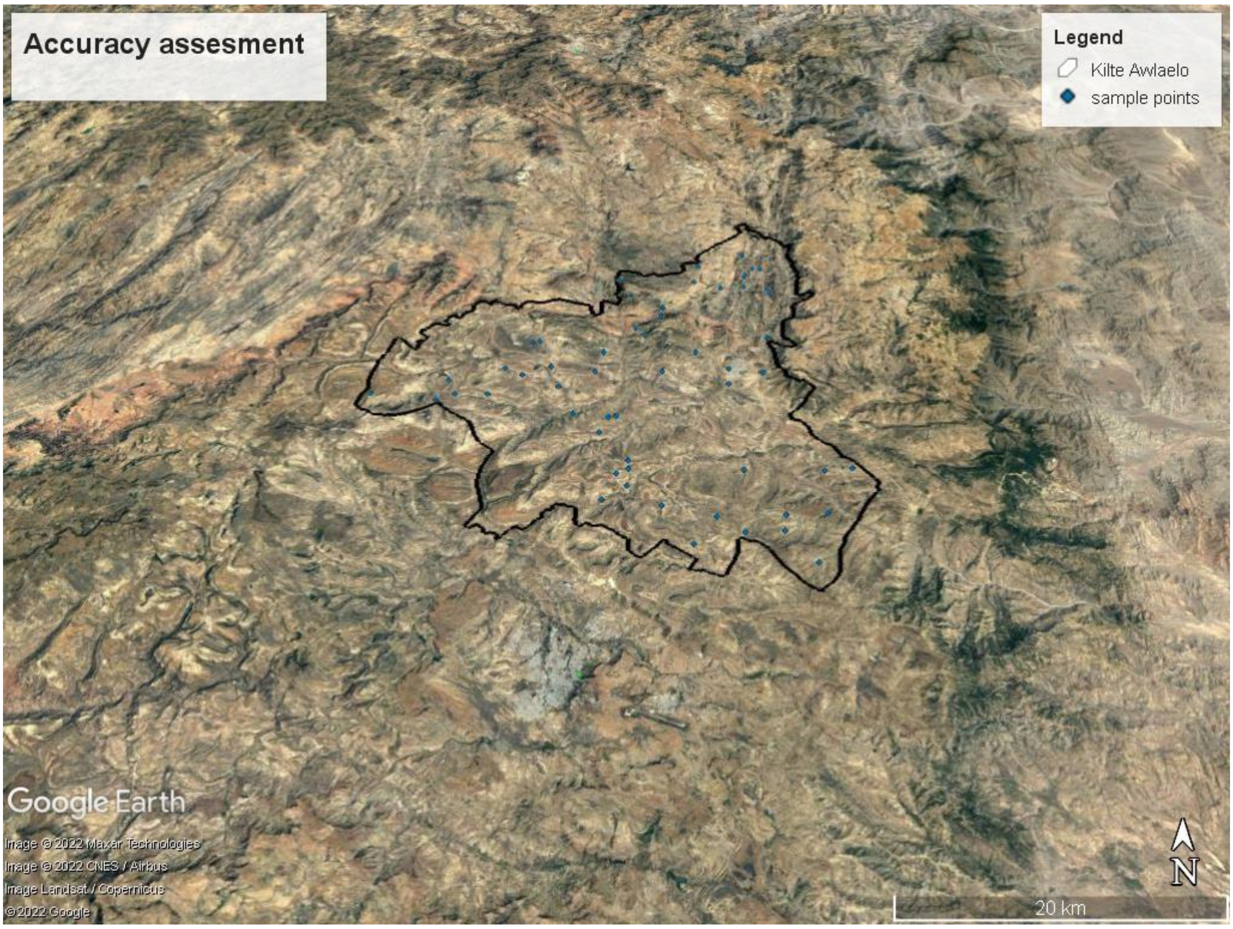


Figure 4.3 Accuracy assessment of produced supervised classification using ground truth (Debebe et al., 2023)

Individual accuracy right end column table 2) = $\frac{Correctly\ matched\ reference\ values}{Row\ total}$ … .eq. 4. 5

1. Dense vegetation = $\frac{8}{8} = \mathbf{100}\%$

2. Pastures= $\frac{4}{6}$= **67%**

3. Crop land= $\frac{8}{11} = \mathbf{73}\%$

4. Rocky= $\frac{7}{11} = \mathbf{64}\%$

5. Built up areas= $\frac{4}{5} = \mathbf{80}\%$

6. Water bodies= $\frac{6}{7}$= **86%**

Overall Accuracy $= \frac{\sum(Diagonals)}{total\ frequeny(total\ sample\ points} \ast 100$, $\frac{(8+4+8+7+4+6)}{48} \ast 100 = 77.1\ \%$ .. Equation 4.6

Kappa coeffient which is another measure of accuracy was also conducted and is calculated according to (Rwanga & Ndambuki, 2017). It measures the level of agreement between the classified values and the reference (ground truth) values.

$$K = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_i + X_{x+i})}{N^2 - \sum_{i=1}^{r}(x_i + X_{x+i})}$$ …………… eq. 4

$$K = \frac{(37\ast48)-[(8\ast10)+(6\ast5)+(11\ast12)+(11\ast10)+(5\ast4)+(7\ast8)]}{48^2-[(8\ast10)+(6\ast5)+(11\ast12)+(11\ast10)+(5\ast4)+(7\ast8)]} = 72\%$$

Where:

r = number of rows and columns in error matrix,

N = frequency (pixels)

Xii = observation in row i and column i,

Xi+ = marginal total of row i, and X+i = marginal total of column i

4.3.5 Antecedent moisture condition

The moisture condition of the catchment is another useful criterion influencing the value of curve number. Based on the moisture condition of soils in the catchment before runoff occurs, the Antecedent moisture condition- AMC is classified in to AMC I, AMC II and AMC III. AMC I represent catchments or basins are dry and the moisture content is at wilting point. AMC III on the other hand stands for areas with a heavy rainfall and soil moisture is at its field capacity. AMC II is the average antecedent moisture condition and this is used for initial curve number estimation. Adjustments to curve numbers are done later according to actual soil moisture condition of the area under study. For this case study, the catchment is a semi-arid with a long dry season which corresponds to AMC I. Therefore CNi (AMC II) were converted to CNi (AMC I) by using interpolation.

4.3.6 Hydrologic Condition

Hydrologic condition is associated with how dense an area is covered with vegetation. It is also linked with the formation and depth of humus, a litter formed from undecomposed leaves, twigs, bark and other vegetative debris. Humus contains a mixture of organic matter and increases with the age of the forest (trees) or other herbaceous. It improves infiltration of soils because of its porous nature(Mishra & Singh, 2003) thus favouring a good hydrologic condition. The hydrologic condition is thus classified as good, fair and poor based on the status of the vegetation cover(Usda, 1986). A poor hydrologic condition refers to an area that is overgrazed and eroded with only little grass cover. A good hydrologic condition is an area with dense vegetation and less runoff. This helps the soil to be conserved and it increases the infiltration rate. A fair hydrologic condition lies in between the two. The catchment in our case study is categorized as poor hydrologic condition.

4.4 Result and discussion

Three dominant hydrologic soil groups: namely HSG B, HSG C and HSG D were identified for the entire area. Areas near water bodies were dominated by sandy loam and falls under category of HSG B. Pastures and crop lands were dominated by clay loam equivalent to HSG C. Dense vegitation, built up areas and steep slopes were dominated by clay or HSG D. Six Landuse types have been identified via supervised classification (table 4) namely: Dense vegetation containing bush lands and trees (7.8 %), Pastures containing mainly grazing land and grasses (14.7%), crop land, area of land ploughed for growing rain fed crops (7.4%), rugged topography (52.2%), and water bodies (1.63%).

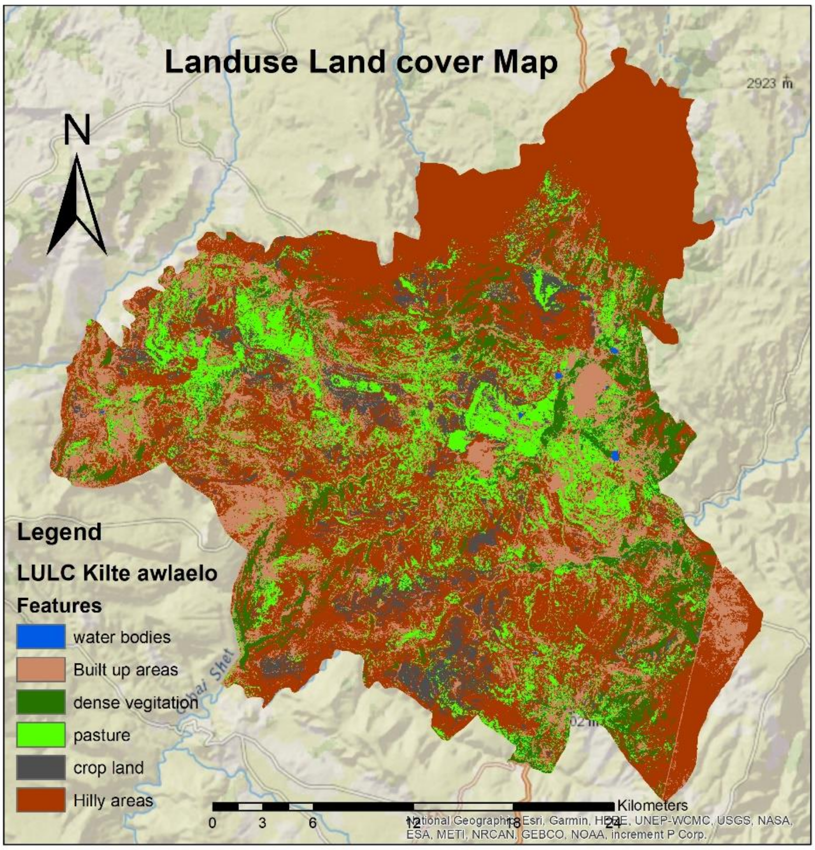


Figure 4.4 land use land cover map of kilte Awlaelo northern Ethiopia

Conducted overall accuracy assessment made showed that classified land cover types were acceptable with overall accuracy 77.1. Similarly, the accuracy assessment using the Kappa quoefficient showed 72% level of accuracy. The amount of run off estimated from 2011 – 2021 showed significant variation among the years. In general the run off volume showed an increasing trend with minimum run off rate (6.76Mm^3/year) obtained in year 2010 and maximum run off rate (54.26 Mm^3/year) obtained in year 2018 followed by 49.26Mm^3 in year 2021 .the annual run off computed (Fig 4.5) showed gradually an increasing trend indicating high rainfall variability. This long-term increase in run off volume can be attributed to the previous massive land degradation and vegitation clearance in the region(Haregeweyn et al., 2012). This supports the hypothesis that runoff has been increasing than ever due to anthropogenic/ human induced factors such as climate change, deforestation, agricultural land expansion which all leads to desertification.

Table 4.3 Different land use types, their area coverage and adjusted curve numbers

ID No	**Feature**	**Area_ha**	Soil Texture	HSG soil group	CNi (AMC II)	Adjusted CNi	(CNi*Ai)
1	Dense vegetation	7816	Clay	HSG D	77	59	461,144
2	Pasture	14695	Clay loam	HSG C	86	72	1,058,040
3	Crop land	7423	Clay loam	HSG C	80	63	467,649
4	Built up areas	17826	Clay	HSG D	86	72	1,283,472
5	Water bodies	163	Sandy loam	HSG B	100	100	16300
6	Steep areas	52172	Clay	HSG D	98	94	4,904,168
Total		**100,096 ha**					**8,190,773**

Weighted Curve number =$\frac{819073}{100,096}$= **82**

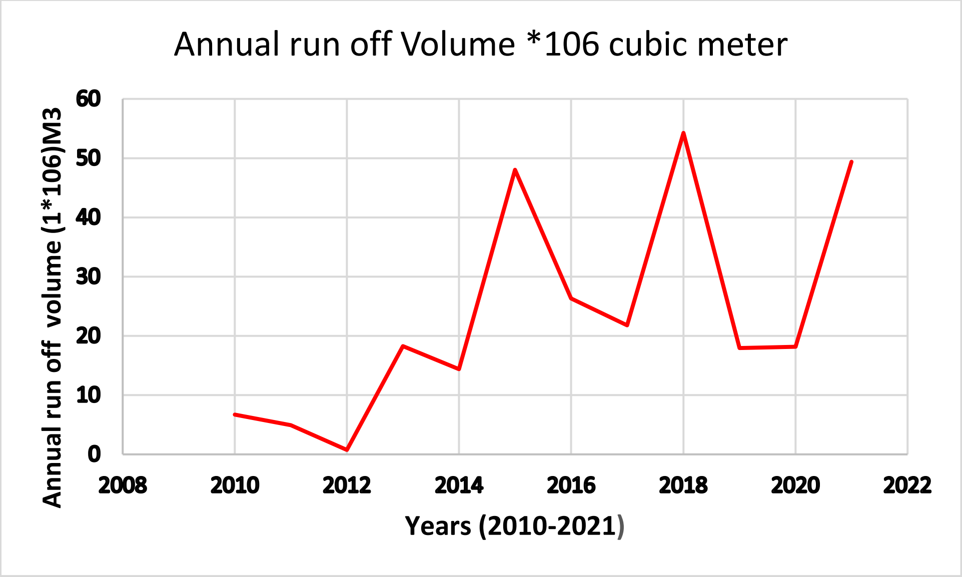


Figure 4.5 Annual runoff volume in Mm^3 2011-2021

The low runoff rate in the last 10 years could imply that the landuse was dominated with vegitation and thus minimal run off was generated. Vegitation cover reduce run off rate by intercepting rainfall through their canopies and their roots. Plant canopy serves as a protective layer that slows down the precipitation (David et al., 2005). The slow movement of water on the surface helps the plant root system to both store and infiltrate the water (Schulze et al., 2019). The roots of plants stabilizes the soil surface and increases soil aggregate stability there by increasing its infiltration rate. In addition to this, Plant cover reduces runoff rates by blocking the water flow. In fact, run off is a complex process which is determined by a multitude of factors such as slope, rainfall, vegetation cover etc. This complexity of run off and vegetation cover is indicated on their correlation, $R_r = e^{-bc}$ (Hugo et al., 2008) where (R_r) = run off and vegitation cover (C) are negatively correlated and b is a constant number that depends on type of vegitation. Rainfall characteristics such as amount of rainfall, intensity and frequency is also another factor that determines run off rate. When comparing the run off rates between 2010 and 2011, there is relatively more frequent and uniformly distributed rainfall in 2010. On contrary, a very high variability in precipitation and limited rainfall amount inducing run off were observed in 2011. As the magnitude of the rainfall variation increases, so will be the run off rate. For example the highest run off rate was recorded in 2018 (54.25 Mm^3).However, there were only five rainfall events recorded on that year that were able to generate runoff. In 2021 where 28 rainfall events recorded, 48.06Mm3 run off was obtained.

This implies precipitation amount is the determining factor for run off followed by rainfall frequency. The frequent variability in rainfall is indication of the semi-arid nature of the prevailing climate (Zenebe et al., 2013).

4.5 Conclusion

It can be concluded that rainfall characteristics and vegitation cover are the most prominent parameters that governs runoff. Up to 54 Mm^3 $Year^{-1}$ water can be potentially harvested from an area of 1001 Km^2 if effective rainwater-harvesting practices are employed. This is equivalent to 54 m^3 water per each meter square of land. On the other hand, surface runoff for arid areas of sub Saharan Africa is too little (< 100 mm) to grow staple food such as corn which requires minimum 500 mm runoff per year (Rockström & Falkenmark, 2015). In order to utilize optimum run off potential, it is crucial to undertake a detail feasibility and suitability assessment prior to construction. Equally to construction of RWH, regular maintenance and monitoring need to be conducted. Since RWH are labour intensive and require high initial cost, government bodies must provide incentives and or subsidize the projects.

Chapter 5. Evaluation of existing soil - water restoration techniques on soil physicochemical properties

5.1 Introduction

Currently, 75% of Earth's land area is massively degraded affecting about 3.2 billion people at global scale (Weeraratna, 2022). Land degradation refers to a decline in land productivity and depletion of its ecosystem services (Nkonya & Mirzabaev, 2016). It is caused by combination of anthropogenic and natural induced factors including vegetation clearance, soil erosion, population pressure, unwise use of resources, mono culture practices, overgrazing etc (Challa et al., 2016; De Boever et al., 2013; Nkonya & Mirzabaev, 2016). Neglecting the natural processes that support soil formation and agroecosystem resilience, and over-reliance on external inputs, are all contributors to land degradation.(Kuria et al., 2018). The costs of land degradation (costs due to loss of ecosystem services) at the global level are estimated to be 300 billion USD (Nkonya & Mirzabaev, 2016). Soil degradation as the main driver of land degradation is a serious threat to agriculture and food security particularly in dry lands were moisture deficit is common (Mesfin et al., 2019). Since soils are the main medium for storing, filtering, and transformation of water and nutrients to crops (De Boever et al., 2013), their erosion leads to the deterioration of soil quality, affecting soil texture, soil structure, soil organic matter, and soils ability to absorb water (Bezak et al., 2021). Land degradation is interrelated with water scarcity because, when a land is degraded; it loses the ability to store and infiltrate water and rather induces run off (Guerquin, 2020).

Mitigation approaches such as land degradation neutrality (LDN) has been at the forefront of the UN sustainable development goals- SDG6 that focuses mainly on integrated measures to combat land degradation, to ensure water security and reverse the decline of ecosystem functions (Feng et al., 2022). Some of the LDN measures conducted are integrated land and water management, watershed management, soil and water conservation techniques, enhancing water harvesting, irrigation expansion and water use efficiency (Guerquin, 2020).

Ethiopia as a sub-Saharan country is among the seriously affected countries by land degradation (Megerssa & Bekere, 2019). About 75% of its total land area is dryland most of which are affected by land degradation, climate fluctuation, water scarcity and food insecurity (Haregeweyn et al., 2015; Peng et al., 2021). Major factors contributing to land degradation in Ethiopia include poor agricultural management practices, cropping on marginal lands, monoculture practices, erratic rainfall, rugged topography, removing of crop residuals, population pressure and deforestation (Megerssa & Bekere, 2019). Land degradation poses an immediate threat to small-scale farmers who rely solely on rainfed agriculture, leading to consequences like the depletion of organic matter, decreased crop yields, and negative socio-economic outcomes, including increased poverty and hunger (Abiye, 2020). To reverse land degradation, different restoration measures have been conducted by the Ethiopian government with focus in northern Ethiopia where soil erosion is severe since early 1980s(Haregeweyn et al., 2015) . Examples include rainwater harvesting, soil-water conservation (Govers & Moeyersons, 2005; Jan Nyssen et al., 2010), integrated watershed management (Gebregziabher et al., 2016), area exclosure (Solomon et al., 2017), mulching (Hengsdijk et al., 2005)etc.

In situ rainwater harvesting (RWH) such as terracing , stone bunding and exclosure areas also commonly known as soil water conservation techniques play a crucial role in soil and water management, soil quality enhancement, increasing infiltration and soil water holding capacity (Oweis et al., 2012; Rockstr & Falkenmark, 2015). Research conducted in eastern Tigray of the long term impacts of terraced hillside increased total nitrogen and soil organic carbon (Hishe et al., 2017). Exclosure areas as part of soil and water conservation measure contribute to the formation of humus, an organic enriched mineral at the soil surface (Descheemaeker et al., 2009). Other studies conducted on the combined effect of tied ridges and straw mulch greatly reduced total nitrogen and phosphorus losses in Tigray northern Ethiopia (Grum, Woldearegay, et al., 2017).

Despite the implementation of many instu RWH in the region, their impact on soil physico - chemical properties and soil nutrient availability is not sufficiently explored (Balehegn et al., - 2019). Besides, there is no previous study conducted on the study site on assessment of instu rwh techniques on soil quality improvement. Evaluation of existing instu rainwater harvesting techniques on soil quality improvement in the study area has wide range implications in the selection and adoption of suitable RWH techniques. Therefore, this section was intended to evaluate the impact of three-in situ rainwater harvesting techniques: terraced land, stone bunds, exclosure and grazed area (control group) on selected soil physico chemical properties as well as to determine the relationship between the various soil physical and chemical parameters.

5.2 Material and Methods

5.2.1 Study Area

The study was conducted at Ganta afoshum district in eastern Tigray, northern Ethiopia. It is situated at [14017’46.39’’ -14^{0}18’51.62’’ N and 39^{0}28’29.86’’ -39^{0}30’1.17’’ E] (Fig. 1) in the outskirt of Adigrat city. The site is dominated by rugged hilly topography with an altitude of 1901m in the valley of eastern part to 3298m of steep slopes on the western and southeast direction(KASSAYE, 2006; Zeabraha et al., 2020). Agriculture is a backbone to the regional GDP, accounting for approximately 57% of which crop production contributes around 36%, livestock contributes around 17%, and forestry contributes about 4% (Tesfay, 2011). The mean annual precipitation is 565mm with around ¾ of the precipitation receiving in summer and mean annual temperature is 17.3 ^{0}C (*Fig. 2*). The topography contains flat surface in the center, mountainous clips in the western and southwestern part and a rolling topography in eastern direction(Zeabraha et al., 2020). The area contains an integrated agricultural system that combines both crop cultivation and livestock farming with rainfed dominated crop production. The average landholding size is less than one hectare (Hishe et al., 2019). Typical crops in the area include Teff (*Eragrostis tef [Zucc*.), barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), and maize (*Zea mays*). The area has geological formations including Enticho sandstone, Adigrat sand stone, Edaga arbi glacial and basalt basement rocks(Zeabraha et al., 2020). Soil type in the area has a moderately acidic, sandy loam structure with 69 g/Kg of sand, 19 g/Kg silt and 21 g/Kg clay and poor soil nutrient status.

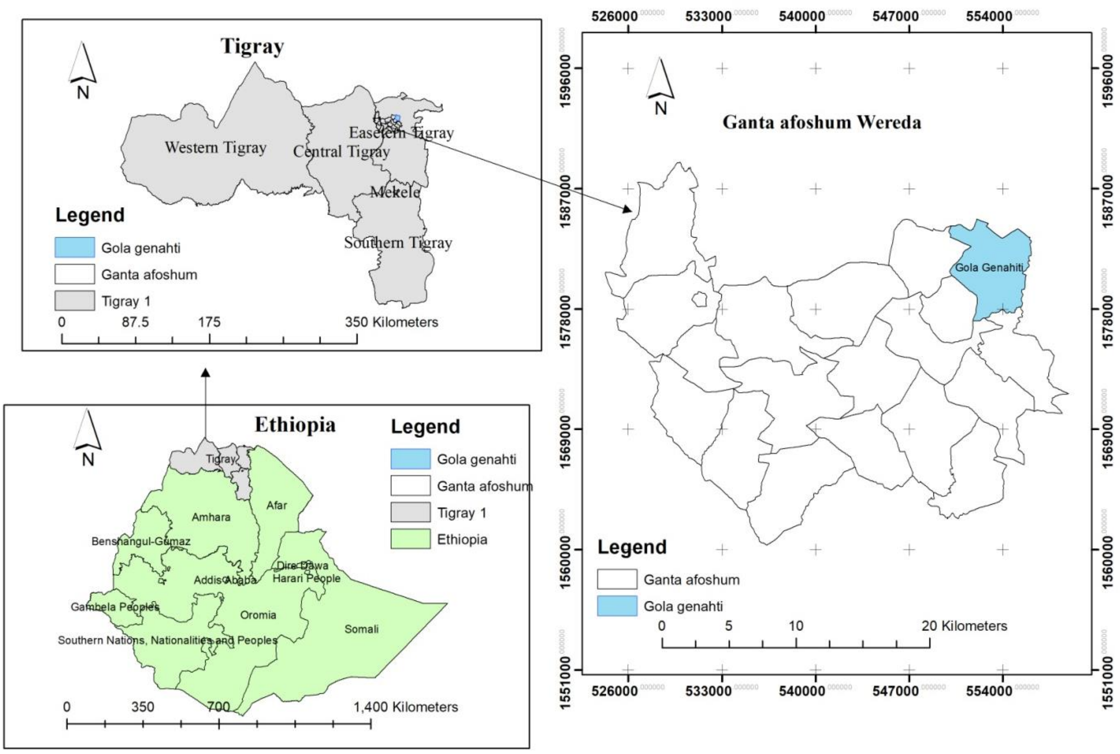


Figure 5. 1. Study area map of Gantafoshum- eastern Tigray, Ethiopia

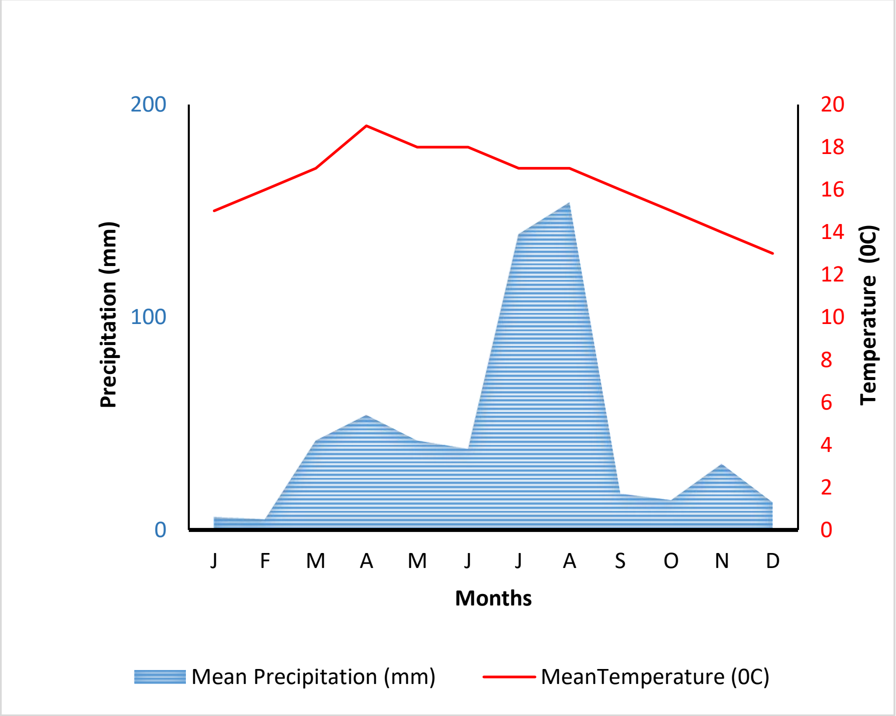


Figure 5.2 average monthly Rainfall and Temperature of the stud area

5.2.2 Soil Sampling and data collection

The sampling process was preceded by a field survey to the field plots. A clustered sampling technique was used to collect representative soil samples from terraced lands (TL), stone bunds(STB), exclosure (EX) and free grazed lands (GL) adopted from (J. Li, 2019). These in situ RWH techniques (STB, TL, and EXA) were constructed in the year 2011 as part of community based soil & water conservation campaigns. Three independently replicated 10 × 10 m plots were identified for each landuse types at the deposition zone (foot slope) on March 2021. The plots were divided in to four equal square grids and the centres of each square grids (the centroid) were marked from which a circular sampling area was created with a diameter equal to the side of the square grids (5 m). A small stone was thrown with eyes closed by standing on each centroid at a random direction and each plots were demarcated using a stick for sample collection. Soil samples were collected at 0 -20 cm depth using a spade. The steps were repeated and six 200-gram soil samples from each landuse types were collected totalling 24 samples. Final soil samples were thoroughly mixed to represent a homogenous soil sample and were packed in plastic bags for laboratory analysis. Each of the above restoration techniques share common soil parent material, age, topography, and agro ecological conditions, and any differences observed were assumed the result of changes in landuse.

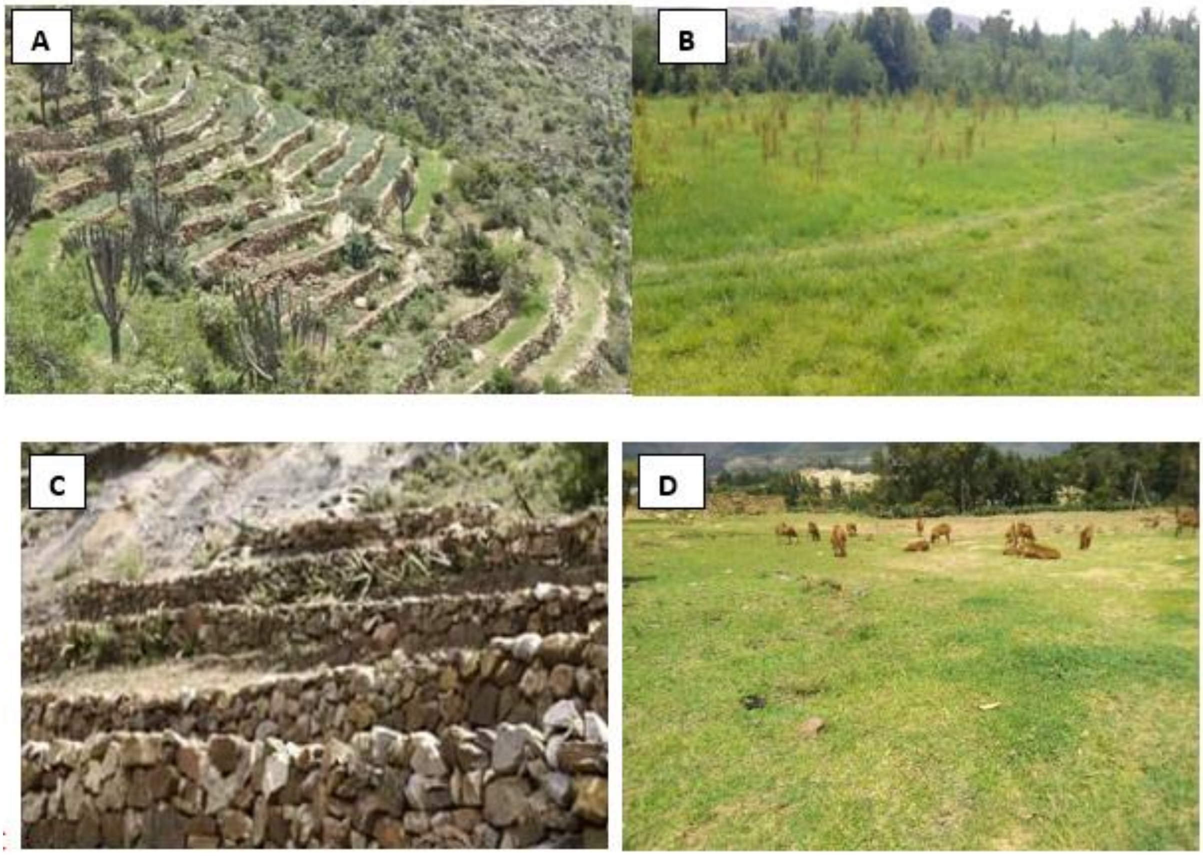


Figure 5.3 Diferent instu rainwater harvesting techniques practiced in northern ethiopia - eastern tigray, A= Terraced land, B Exlosure area, C stone bund and D grazed area (control)

5.2.3 Soil Laboratory analysis

The analysis of soil physico chemical properties was conducted using the updated FAO guideline for soil and plant analysis (Motsara & Roy, 2008). Selected soil physicochemical properties were soil texture, moisture content, pH, EC, SOC, SOM, Av.P, and TN. The soil texture analysis was conducted by bouyocos hydrometer method which uses sodium metha hexate- Na6 (Po3)6 as a dispersing agent(Peters, 2018). Soil pH was measured with 1:2.5 soil water ratio using pH meter. Soil organic carbon (SOC) was determined by walkey and black wet digestion method (Nandalal & Ratmayake, 2010). Soil Organic matter - OM was determined by multiplying SOC by the factor 1.724 assuming SOC comprised of 58% organic matter. Available phosphorus was measured by using Bray *1* method (Bray RH & Kurtz LT, 1945) while total nitrogen was computed by Kjeldahl method (nelson & sommers, 1982). Soil moisture was determined by the gravimetric method of oven drying the sample at 105 ^{0}C for

24 hrs. The difference in weight of the soil is thus the water Present in the soil. Electrical conductivity EC was measured by EC meter by preparing 0.01potassium chloride reagent solution.

5.2.4 Statistical analysis

The datas were analysed using IBM SPSS V 26 after the assumption of normality test was carried out using Shapiro-Wilk test. Variations in certain soil physical and chemical parameters among the different instu rainwater harvesting techniques and their adjacent freely grazed areas were assessed using one way ANOVA. Significant differences between means were compared using a Tuckey test. Relationship between various soil physical and chemical parameters was analysed using Pearson correlation.

5. 3 Result

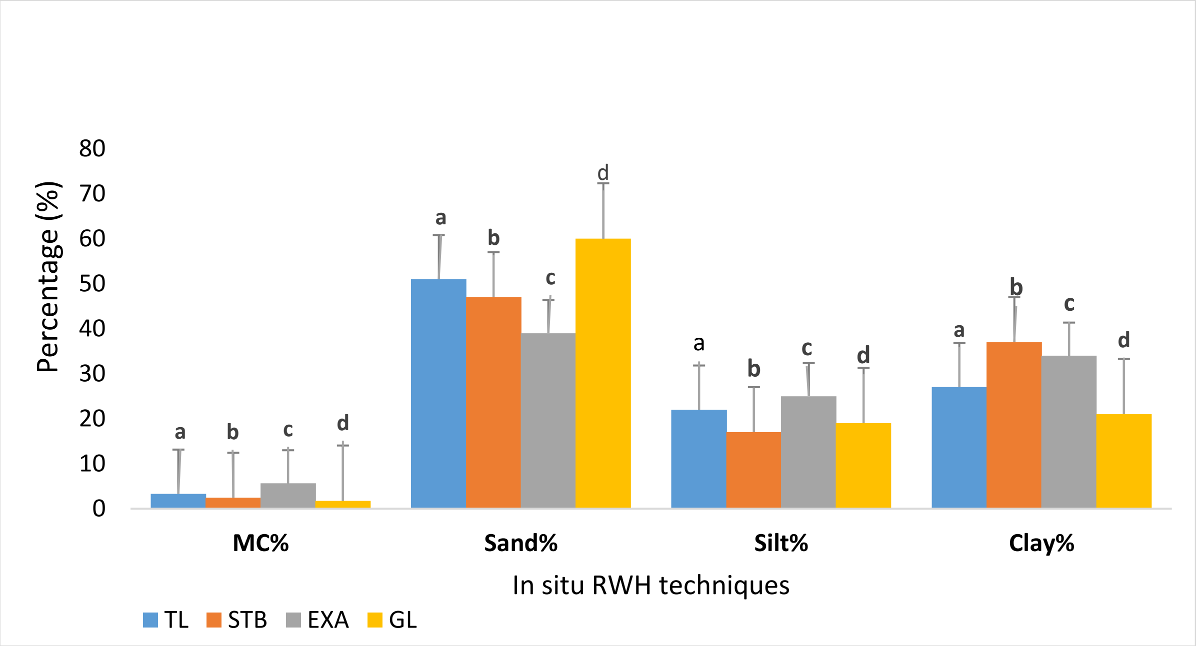
5.3.1 Effect on Soil physical properties

There were significant differences in soil texture between the treatments at $p<0.05$. Exclosure area had lowest sand% while the free grazed lands had highest sand%. Maximum clay particles were observed under exclosure followed by stone bunds and terraced lands. Based on USDA soil textural classification, both stone bunds and exclosure had a clay loam texture (Domingo-santos et al., 2022) (*Table 5.1*). Terraced land had a sandy clay loam whereas free grazed land had sandy loam textural class. The mean moisture content (*table 5. 2*) of all the treatments indicated a significant difference at $p <0.05$. Maximum and minimum moisture content was exhibited under exclosure area and free grazed land. EXA, TL, and STB exhibited an increase in their soil water content by 69.2%, 47.5%, and 29.4% respectively relative to grazed land -GL. Free grazed lands (GL) had highest electrical conductivity (EC) while EXA had minimum EC. No significant variation was found between STB and TL.

Table 5.1 Mean (n= 3) effects of in situ RWH on selected soil physical properties

Treatments	**Soil physical properties**					
	EC (ds/m)	**MC%**	**Sand%**	**Silt%**	**Clay%**	**Texture class**
TL	0.21±.01^{a}	3.31±.11^{a}	51±.36^{a}	22±.60^{a}	27±.82^{a}	Sandy clay loam
STB	0.24±.05^{a}	2.45±.18^{b}	47±.70^{b}	17±.64^{b}	37±1.2^{b}	Clay loam
EXA	0.76±.02^{b}	5.62±.07^{c}	39±.24^{c}	25±.21^{c}	34±.08^{c}	Clay loam
GL	0.18±.01^{d}	1.73±.04^{d}	60±.95^{d}	19±.79^{d}	21±1.6^{d}	Sandy loam
F value	751.94	120.82	105.2	40.2	48.3	-
P value	0.00	0.00	0.00	0.01	0.01	-

Means are significantly different at P< 0.05, means followed by the same letter along the column are not significant each other, EC= electrical conductivity, MC = moisture content, TA = Terraced area, STB = Stone bunding, EXA = Exclosure, GA = grazed area



Data are means ±SE; n=3 means followed by same letter with in a column are not significantly different from each other

Figure 5.4 Effect of In situ RWH techniques on soil texture and soil moisture, MC = moisture content, TL= terraced land, STB = stone bunds, EXA =exclosure, GL = free grazed land

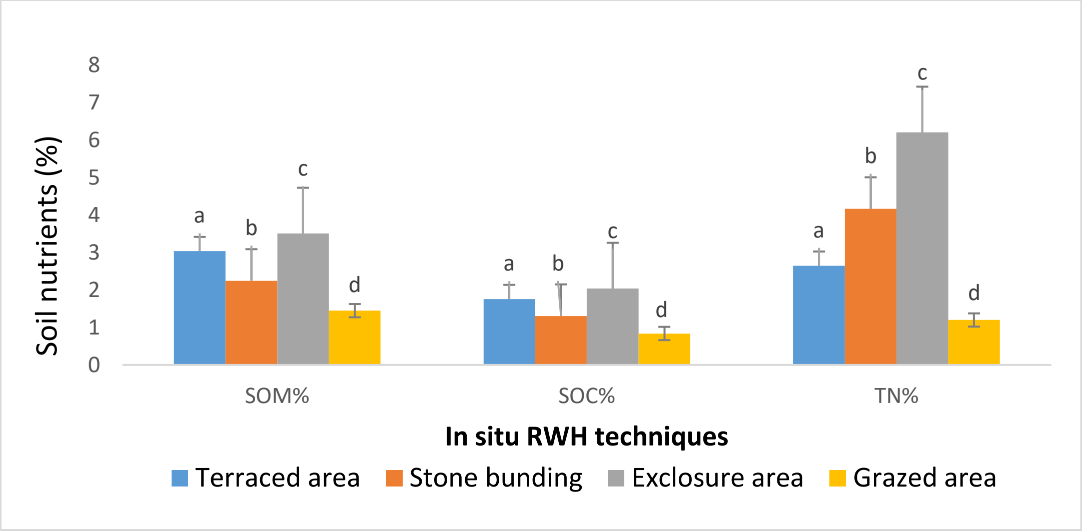
5.3.2 Effect on Soil chemical Properties

Similar to soil physical properties, significant variations were observed in soil chemical properties (*Table 5.2*). All the treatments significantly increased in pH level ranging from moderately acidic (5.13) in the GL to slightly acidic (6.1) in EXA. PH increased by 25.7%, 19.6%, and 6.6% under EXA, TL and STB respectively relative to GL. Both soil organic matter and soil organic carbon values had statistically significant difference among all the treatments (P<0.05). Highest SOC & SOM values (2.04% & 3.51%) were exhibited under EXA. Conversely, GL had least SOC & SOM values (0.84% & 1.45%) were observed. Similarly, TN and Av.P exhibited significant variation between the treatments with EXA being the highest. Stone bunds and terraced lands increased TN by 71.2% and 54.7% respectively compared with grazed areas (*Fig. 5*). Av.P was found to be the highest under EXA and minimum under the controlled plots –GL. Stone bunds had higher Av.P than terraced areas.

Table 5. 2 mean (n=3) effects of in situ RWH on selected soil chemical properties

Treatments	**pH**	**SOC-%**	**SOM-%**	**TN-%**	**Av. P -mg/Kg**
TL	6.38±.14^a	1.76±.01^a	3.04±.03^a	2.65±.01^a	1.55±.34^a
STB	5.47±.18^b	1.31±.03^b	2.25±.02^b	4.17±.01^b	2.43±.07^b
EXA	6.91±.13^c	2.04±.01^c	3.51±.06^c	6.21±.02^c	3.82±.17^c
GL	5.13±.24^d	0.84±.05^d	1.45±.08^d	1.2±.01^d	0.43±.08^d
F value	39.70	188.3	168.48	214.93	152.1
P value	0.004	0.00	0.001	0.00	0.01

Data are means ±SE n= 3 - means followed by the same letter within a column are not significantly different from each other, SOC =soil organic carbon, SOM = soil organic matter, TN= total nitrogen, Av.P =available Phosphorus TL= terraced lands, STB= stone bunds, EXA= exclosure areas, GL = grazed lands



Data are means ±SE n= 3 - means followed by the same letter within a column are not significantly different from each other

Figure 5.5 effect of instu rainwater harvesting techniques on total nitrogen -TN, soil organic matter - SOM and soil organic carbon - SOC, means followed by the same letters within a column are significantly different from each other

5.3.3 Pearson Correlation between soil physical and chemical properties

Positive and significant correlation was observed between SOM and pH, EC, TN, and Av. P (*Table5. 3*). Total nitrogen and Av. P had significantly positive correlation (r=0.97, $P< 0.05$) which is similar to the research by (Hishe et al., 2017; R. Liu et al., 2020). pH was positively and strongly correlated with SOM, SOC, and Av. P. Soil texture exhibited strong significant correlation with soil chemical properties (*Table 5. 4*). Sand particles had significant but negative correlations with all soil chemical properties, mainly SOC and SOM (r = -0.93). The negative correlation can be linked to lower nutrient retention capacity of sand particles (Arthur et al., 2011; Taye et al., 2018). Both Silt and clay particles were positively correlated with TN, Av. P, SOM and SOC.

Table 5.4. Pearson correlation coeffient between soil texture, and soil chemical properties

Pearson Coefficient (r)	Soil chemical properties				
Soil texture	pH	SOC	SOM	TN	Av. P
Sand	-.81**	-.93**	-.93*	-.75**	-.856**
Silt	.481	.53	.53	.748**	.722**
Clay	.665*	.807**	.807**	.508	.624*

**Correlation is significant at the 0.05level, **Correlation is significant at the 0.01 level where EC-electrical conductivity, SOC –soil organic carbon, SOM – soil organic matter, TN – total nitrogen, Av.P –available phosphorus*

5.4 Discussion

5.4.1 Soil physical properties

The Lower proportion of sand particles in EXA, STB and TL may be attributed to runoff concentration on the conserved landscape and the deposition of surface litter (Amare et al., 2013). Soils are composed of some sand, silt, clay, and organic matter and the makeup of a soil determines the extent to which nutrients are available to plants(Moral & Rebollo, 2017).soil texture affects how well nutrients and water are retained in the soil (Taye et al., 2018). The freely grazed area - GL dominated by sand particles could be linked to run off induced erosion of the top soil or due to overgrazing by animals (G. U. O. Wang et al., 2012). The results are in agreement with (Hishe et al., 2017) which reported low sand% in terraced lands and exclosure areas in eastern Tigray with similar agroecology . The presence of more sandy soil in the grazed areas implies more water drainage with nutrients being leached down streams (Moral & Rebollo, 2017). Maximum clay particles in the conserved landscape (EXA, STB, and TL) can be due to accumulation of fine soil particles following restoration measures (Masha et al., 2021). The more clay the soil contains, the better soils hold nutrient and water(Moral & Rebollo, 2017). It is obvious to see an increase in moisture content in conserved landscapes since the rainwater is harvested and slowly accumulated in the soil profile. The highest moisture content under exclosure areas could be due to the maximum vegitation cover present in EXA that enables them retain rainwater via interception and run off reduction(Stuart Chapin et al., 2012). EC is a property that measures total dissolved salts in a solution and influences plants ability to absorb water(Samarakoon et al., 2006). The low EC values under in situ RWH areas indicates the non salinity of the areas making it favorable for crop growth (Moral & Rebollo, 2017). Al-Seekh and Mohammad (2009) also reported similar decrease in EC on terraced lands and circular bunds under semi-arid conditions.

5.4.2 Soil chemical properties

Soil pH is the most influential factor which affects nutrient availability, toxicity, and microbial activity (Dagnachew et al., 2020). The mean pH values ranged from moderately acidic (5.13) in GL to slightly acidic (6.1) in the exclosure areas that implies higher pH values in the conserved areas. Similar findings were found by (Yeshaneh, 2015). The low pH value in GL might be associated with declining of base saturations leading to an increase in H^+ (Mammo et al., 2020).

SOC and SOM values were the highest under exclosure areas followed by terraced areas and stone bunds. This showed that implementation of in situ RWH has the capacity to reverse degraded soil possibly due to reduction in leaching of soil nutrients (Vohland & Barry, 2009). The highest SOM in exclosure areas implies the formation of humus, an organic matter and organic rich minerals through increased organic matter inputs by the diverse vegetation (Rusu et al., 2013). The formation of humus is affected by topography, climate, parent material, chemical composition of litter, soil type, and soil organisms(Descheemaeker et al., 2009). Mahari et al. (2015) reported similar increase in organic matter and organic carbon in the dry Afromontane forest in northern Ethiopia. The stability of SOC in soils is highly reliant on the range of climatic, edaphic and biotic factors thereby affecting SOC dynamics through both direct and indirect pathways(Luo et al., 2017). Av.p increased significantly in the conserved landuse than the freely grazed area. Phosphorus in soils is essential for promoting early root formation and growth (Mullins, 2009). An in increase in Av.P was observed by (Vagen et al., 2008) on terraced lands in Tigray. The availability of phosphors in soils is dependent on a lot of factors including soil texture, land use pattern, drainage etc. (Hishe et al., 2017).

A significant difference in total nitrogen-TN was observed between the treatments with highest mean TN in EXA followed by STB, TL and GL. Similarly, Mammo et al (2020) found 50% increase of TN in soil bunds supported with *Acacia* and *Sesbania sesban* tree species, typical legume trees that enable nitrogen fixation. Another study on terraced area conducted by Amare et al. (2013) reported a higher TN at deposition zone(lower part of the terrace) than at the loss zone. Nitrogen is available to plants as NH^{3-} or NH^{4+} through mineralization process(Watson & Laughlin, 2013). This conversion is done either by free-living bacteria in the soil or plant associated nitrogen fixing bacteria which occurs under anaerobic conditions in root nodules of legumes or in free-living cyanobacteria (Schulze et al., 2019). soil nitrogen mineralization is dependent on climatic factors such as rainfall and affects both soil nitrogen supply and nitrogen uptake to plants(Watson & Laughlin, 2013).

5.4.3 Correlation between soil Physical and chemical properties

Positive and significant correlation was observed between soil organic matter and pH, Electrical Conductivity (EC), TN, and Av. P, which could imply that having higher organic matter governs higher nutrient availability and favorable pH conditions (Corral-Nuñez et al., 2014). Soil organic matter is crucial for improving soil physical, chemical and biological characteristics(Lal, 2014). Both soil organic matter and soil organic carbon were significantly and strongly correlated (r= 0.98). This might be linked to the fact that they both share a composition rich in organic minerals (Lal, 2014). Similar results were reported by Belayneh et al. (2019). Likewise, TN and Av. P had significantly positive correlation (r=0.97) .Similar results were found by (Hishe et al., 2017; R. Liu et al., 2020). Higher Av.P present in the soil can increase microbial activity (Zhu et al., 2018) and this can facilitate organic matter decomposition resulting in higher TN (R. Liu et al., 2020). pH was positively correlated with SOM, Av. P. and TN. This could be attributed to the influence of pH on the various soils biogeochemical process and control of soil microbial activity (Neina, 2019). Soil texture exhibited both positive and negative correlation with soil chemical properties. Sand particles had significant negative correlations with all soil chemical properties particularly, SOC and SOM (r = -0.93). Similar results were found by (Vagen et al., 2008) who observed negative correlation between sand particles and soil nutrients. The negative correlation can be linked to lower nutrient retention capacity of sand particles due to their low surface area hence faster nutrient leaching (Arthur et al., 2011; Taye et al., 2018). Both Silt and clay particles had strong positive correlations with TN, Av. P, SOM and SOC. The positive correlation of clay particles with SOC and SOM might be attributed to their smaller particle sizes and pore space resulting in high surface area favorable for binding organic matter (Widowati et al., 2020).

5.5 Conclusion and Recommendation

Exclosure, terraced land and stone bund had significant variations on both soil physical and chemical properties compared to the freely grazed lands. There was a significant reduction in sand particles and an increase in clay content and soil moisture. Instu RWH structures substantially increased pH and soil organic matter content with the highest values observed in exclosure. Moreover, both total nitrogen (TN) and available phosphorus (Av. P) content increased significantly under the conserved landscapes than the control. The positive and significant correlations observed among various soil properties further highlighted their interdependence and the potential benefits of instu RWH techniques for sustainable soil – water management. In conclusion, the study's findings indicated the adoption of in situ RWH techniques are instrumental for enhancing soil quality, restoring degraded landscapes. Further research on the impact of in situ rainwater harvesting on soil microbial activity and the study on socioeconomic impacts of in situ RWH can support in designing sustainable soil - water management practices.

Chapter 6. Evaluation of existing agroforestry legume trees on Arbuscular Mycorrhizal Fungi and Soil Properties

6.1 Introduction

Agroforestry systems (AFS) are multi-functional land use management techniques which involve an intentional integration of trees and crops on the same land unit in order to maximize ecosystem services, diversify farming products and maintain soil fertility (Sarvade et al., 2015; Sobola & Amadi, 2015). They are practiced in various climatic zones but are of more importance in tropical regions that are known for small holder and low input farming systems (Fungo et al., 2021). AFS are reported to positively influence soil quality and contribute to environmental sustainability (Laurindo et al., 2021). Compared to monoculture farming, agroforestry enhances soil organic carbon, soil nutrient availability and soil microbial dynamics(Dollinger & Jose, 2018). The inclusion of trees in agroforestry systems (AFS) provides increased input of soil organic matter which serves as a food source for the soil microbes and influences soil biodiversity(Fungo et al., 2021). Moreover, Inclusion of leguminous trees in to crops increases soil nitrogen via biological nitrogen fixation(Zomer et al., 2014). Deep rooted trees in AFS also have the capacity to absorb nutrients that have leached below the root zone(Bergeron et al., 2011; P K Ramachandran Nair, 2014). These nutrients are eventually recycled via leaf litter and fine root turn over ultimately enhancing nutrient use efficiency (P K R Nair et al., 2008). Besides their contribution to nutrient cycling, agroforestry systems (AFS) can enhance soil microbial biomass and diversity such as Arbuscular mycorrhizal fungi (AMF) due to their ameliorative effects (Sérgio et al., 2012).

AMF are essential soil microbes that form obligate symbiosis with tree/plant roots through their hyphal extension (Bonfante & Anca, 2009). AMF benefits the host tree with enhanced nutrient uptake, increased resistance against environmental stress, suppression of root pathogens and facilitation of vegetation establishment in disturbed areas (Battie-laclau et al., 2020; Birhane et al., 2018; Dobo et al., 2018; Laurindo et al., 2021). Additionally, the extension of fungal hyphae into the soil helps it explore vast volumes of soil there by facilitating resource mobilization for the host tree thus, making the mycorrhiza associations ideal for nutrient acquisition and biogeochemical cycles (Battie-laclau et al., 2020; Birhane et al., 2021; Fall et al., 2022; Hailemariam et al., 2018). The host trees on the other hand provide the AMF with a continuous supply of organic matter that enable the AMF to grow (Fall et al., 2022). AMF fungal community composition and distribution is highly influenced by the host plant species through differential effects on hyphal growth and prevailing climatic conditions(Alguacil et al., 2016; Burrows & Pfleger, 2002).Moreover, Agroforestry contributes to a stable soil aggregates and better soil structure than monoculture which can create a favourable microenvironment for more AMF colonization (Alguacil et al., 2016). The Presence of various legume trees and diverse root systems under agroforestry also enhances the colonization potential of arbuscular mycorrhizal fungi (AMF) resulting in higher AMF abundance and diversity (Battie-laclau et al., 2020).

Adding tree legumes to agroforestry systems has a profound impact on soil health and sustainable management (Meena et al., 2018). Tree legumes are fast growing multipurpose tree species that form mutualistic association with arbuscular mycorrhizal fungi in which the AMF colonize their roots and form arbuscular mycorrhizal structure enabling nutrient exchange between the trees and the AMF(Sérgio et al., 2012; Zerihun et al., 2013). In addition to their symbiosis with AMF, legume trees have special feature of their symbiotic interaction with rhizobial bacteria which fix atmospheric nitrogen biologically through the formation of root nodules(Sérgio et al., 2012). Besides, tree legumes release root exudates in to the soil which serves as a nutrient for the AMF (Eisenhauer et al., 2017). These root exudates also contain specific signalling molecules such as flavonoids that stimulate AMF root colonization(Sugiyama & Yazaki, 2012). These characteristics of legumes makes them preferable for regeneration of degraded dry lands and nutrient depleted soils (Bilgo et al., 2012; Boudiaf et al., 2013; Meena et al., 2018).

In the northern dry lands of Ethiopia- Tigray region, various native tree legumes including *Faidherbia albida* and *Vachellia abyssinica (vachellia* genus*)* are used by small holder farmers for soil fertility enhancement under traditional agroforestry (Birhane et al., 2018; Hachoofwe, 2012; K. M. Hadgu et al., 2009). The *Vachellia* genus are third dominant tree legumes in Ethiopia encompassing over 49 native species and are evenly distributed in altitudes of up to 3400 meters above sea level (Zerihun et al., 2013). In addition to these native trees, exotic tree legumes has also been used as a source of fodder (Mahdhi et al., 2020; Oosting et al., 2011) and soil fertility restoration (Dessalgn & Wolde, 2021; Hachoofwe, 2012; Nigussie, 2013) in many parts in Ethiopia. Various researches have been conducted in the studied region on the effects of *Faidherbia albida* and *Vachellia abyssinica* trees on soil physicochemical properties as well as soil microbial activity (Birhane et al., 2018; Hachoofwe, 2012; K. M. Hadgu et al., 2009; Hailemariam et al., 2018). However, very limited information exists on the effect of exotic tree legumes such as *Sesbania sesban* on Arbuscular mycorrhizal fungi root colonization and spore abundance. Research from previous studies has shown that the introduction of exotic tree legumes (*Acacia holosericea*) induced disturbances in soil microbial communities and altered the structure of AMF communities in native legume - *F.albida* (Faye et al., 2009). Similar study highlighted that invasion of exotic legumes can disrupt native below ground mutualisms and reduce native legume fitness due to the simultaneous introduction of exotic but ineffective symbionts when colonizing native legumes(Ferna & Ruiz-dı, 2012). Conversely, another study demonstrated that exotic tree legume *A. longifolia* did not prevent the growth of native tree legumes and they attributed the invasion of the exotic legume to plant specific morphology and other physiological mechanism(Rodríguez-Echeverría et al., 2009).

In the current study, the hypothesis made was that indigenous tree legumes are subjected to higher AMF (Arbuscular mycorrhizal fungi) colonization than exotic tree legumes due to their longstanding coexistence with the local AMF. An understanding on the impact of indigenous and exotic tree legumes on AMF root colonization and spore density is detrimental for conservation of beneficial native legumes and for developing sustainable agroforestry systems. Therefore, the general objective of this study was to assess the difference between the two native tree legumes (*Faidherbia albida* and *Vachellia abyssinica*) and the exotic tree legume (*Sesbania sesban*) on AMF root colonization, AMF spore density and soil properties. The specific objectives were to i) determine the effect of the three-tree species on AMF root colonization and spore density, ii) evaluate their effect on soil physicochemical properties iii) analyse the relationship between tree legumes, AMF and soil properties.

6.2 Materials and Methods

6.2.1 Study area

The study was conducted in Abreha we Atsbeha - located in eastern Tigray (Lat- 13.852283°, Lon- 39.535583°), in the northern region of Ethiopia with elevation varying from 1928 to 2319 meters above sea level (*Fig 6.1*). It is a long valley running approximately from northwest to southeast, with a sandstone ridge to the west and a basalt ridge to the east(Tadesse, Gebrelibanos, & Gebrehiwet, 2016). The area is characterized by steep hillsides covering 45.5% of the land, medium slopes covering 21.5%, and the remaining 34% categorized as gentle slopes (Tadesse, Gebrelibanos, & Geberehiwot, 2016).

Abraha we atsbeha is known for its successful landscape restoration techniques including soil and water conservation, integrated watershed management and area Exclosure(M. Haile & Gebregziabher, 2020) Based on ten years of historical climate data (2010-2020) from Weather and Climate (*https://tcktcktck.org/*), Abreha we atsbeha experiences a semi-arid climate with an average annual rainfall of 365 mm and average annual temperature of 20.2°C. The weather patterns show short, intense rainfall in the summer, followed by extended dry spells in the winter (Fig 6.2). Soils found in the area include very shallow Leptosols and Haplic Arenosols (Ashenafi, 2014). A mixed crop-livestock farming is the dominant agricultural practice in the study site with cereal crops wheat, maize, sorghum, finger millet, and Eragrostis tef being produced as staple food crops (Blerk, 2017). Intercropping is also common in the site and is used for producing fodder, fire wood, shade and for maintaining soil fertility (Sida et al., 2021). Tree species commonly preferred by small holder farmers in the area are *Acacia saligna, Faidherbia albida, Lucean lucocephala* and *Sesbania sesban* (Hachoofwe, 2012).

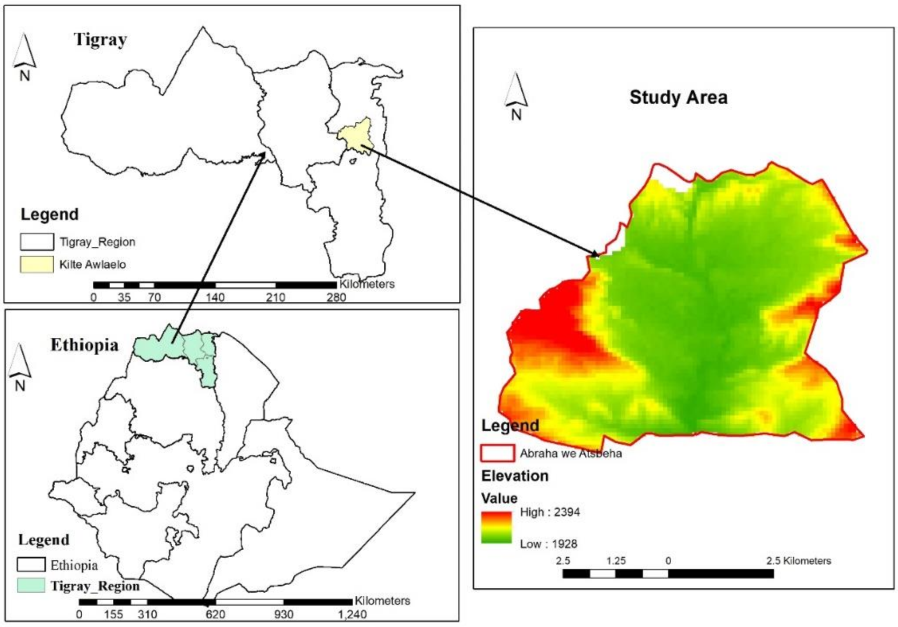


Fig 6. 1. Map of Abraha Atsbeha- Eastern Tigray –northern Ethiopia

6.2.2 Data Collection

Prior to data collection, a transect visit was made to the study area to survey and identify agroforestry fields containing the tree species of interest. Selection of the trees was determined by specific criteria, including their classification as tree legumes, their availability, and the presence of both native and exotic tree legumes. We collected Rhizosphere Soils from four corners of selected trees using a rectangular plot pattern within a radius of 3 -5 m from the outer edge of the tree canopy(Birhane et al., 2021; Bougher et al., 1996). A total of 27 rhizosphere soil samples (3 samples per species*3 tree species* 3 replicates) at depth of (0-30 cm) were collected and taken to Mekelle university soil laboratory. Fine roots were collected from all the tree species for assessment of Arbuscular mycorrhizal fungi (AMF) root colonization. The roots were collected by excavating soil at 0-30 cm depth in four directions from the bottom of the tree trunk towards fine roots with in 3m radius (Birhane et al., 2010, 2021; Sewnet & Tuju, 2013). A total of 27 root samples were collected from each of the four sampling points, a 10-g composite sample of fine roots (diameter <2 mm) were taken for subsequent laboratory analysis. To eliminate any soil particles, the fine root samples were gently rinsed with tap water and placed into tightly sealed plastic jars (Birhane et al., 2010, 2021). To preserve the roots, the jars were filled with 97% ethanol and stored at room temperature (4 °C) for further laboratory analysis(Bougher et al., 1996).

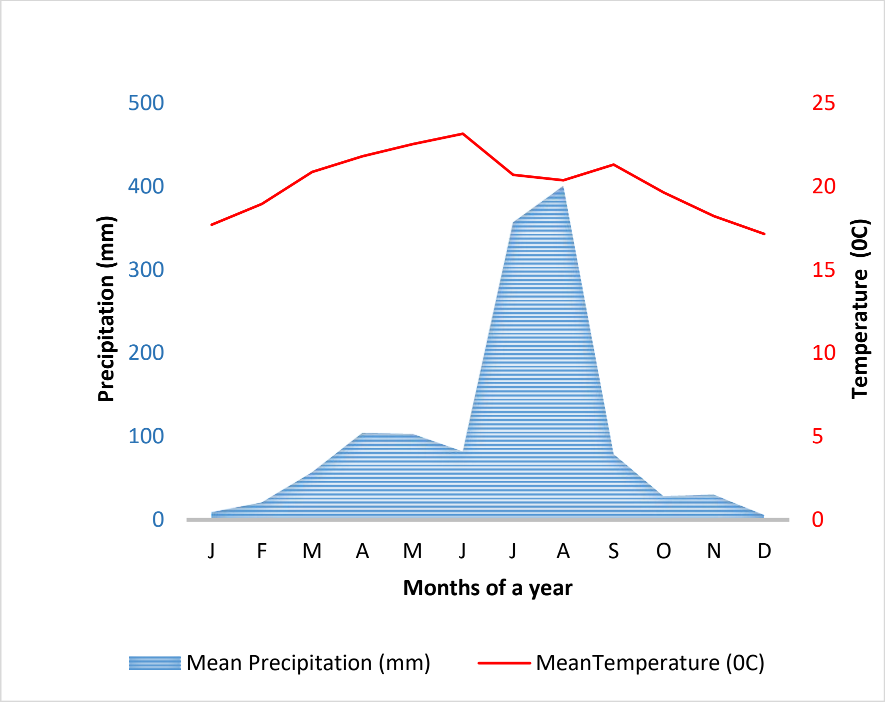


Figure 6.2. Mean monthly precipitation and temperature of Abreha we Atsbeha

6.2.3 Laboratory analysis

Mycorrhizal spores present in the soil were extracted using the wet-sieving and decanting method(Bougher et al., 1996). Rhizosphere soils were dried and sieved through a 2mm mesh size to remove any dirties or debris. A precisely weighed 10-gram soil sample was mixed with 100 mL of tap water in a plastic bottle, shaken for 30 minutes, and was left to settle. The supernatant was separated from the sediment and passed through a series of descending mesh sizes of 300-µm, 100-µm, and 50-µm. Any remaining rock fragments or debris was removed by placing 850-µm sieve on the top. The spores collected in the sieves were carefully transferred into plastic jars with water added, tightly covered and centrifuged at 2000 rpm for 5 minutes. The samples were rinsed again with tap water and sieved using 50-µm sieve. Subsequently, the spores were transferred to plastic containers and subjected to centrifugation again using 50% sucrose at 2000 rpm for 3 minutes. The spores were then rinsed thoroughly to remove the sucrose. Finally, each sample of isolated spores was poured onto filter paper and placed in separate compartments of a petri dish. The petri dishes were labelled with a glass marker for easy counting of the spores. The petri dishes were observed in a stereo microscope with 100× magnifying power. The spores and spore carps of the arbuscular mycorrhizal fungi (AMF) were counted via scanning each filter paper with the 300-µm, 100-µm, and 50-µm sieves(Birhane et al., 2021). Overall AMF spore density was then calculated per 100-gram dry soil.

For AMF root % colonization, preserved roots were stained, cleared, and bleached using the technique in (Bougher et al., 1996). The occurrence of Arbuscules, vesicles, and hyphae of AMF was observed by the gridline intersection method (Brundrett et al., 1984). Arbitrarily selected roots were mounted lengthwise on slides, with nine replicates from each plant sample. Using a compound microscope with 400x magnification, the samples were observed to identify arbuscules, hyphae, and vesicles(Birhane et al., 2010).

Soil physicochemical analysis was conducted based on the updated FAO laboratory guideline for plant nutrient analysis (Motsara & Roy, 2008).pH, electrical conductivity (EC), total nitrogen (TN), available phosphorus (Av.P), available potassium (K),soil organic carbon (SOC), Soil organic matter (SOM) were measured for 27 soil samples. pH and EC were measured by a soil-water suspension with a ratio of 1:2.5(Birhane et al., 2018; Motsara & Roy, 2008). Soil Organic carbon (SOC) was assessed using the Walkley-Black method and SOM was obtained by multiplying SOC by a factor of 1.724 considering SOM comprises 58% carbon (Yeshaneh, 2015) . For the measurement of Av.P, Olsen method was used while total nitrogen (TN) was determined using the Kjeldahl method(Motsara & Roy, 2008). Available potassium (Ava.K) was measured using the flame spectrophotometer method (Motsara & Roy, 2008).

6.2.4 Data Analysis

Datas for AMF percentage root colonization, AMF spore density, and soil properties were statistically analysed using IBM SPSS V26. Prior to analysis, the assumption of normality test was carried out using Shapiro-Wilk normality test(Birhane et al., 2010) to ensure the datas are normally distributed. One-way ANOVA was used to test significant differences in AMF % root colonization and AMF spore density between native and exotic tree legumes. Similarly, significance variations in soil properties were tested among all the tree species using one-way ANOVA. Bivariate correlation analysis was conducted using Pearson correlation coefficient to examine the relationship between AMF root colonization, AMF spore abundance and soil properties (Welemariam et al., 2018).

6.3 Result

6.3.1 Effect of Tree legumes on AMF root colonization and Spore density

All tree legumes exhibited changes in Arbuscular mycorrhizal fungi (AMF) percent root colonization and Spore density (Fig 6.3). Most of the variations in AMF root colonization among the tree legumes were statistically significant ($p < 0.05$). The most abundant root structure observed was Hyphal root colonization (HC) with average 68.32% followed by mycorrhizal hyphal colonization (MHC)- 60.28%, arbuscular colonization (AC) - 28.7% and vesicular colonization structures (VC) 23.4 The degree of AMF root colonization was influenced by whether the host tree was native or exotic. *Faidherbia albida* exhibited highest AMF root colonization while lowest AMF root colonization was found in *Sesbania sesban*. Both indigenous legumes resulted in higher AMF root colonization than the exotic tree legume.

The average AMF spore density observed (Fig 6.4) in the tree legumes ranged from 194 to 263. Significant change was observed in AMF spore density between native and exotic legumes. *Faidherbia albida* resulted in highest AMF spore density followed by *Vachellia abyssinica* and *Sesbania sesban*. The variation in AMF spore density among the tree species were statistically significant ($p < 0.05$). The higher AMF spore density in *Faidherbia albida* may be attributed with its higher AMF % colonization.

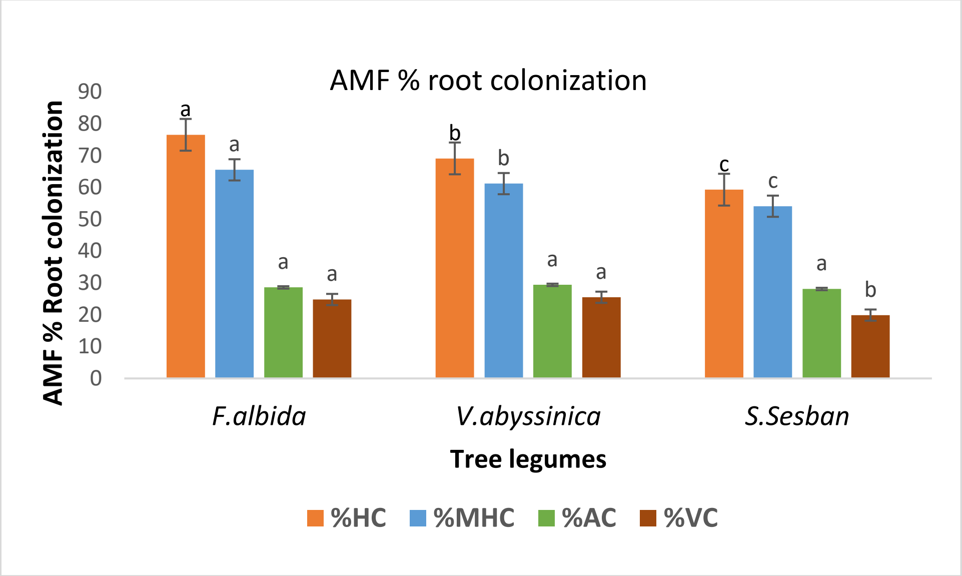


Figure 6.3: effects of Faidherbia albida, Vachellia abyssinica and Sesbania sesban trees on percentage of AMF root colonization. Data are means ±SE; means followed by the same letter with in a column are not significantly different at P< 0.05

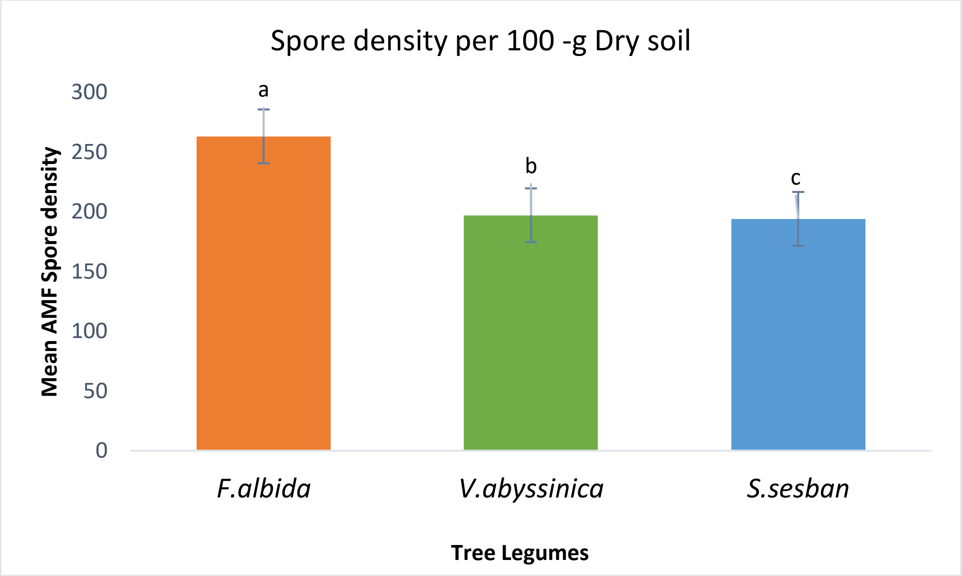


Figure 6.4 means of AMF spore density per 100 g dry soil of Faidherbia albida, Vachellia abyssinica and Sesbania sesban. Data are means ±SE; means followed by the same letter with in a column are not significantly different

6.3.2 Effect of tree legumes on various soil properties

The analysis of various soil properties (Table 6.1) revealed significant changes in pH, SOC, SOM, TN and Ava.K between the tree species. *Faidherbia albida* (*F. Albida*) trees exhibited the highest pH value (7.73), while *Sesbania sesban* (*S. Sesban*) trees showed the lowest pH value (7.43). *Faidherbia albida* trees had significantly higher SOC and SOM values (21.3%) than *Vachellia abyssinica.* Significant changes were observed in TN between native and exotic tree legumes (Fig 6.5). *Sesbania sesban* trees exhibited maximum TN value, while minimum TN values were observed in both native trees. No significant difference was observed in TN between *F.albida* and *V abyssinica*. *Faidherbia albida* trees had significant available potassium (Av. K) values, followed by *Vachellia abyssinica*, while *Sesbania sesban* trees exhibited lowest Av. K (*Table 6.1)*.

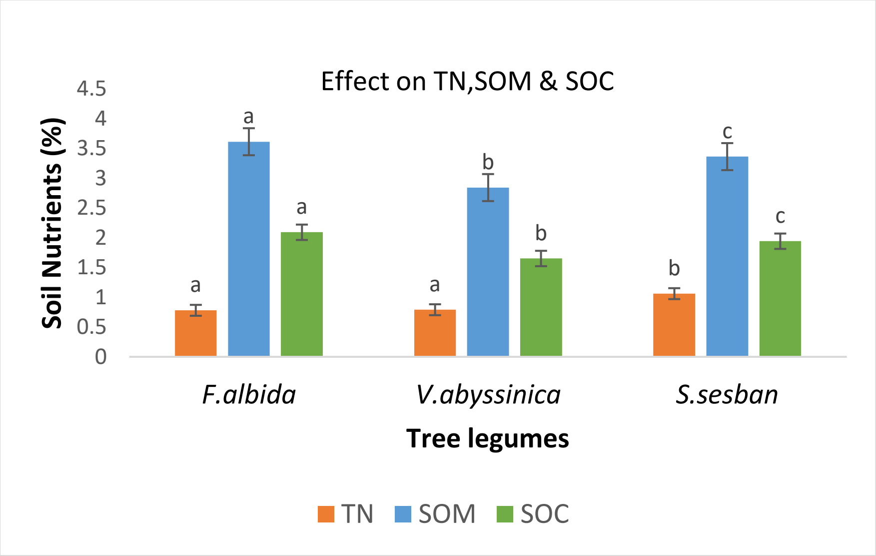
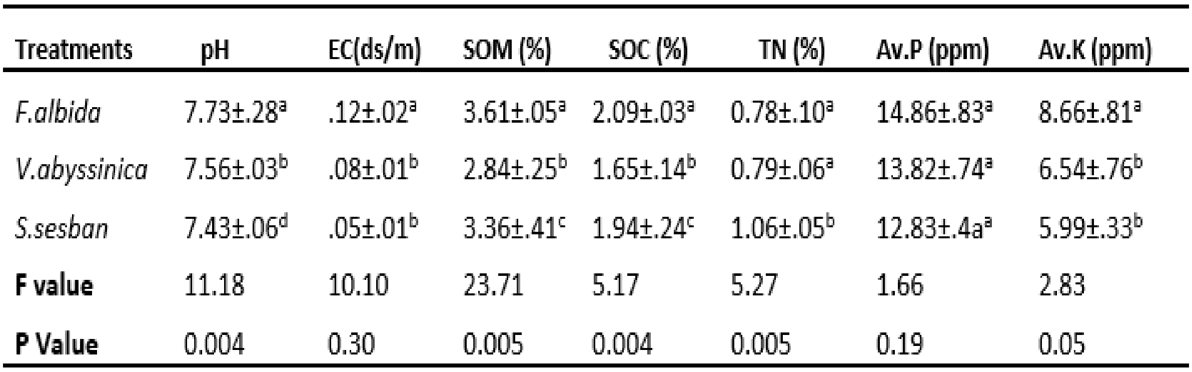


Figure 6. 5: effect of Faidherbia albida, Vachellia abyssinica and Sesbania sesban on SOM, TN and SOC at p = 0.05, means with the same letters across the column are not significantly different with each other. TN- total nitrogen, SOM – soil organic matter, SOC- soil organic carbon

Table 6.1: Mean soil properties of F. albida,V. abyssinica and S. sesban



Treatments	**pH**	**EC(ds/m)**	**SOM (%)**	**SOC (%)**	**TN (%)**	**Av.P (ppm)**	**Av.K (ppm)**
F.albida	7.73±.28^{a}	.12±.02^{a}	3.61±.05^{a}	2.09±.03^{a}	0.78±.10^{a}	14.86±.83^{a}	8.66±.81^{a}
V.abyssinica	7.56±.03^{b}	.08±.01^{b}	2.84±.25^{b}	1.65±.14^{b}	0.79±.06^{a}	13.82±.74^{a}	6.54±.76^{b}
S.sesban	7.43±.06^{d}	.05±.01^{b}	3.36±.41^{c}	1.94±.24^{c}	1.06±.05^{b}	12.83±.4a^{a}	5.99±.33^{b}
F value	11.18	10.10	23.71	5.17	5.27	1.66	2.83
P Value	0.004	0.30	0.005	0.004	0.005	0.19	0.05

Data are means ± SE; means followed by the same letter with in a column are not significantly different at p≤ 0. 05F.Albida- Faidherbia albida, V. abyssinica- Vachellia abyssinica, S. Sesban- Sesbania sesban trees

6.3.4 Correlation between AMF root colonization, Spore density and soil properties

AMF root colonization exhibited very strong positive correlations with pH, SOM and Av. P (Table 6. 2). The strongest positive correlation was observed between VC and SOM (r = 0.552). AMF spore density displayed a strong positive correlation with SOM (r = 0.717). In contrast, both root colonization and spore density showed a negative correlation with electrical conductivity (EC). Furthermore, hyphal root colonization, mycorrhizal hyphal colonization, arbuscular colonization and vesicular colonization were all very strongly correlated with each other. Likewise, very strong positive relationships were exhibited between AMF root colonization and AMF spore density. Correlation analysis between soil properties revealed several positive relationships. Specifically, total nitrogen (TN) and available phosphorus (Ava.P) showed a positive correlation ($r = 0.662$, $P < 0.001$, $n = 36$). A strong positive correlation was also observed between available potassium (Av. K) and electrical conductivity (EC) ($r = 0.649$, $P < 0.001$) whereas, a negative correlation was found between pH and available phosphorus (Ava.P) ($r = -0.344$, $P < 0.05$).

Table 6.2 Pearson correlation coefficient (r) between AmF root colonization, AMF spore density and soil properties

AMF Parameters	Soil Parameters						
	EC(ds/m)	PH	SOC(%)	SOM(%)	Av. P(ppm)	Av. K(ppm)	TN(%)
Spore densty	-.279	.353**	.315	.717**	.46**	.112	2.7
HC	-.46**	.437**	.177	.63**	.42*	-.167	.07
MHC	-.53**	.375*	.128	.61**	.38*	.206	.08
AC	-.61**	.207	-.025	.51**	.352	-.371*	.004
VC	-.502*	.342*	.020	.552*	.520*	.353	-.13

***Correlation is significant at the 0.01 level *Correlation is significant at the 0.05 level HC –hyphal root colonization, MHC- mycorrhizal hyphal colonization, AC- Arbuscular colonization, VC –vesicular colonization.*

6.4 Discussion

6.4.1 AMF Root colonization and AMF Spore density

The study revealed that significant differences were found on AMF root colonization and spore density between indigenous and exotic tree legumes. Similar study on changes in AMF colonization and spore density between indigenous and exotic legumes was reported by (Tibbett et al., 2010). Roots of all tree species were colonized by AMF structures. Average AMF %root colonization ranged from 40.3% under *Sesbania sesban* to 48.86% under *Faidherbia albida* trees and can be classified as medium colonization based on the ratings in root colonization (Zerihun et al., 2013). Higher HC and MHC root colonization structures were observed under native legume species *Faidherbia albida* and *Acacia abyssinica* than the exotic legume *Sesbania sesban.* Lower AMF root colonization structure in *Sesbania sesban* could be associated to lower root turnover rates of the exotic legume or to the influence of the host tree species(Jefwa et al., 2006; Tibbett et al., 2010). Other reasons might be due to the susceptibility of *Sesbania sesban* trees with root Knot nematodes (Meloidogyne spp), a parasitic worms which might have limited AMF root colonization(Bationo et al., 2011). Higher

AmF root colonization by the native legumes might be attributed to the secretion of higher root exudates which attract more AMF to the host roots(Sugiyama & Yazaki, 2012).

In contrast to our findings, Faye et al (2009) reported higher AMF root colonization of exotic legume species relative to native legumes and asserted that exotic tree legumes could alter soil conditions and AMF microbial functionalities. This might have negative influence on the symbiotic effectiveness of native legumes. Another study by Rodríguez-Echeverría et al (2009) reported significantly higher AMF colonization in exotic legume compared to native legumes. and attributed the change to host specificity or other physiological mechanism (Rodríguez-Echeverría et al., 2009). The variation in AMF root colonization among tree legumes could be related to various factors, including plant-specific interactions, disparities in the composition and quality of root exudates, and genetic variations. (Burrows & Pfleger, 2002). Significant difference was also observed on AMF colonization between the two native legumes *F. albida* and *V. abyssinica* with higher AMF root colonization under *F. albida*. Similar studies were reported by (Zerihun et al., 2013).

Higher AMF root colonization in *Faidherbia albida* might be possibly due to its extensive and deep root systems enabling it to expand mycorrhizal symbiosis with AMF(Mahdhi et al., 2020). In general, AMF colonization and species richness is influenced by various parameters including plant diversity, soil pH, and phosphorus availability (Burrows & Pfleger, 2002). Root colonization process begins with the establishment of the symbiosis of fungal and the host at the rhizosphere and later extended horizontally with the help of spores and hyphae that bridge the soil and plant roots. The propagules (spores & hyphae) functions by creating a vast web network connections making a highway for horizontal nutrient movement(Bonfante & Anca, 2009; Fall et al., 2022).

The number of AMF spores per 100 g dry soil was significantly higher under native legumes than the exotic legume *Sesbania sesban*. AMF Spores are important indicators of AMF colonization potential (Khaliq et al., 2022) indicating reproductive capacity of available AMF species and is affected by variations in size and germination potential among the spores (Burrows & Pfleger, 2002). AMF spore density of the legumes in decreasing order was *Faidherbia albida*, *Vachellia abyssinica* and *Sesbania sesban*. This is in line with a study by Birhane et al., (2018) ; Zerihun et al., (2013) which reported higher AMF spore density under native tree legume. Unlike our findings, other studies (Bainard et al., 2011; Remigi et al., 2008;

Rodríguez-Echeverría et al., 2009) reported a greater abundance of AMF spores in exotic legume species compared to native woody legumes. The differences in AMF spore abundance may be explained by changes in sporulation patterns within the AM fungal taxa or changes in root exudates (Alimi et al., 2021).

6.4.2 Effects on soil properties

pH, SOM, SOC and Av. K were significantly higher under native tree legumes mainly in *Faidherbia albida* trees than in the exotic legume - *Sesbania sesban*. This might be attributed to the higher AMF root colonization and spore abundance observed under native legumes. Similar findings were obtained by Birhane et al.(2018) that reported higher soil organic matter and organic carbon with the presence of *Faidherbia albida* trees. In contrast to our findings, Higher soil organic carbon and available phosphorus was obtained in exotic legume species by (Remigi et al., 2008). Higher total nitrogen value in the *Sesbania sesban tree* (exotic legume) might be related to the specific characteristics of the legume in nitrogen fixation (Nigussie, 2013; Siddique et al., 2008). Higher Av. K was recorded under *Faidherbia albida* whereas lower Av.K was found under *Sesbania sesban* trees which might be due to the higher pH value und the resulting alkaline environment might have favoured more potassium availability.

6.4.3 Correlation between AMF colonization, spore density and soil properties

Strong positive correlation (r=0.97) was observed between AMF root colonization structures HC (hyphal colonization) and MHC (mycorrhizal hyphal colonization). Besides, HC and MHC structures were positively correlated with Soil organic matter, pH, Av.P and organic carbon (Table 6.2). These findings are also in line with Birhane et al. (2017). AMF spore density was very strongly correlated with HC, MHC, AC and VC root colonization structures with maximum correlation between hyphal colonization (*r= .837*) and minimum positive r/ship was observed between Arbuscular colonization (r= *0.73*). AMF spore density also showed strong association with SOM (r = .715). This might be associated with the presence of humus (a carbon rich component of the organic matter) which is consumed by the AMF community as their source of food(Herman et al., 2012). Various soil properties showed strong positive relationship with each other (*Table 6.2*). TN was strongly correlated with Av.P (r= 0.662, n = 36). This correlation could be associated to several soils interconnected processes. The presence of Av.P in the rhizosphere can stimulate plant growth thus promoting nitrogen fixation finally increasing nitrogen amount in the soil (Zhu et al., 2018).Similar findings on positive correlation between TN and Av.P was reported by Molla & Linger, (2017) . Electrical conductivity was also strongly related with Potassium (K^+) (r= 0.649, P< 0.001, n= 9). This might be due to the contribution of K^+ ions to the soils ionic concentration which can increase EC of the soil. The negative correlation between pH and available phosphorus (Av.P) in the soil maybe be associated with the formation of complex /insoluble phosphorus compounds at higher pH level which reduces its availability(Zhu et al., 2018).

6.5 Conclusion and Recommendation

The findings demonstrated significant changes in the percentage of AMF root colonization and spore density between native and exotic legumes. Among the legume trees, *Faidherbia albida*- a native legume had the highest AMF root colonization, followed by *Vachellia abyssinica* and *Sesbania sesban*. Both native tree legumes exhibited significantly higher soil nutrient including SOM, SOC and Av. K than *Sesbania sesban* – an exotic tree legume. The study also highlighted significant relationships ranging from moderate to very strong association between arbuscular mycorrhizal fungi colonization, AMF spore density and soil properties. In conclusion, *Faidherbia albida* and *Vachellia abyssinica* (*indigenous tree legumes*) exhibited greater AMF root colonization, AMF spore density as well as higher soil nutrients compared to *Sesbania sesban* (exotic legume). These findings emphasize the importance of carefully selecting tree species to enhance AMF colonization and spore production in land scape restoration and sustainable land management practices. Understanding the impact of native and exotic tree legumes on AMF root colonization and spore density can contribute to the conservation of beneficial indigenous tree legumes and the development of sustainable agroforestry practices which promote soil fertility and ecosystem resilience. Future agroforestry studies should focus more importantly on the mechanisms and complexity of the below ground AMF- root interactions.

Chapter 7. RWH based small scale agroforestry system and its effect on crop Yield and soil properties

7.1 Introduction

A significant portion of the population(27.1%) in Sub-Saharan Africa (SSA) is currently experiencing food insecurity (Wudil et al., 2022). This issue is exacerbated by the severe impact of intermittent rainfall, which hampers crop productivity in over 90% of the region's rainfed croplands (Kim et al., 2021). Moreover, the problem of food insecurity is expected to worsen due to increasing population pressure in SSA and the resulting demand for food production (Tantoh, 2023). The erratic nature of rainfall has caused longer dry spells (Biazin et al., 2012; Rosa et al., 2020) which in turn resulted in excessive moisture stress and massive yield losses(Malin Falkenmark, 2020). Even farmers with close proximity to rivers cannot easily access the water for irrigation because of various biophysical, economic and institutional barriers(Ahmed et al., 2022). In situ rainwater harvesting which is capturing rainwater in soils and storing excess runoff can bridge dry spells, prevent soil erosion and yield losses. However, green water management is not yet included in to investment strategies and policies for development (Rockström & Falkenmark, 2015). This can negatively influence small-scale farming across the region, which form the building block of agriculture in tropical and subtropical regions. Globally, there are approximately 562 million small scale farming out of 609 million farms (V. D. Nair et al., 2017a). Regenerative measures such as agroforestry systems can support the livelihood of smallholder farmers by providing diversified incomes and maintaining soil fertility (Fahad et al., 2022).

Agroforestry practices can have significant potential in creating a climate resilient agriculture as well as providing diverse ecosystem services compared to mono culture farming (Dev et al., 2018). The integration of trees with in farming systems provides a continuous organic matter input to the soil via their leaf litter and root turnovers which enhances soils physical, chemical and biological characteristics (Fahad et al., 2022). According to Silva et al. (2022), agroforestry systems brought a short term effect on soil quality indicators including increased pH and potassium levels compared to pastures and forests in southern brazil. In designing agroforestry systems, it is desirable to select fast growing multipurpose trees that can simultaneously increase soil organic matter and provide high market values (Mengistu et al., 2022). For instance, a recent study on eucalyptus based agroforestry system in India has resulted in higher soil organic carbon and total nitrogen than mono cropping(Singh et al., 2021). Another study in semi-arid area in India reported an increase in barley yield, soil nitrogen, phosphorus and potassium under eucalyptus based agroforestry systems (Bhardwaj et al., 2017). When trees are intercropped with crops, it is obvious trees may outcompete for resources such as water due to their extensive root and high biomass production rates. Incorporating rainwater harvesting techniques with agroforestry systems can maintain the balance.

In situ rainwater harvesting also known as micro-catchment runoff water harvesting refers to a collection of surface runoff from a small catchment area and storing it in the root zone of soil profile or an adjacent infiltration basin often planted with a tree, a bush or with annual crops(Frezghi et al., 2019). Rainwater harvesting can bridge the mismatch between the rainfall supply and the crop water demand under arid/semi-arid rainfed agriculture. RWH techniques such as stone bunds, terraces, pits, or trenches are a low cost soil and water management techniques that help retain more water on the soil profile by minimizing soil evaporation(Biazin et al., 2014; Rosa et al., 2020). The ratio of catchment area to cropping area can range from 1: 1 to 25: 1 depending on the topography, aridity and soil type (Biazin et al., 2012; Oweis et al., 2012). Due to the small size of the catchment, it can be easily managed and adopted by smallholder farmers. Application of in situ rainwater harvesting such as tied contours and infiltration pits in a semi- arid environment has been reported to increase maize and barley yields compared to solely rainfed crops (Al-Tawaha et al., 2018; Chiturike et al., 2023). In situations where the soil is nutrient depleted, a combination of rainwater harvesting and soil organic amendments can sustainably increase crop productivity (Kubiku et al., 2022).

While Soil moisture stress can be addressed by installing onsite rainwater harvesting techniques(Biazin et al., 2012), nutrient losses of the soil can be compensated by soil organic amendment, a process of altering soil characteristics by using different soil additives (Widowati et al., 2020). Both bio resources and inorganic fertilizers can be utilized as soil fertility enhancement varying in their application from conventional methods to technological advancements (Omotayo & Chukwuka, 2009). However, the high cost of inorganic fertilizers coupled with its adverse environmental impact cannot sustainably reverse exacerbating soil infertility (Halpern et al., 2015). Organic soil amendment have become popular due to their potential to transform or minimize the use of inorganic fertilizers. They can be applied with less cost and without disrupting the environment (Eyhorn et al., 2019). Different bio resources have been applied in the literature such as green manure, poultry litter (raw and its bio char), wood ash, straw, mulches, cover crops etc. in order to enhance soil properties, sequester carbon, and increase crop yield (Amusan et al., 2011; An & Park, 2021; Blair et al., 2014; Management, 2021; Pokhrel et al., 2021). Poultry litter, a mixture of poultry manure and a bedding material from poultry farms has been used for soil amendment due to its high nutrient content (Joardar, 2019). Wood ash is often applied to acidic soils as a liming agent and has been reported to increase pH and essential soil macronutriens(An & Park, 2021). Organic resources that are low cost, locally available and nutrient rich resource substantially improve soil fertility and are the best candidate for selection (Laghari et al., 2016). Poultry litter, poultry litter biochar and wood ash were used in this study to enrich nutrient status of the soil based on the above selection criteria.

Incorporating both organic soil amendment and rainwater harvesting in to an agroforestry system can address the problems associated with competition for water and nutrients between trees and crops. In most parts in Ethiopia, eucalyptus tree is preferred by smallholder farmers due the producing of wood, timber, and wood fuel , and has been usually grown on marginal lands (Alemayehu & Melka, 2022). Nowadays, some smallholder farmers are even motivated to convert their cropland with eucalyptus tree plantation because it is considered as the major player of income in the rural livelihood (Alemayehu & Melka, 2022). Despite the popularity of eucalyptus tree by smallholder farmers and its ecological and economic implications, concerns arise due to the high water demand of eucalyptus and its competition for resources when intercropped with annual crops (Mengistu et al., 2022). The combination of rainwater harvesting and soil organic amendments with *eucalyptus globulus* based agroforestry system in a holistic approach can provide both ecological and socioeconomic benefits while simultaneously addressing the concerns associated with resource competition.

An extensive research has been conducted on the separate applications of soil-water management techniques mentioned above, focusing on their impacts on crop yield and soil quality improvement. Nevertheless, there is a gab of literature on the combined or synergistic effects of these techniques on soil quality, crop yield and biomass. Very few study exist on combination of rainwater harvesting and agroforestry systems such as a study by (Casanova et al., 2021) in the degraded area of Mediterranean zones. The integration of agroforestry systems, rainwater harvesting and soil amendment techniques can have a potential for maintaining soil fertility, increasing crop yield and reducing the risk of food insecurity particularly for smallholder farmers in arid/semi-arid climate (Kugedera et al., 2022).

Therefore, the main objective of this research was to determine the combined effect of a eucalyptus tree based agroforestry system supported with in-situ rainwater harvesting and organic soil additives on soil properties, maize and barley yield, as well as their biomass. The specific objectives were to determine effect of five treatments (rainfed, rainwater harvesting, PLRWHAFS, PLBRWAFS, WARWAFS) on i) soil chemical properties, ii) to determine their effect on maize and barley yield, iii) to evaluate their effect on maize and barley above ground biomass and iv) to determine the relationship between soil parameters and crop yield.

7.2 Materials and Methods

The field experiment was carried out in eastern Tigray at Ganta afoshum district (*see section 5.2.1*). The experimental site is a hilly and rugged topography surrounded by scattered eucalyptus trees (*Eucalyptus globulus*). The selection of the experimental site was made based on various biophysical and socio-economic considerations (Debebe et al., 2023) including slope, soil type, run off , catchment area, distance from settlement etc. It has an area of approximately ($750m^2$). Based on processed elevation model, the experimental site had an elevation ranging from 2161-2621 meters above sea level and a slope ranging from 10 -15^0 in the east and northeast directions to steep slopes as high as 70^0 facing west and southwest direction. The soil was characterized as a sandy loam with a moderately acidic nature, having a pH of 5.53 and an electrical conductivity (EC) of 0.06 dS/m. It exhibited low levels of soil organic matter- 0.23% than the average SOM in the region(Corral-Nuñez et al., 2014). Total nitrogen content was 1.35%, while available phosphorus (Av.P) was measured at 10 mg/kg. In accordance with the guidelines provided by the Ethiopian Agricultural Transformation Agency (Hishe et al., 2017), the soil had low nutrient content and poor water retention capacity.

The novel agroforestry system integrated three methods considering the slope, soil type and topography of the location namely: 1) In-situ rainwater harvesting (stone bunds and rainwater harvesting pond), 2) soil organic amendment (poultry litter, poultry biochar and wood ash and 3) barley (*Hordeum vulgare L*) - maize (*Zea mays*) – *eucalyptus globulu*s intercropping.

7.2.1 In-situ RWH & Supplemental irrigation

Both rainwater harvesting techniques – stone bunds and RWH pond were installed based on the concept of catchment area - cropping area (Oweis et al., 2012) . Stone bunding , an in-situ RWH (5 meter length and 40 cm height) was installed using stones at the upper zone in order to slow down the run off volume and prevent soil erosion (*Fig 7.1*). This reduction in runoff volume allows more time for the water to infiltrate in to the soil. The RWH pond was installed at the foot slope adjacent to the cropping area aimed to store excess run off and serve as supplemental irrigation. The pond had 3 m depth, radius of 5m and size of 225m^3 (*Fig 7.1*). The bottom part of the pond was rocky surface that hardly infiltrates the water. So, seepage losses to ground water were assumed negligible .The pond was covered using metal sheets to prevent evaporation losses.

A total of 33.75 cubic meters of run off was collected (as measured using a measuring stick) by the RWH pond during the entire experiment, which is equivalent to 15% of its full capacity. The minimal runoff was a result of the dry weather conditions during the period from December 2020 to February 2021, with little rainfall, leading to insufficient runoff generation. The crop water requirement for maize and barley was 600mm and 500mm respectively based on FAO recommendations. The collected run off contributed to approximately 47% of the total crop water requirement of both crops – 72 cubic meters (30 number of plots ×4m^2 per plot × 0.6m- maximum crop water requirement). The rest water deficit was supplied by transporting water in jars from nearest hand-dug well approximately 2km away from the cropping area. In general, a supplemental irrigation (combination of direct rainfall when available, RWH pond and well) was applied for the whole crop growth stages. The total growing period took 150 and 120 days for maize and barley respectively. The average irrigation schedule involved 20mm water every five days irrigation interval totalling 30 irrigation days for maize and 25 for barley as per the FAO guideline for supplemental Irrigation(Anderson & French, 2019).

7.2.2 Soil organic resources amendment

Poultry litter (raw and its biochar) and wood ash were selected as soil amenders for both economic and environmental reasons (*Fig 7.2*). These organic resources are locally available waste resources, which contain high soil nutrients with a potential to partially replace the increasing costs of chemical fertilizers (Chan et al., 2008; Romdhane et al., 2021). During a field survey, It was observed that a significant portion of these resources were simply disposed of in farmer's back yards or on nearby open fields. Being the area upstream, it is likely that some if not most of these wastes carried away during periods of heavy rainfall ultimately reaching the shallow wells and rivers downstream. This phenomenon can result in water contamination due to the excessive discharge of nutrients, including nitrogen and phosphorus, into water bodies, potentially leading to eutrophication and a decline in oxygen levels (Katuwal et al., 2022). These changes in water bodies can ultimately lead to the loss of aquatic life, as outlined (Mullins, 2009). The poultry litter was collected from a nearby poultry farming while the wood ash was collected from a kitchen as remains of the firewood after cooking. A total of 72*Kg* of Poultry litter was collected in a sack and transported in to the experimental site 48 Kg of which was used for producing poultry litter biochar assuming 50% weight loss following pyrolysis(Y. Wang et al., 2015). Similarly, 24 Kg of wood ash was collected from the farmer's kitchen in a sack. All the soil additives were sun dried for 24 hours prior to application. They were applied to the soil manually two weeks prior to planting and were regularly watered to ensure effective interaction with the soil (Ali et al., 2017). Each treatment plot (2m×2m) received 4 Kg soil amenders applied at a rate of 10 ton/ha. The same poultry litter dosage amount applied by (Joardar, 2019) showed maximum positive effect on nutrient & plant growth and was used as a reference for all the treatments in this experiment.

Fig 7.1: Stone bunding and rainwater harvesting as in situ RWH methods

7.2.3 Poultry litter Biochar preparation

Poultry litter bio char was prepared on site using a traditional earth kiln made of clay and metal. The collected poultry litter (48Kg) from the poultry farm was sun dried and placed in to the earth kiln at six rounds. The top of the earth kiln was set up with a round, bowl shaped metal container on which the poultry litter was placed and covered with a metal sheet (*Fig 7.3*). The bottom of the earth kiln had a small opening hole for firing. Dried eucalyptus leaves, barks and stems of cactus were used as a fuel source for heating the poultry litter. The pyrolysis process took place in the absence of oxygen where poultry litter was heated for nearly 3 hours resident time and a slow heating rate typical for producing biochar in Ethiopia (Yaebiyo et al., 2023). Due to limitation in the working environment, it was not possible to directly measure the onsite pyrolysis temperature. However, characterization of the produced bio char was similar to those produced at slow pyrolysis temperature of 300 ^{0}C (Laghari et al., 2016). Nair et al.(2017b) also reported biochar produced using sophisticated methods likely exhibit similar behaviour with those produced using simple kilns when applied to a specific soil type. In addition, The slow pyrolysis (250 – 400 ^{0}C) often results in higher biochar yield, higher organic carbon recovery from the feedstock and more functional groups useful for nutrient exchange (Cantrell et al., 2012). After combustion of the feedstock, we opened the metal cover, cooled the biochar naturally, and placed it in a barrel for subsequent use. The produced biochar was a black in colour and solid texture similar to those reported in the literature (V. D. Nair et al., 2017b).

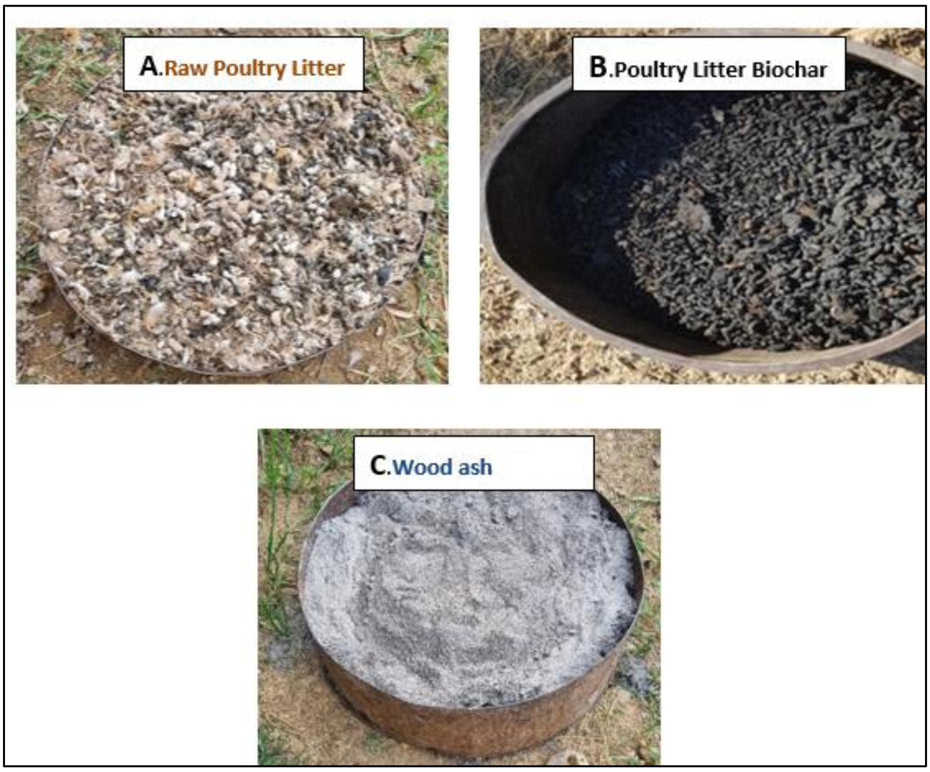


Figure 7.2 .Soil additives for organic soil amendment) A) poultry litter B) Poultry litter bio char, C) Wood ash

7.2.4 Characterization of Soil additives

All soil additives were characterized for selected nutrients including organic matter, organic carbon, total nitrogen, and available phosphorus as in (Motsara & Roy, 2008) at the environmental engineering laboratory – Addis Ababa institute of technology (*Table 7. 1*). From the three soil additives, poultry litter bio-char had highest SOM, SOC, and Av.p followed by raw poultry-litter and wood ash. Poultry litter had maximum total nitrogen-TN followed by poultry bio char and wood ash. High alkaline pH values were observed under wood ash and poultry litter bio-char treated soils while raw poultry-litter had a neutral pH. Wood ash contained the lowest soil TN, Av.P and SOM compared to both poultry litter and its biochar. This could be attributed to the higher nutrient source of animal-based organic resources than plant derivatives(Chan et al., 2008).

Figure 7.3 producing of poultry litter bio char in an earthen kiln and applying to the soil

7.2.5 Eucalyptus - Maize –Barley –intercropping

Simplified illustration of the implemented *eucalyptus tree* based agroforestry system is given in (*Fig 7.4).* Approximately twenty-five scattered *Eucalyptus globulus* tree species ranging from the youngest 1.5 meter height to the highest 7m were present already at the start of the experiment on the upper to mid slope surrounding the crops in a zonal arrangement. The *Eucalyptus globulu*s plantation started 5 years ago in approximately 750m^2 (30 m width × 25m long) area. The spacing between the trees and the crops varied, ranging from as close as 1 meter to as far as 10 meters. The trees were pruned regularly to minimize water and nutrient consumption. In addition, mature eucalyptus trees were cut down regularly for wood and wood fuel purposes, and substituted with new eucalyptus tree seedlings. The deep roots of eucalyptus trees also helps withdraw water and nutrients that are percolated below the root zone and this facilitates nutrient and water recycling making it available for the crops (P. K. Ramachandran Nair, 2011). *Barley- Hordeum vulgare* and maize - *Zea mays* were sawn on the lower zone (Fig 7.5). These crops were selected because both are typical staple food crops preferred by most of the local farmers. The seeds were soaked in water for 24 hours prior to sawing in order to facilitate germination. Sawing for both crops started on January 2021. The maize - *Zea Mays L.* was sown in rows with two seeds per hill and 20 cm spacing between the hills and later thinned after germination to one seed per hill as in (Farhad et al., 2009). Similarly the barely - *Hordeum vulgare* was sown by hand at 20 cm inter row spacing and a depth of 5 cm (Mutlu, 2021) *.* The crop field was protected with fences to prevent it from animal grazing. Weed removal took place manually at a regular interval throughout the experiment for maximum resource utilization. The yield and biomass of both crops were estimated using whole plot harvest method (Fermont & Benson, 2011) . This method is bias free since it involves harvesting the entire plot. For maize plots, the ears were collected from each maize plant, dried and manually separated the kernels from the corncobs. The kernels were then accurately weighed using a balance, and the yield was calculated by averaging values of the three replications. For maize biomass, all above ground leaves, stalks, corncobs, and husks were collected from each square plots and air-dried. Subsequently, the dried samples were cut in to manageable sizes and weighed for biomass estimation. Similarly, the barley plots were harvested after drying and the grains were separated manually from the crop for each square plots. Yield and biomass were finally estimated by weighing the samples.

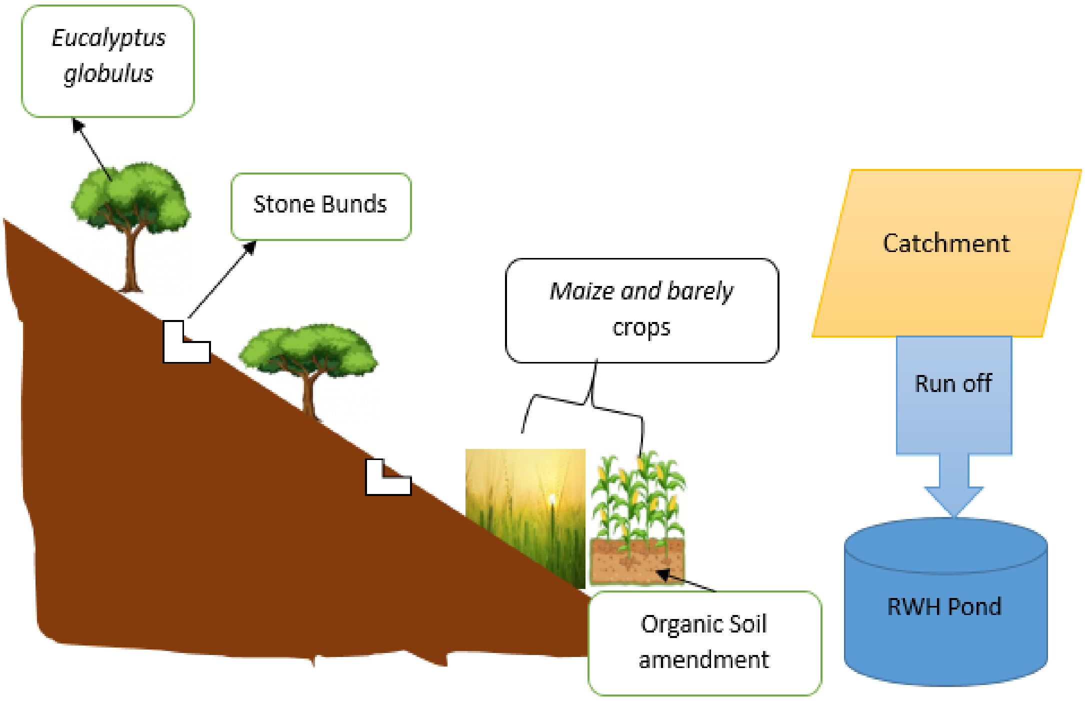


Figure 7.4 partial Schematic illustration of an integrated eucalyptus based rainwater harvesting - agroforestry system intercropped with maize and barley, image of trees and crops were taken from www.Freepik.com accessed on 20.10.2023*: CC BY 4*

7.2.6 Experimental Design

The field experiment was conducted from October 2020 –June 2021. We analysed the effect of a *eucalyptus globulus* tree based agroforestry system – AFS intercropped with *Hordeum vulgare* and *Zea mays* maize. The AFS was combined with in situ rainwater harvesting and soil organic amendments. The effect this combination was assessed on soil nutrients, crop yield and biomass production. The experimental design used was a completely randomized design (CRD) with five treatments and three replications wherein treatment groups randomly allocated to the plots in order to minimize any potential bias. This method was chosen because the area had relatively homogenous soil type. Thirty plots (2m×2m) were prepared for the experiment for both crops. The treatments were based on a combination of in situ rwh and organic soil resources (poultry litter, poultry litter biochar and wood ash) with a *eucalyptus globulus* based agroforestry system. Five treatments were used for each crop with three replications. The treatments were PWAFS, BWAFS, AWAFS, WAFS and AFS (the control) where WAFS refers to the combination of rainwater harvesting (RWH) and agroforestry system (AFS) while the letters P,B, and A refers to poultry litter, poultry litter biochar, and wood ash added to the system. Sample plots of the field experiment are given in *Fig 7.6*. The *eucalyptus globulus* based agroforestry system –AFS is applicable to all the treatments. The difference arises in weather the agroforestry system utilizes supplemental irrigation, organic soil amendment, a combination of both or none at all. Detailed description of the treatments are stated in table below.

Figure 7.5 Eucalyptus globulus based small-scale agroforestry system intercropped with Zea mays & Hordeum vulgare integrated with in situ RWH and organic soil amendment

Table 7.1: description of treatments used for the experiment and their components

Treatments	Components of treatments in the agroforestry system	Soil additive Dosage
1.PWAFS	poultry litter+ supplemental irrigation +AFS	10 ton/ha
2.BWAFS	Poultry biochar+supplemental irrigation+AFS	10 ton/ha
3.AWAFS	Wood ash + supplemental irrigation+AFS	10 ton/ha
4.WAFS	Supplemental irrigation, no soil additive + AFS	None
5.AFS /control	No supplemental irrigation , no soil aditive +AFS	None

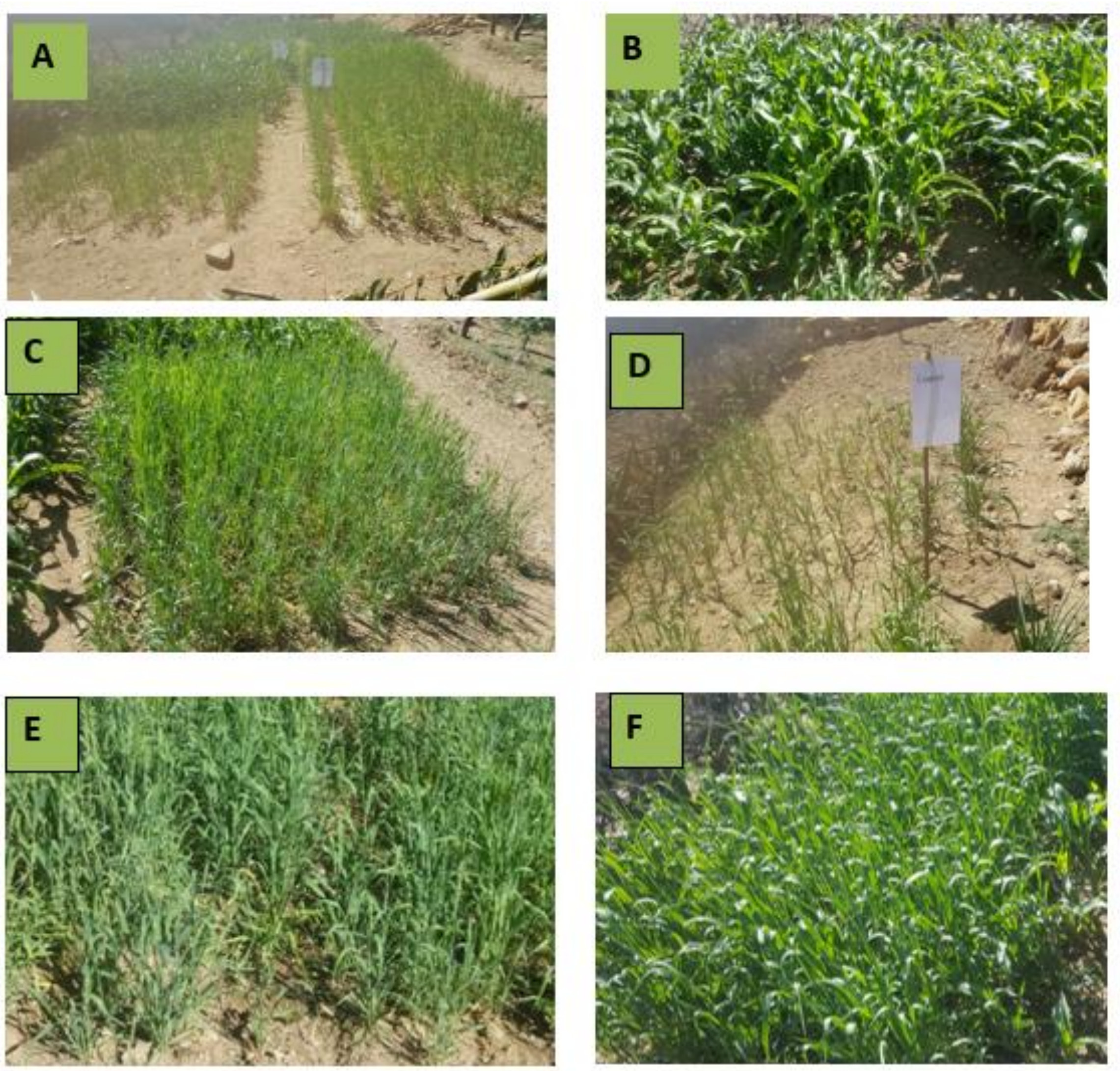


Figure 7.6 Some Sample field plots of maize and Barley intercropped with Eucalyptus: A) Barley plots with wood ash, B- Maize plots with poultry biochar C= Barley plots with poultry litter bio char, D – control plots with maize (with nether soil amendment nor rwh), E =Barley plots with only rwh (no soil amendment), F –maize plots with raw poultry litter

7.2.7 Soil sampling and Laboratory Analysis

Thirty soil samples were collected from the field plots after harvest (150 days for *Maize* & 120 days for *Barle*y). We collected four soil samples with a hand spade from each corner of the plots and one from the center at a depth of 0 – 20 cm using a systematic soil sampling technique (J. Li, 2019). Collected samples were thoroughly mixed to get a homogenized representative soil sample. The samples were packed in plastic bags, labelled and subsequently transported to the environmental engineering laboratory at Addis Ababa institute of technology for soil chemical analysis. In addition to the soil samples, three samples were collected from each soil additives (poultry litter, poultry biochar and wood ash). The samples were air-dried ground and passed through < 2mm sieve for characterization of selected nutrients(Y. Wang et al., 2015). The analysis was conducted using the updated FAO guideline for soil and plant analysis for moderately acidic soils (Motsara & Roy, 2008). Selected soil parameters were pH, EC, SOC, SOM, Av.P, and TN. Soil pH was measured with 1:2.5 soil water ratio using pH meter. Electrical conductivity EC was measured by EC meter by preparing 0.01potassium chloride reagent solution. Soil organic carbon (SOC) was determined by walkey and black wet digestion method. Soil Organic matter - OM was determined by multiplying OC by the factor 1.724 assuming SOC comprised of 58% organic matter. Available phosphorus was measured using Bray 1 method (Bray RH & Kurtz LT, 1945) while total nitrogen was computed by the Kjeldahl method (nelson & sommers, 1982). Soil samples were characterized for soil macro and microelements (*Ca, Mg, K, Mn, Cu, Fe, Mo, and Zn*) by using inductively coupled plasma - optical emission spectrometry -ICP-OES , M 02.015 at the central laboratory TU Hamburg. The samples were first freeze –dried, ground and dissolved with Aqua regia- HF for analysis.

7.2.8 Statistical analysis

Assumption of normality test was carried out using Shapiro-Wilk test prior to data analysis. The datas were analyzed using a statistical package IBM SPSS statistics V26. Variations in selected soil properties, crop yield and crop biomass were analysed between the treatments rainfed (control), in situ rwh and rwh + organic amendment for significance differences using a one way ANOVA and a *Tuckey test* was used to determine significance difference between treatments. The relationship between selected soil chemical properties, crop yield and crop biomass was analysed using Pearson correlation coeffient. Significance variation in crop yield and biomass between the treatments was analysed using one-way ANOVA.

7.3 Result

7.3.1 Soil chemical properties

Soils treated with biochar & RWH (BWAFS) had higher pH value followed by AWAFS (wood ash & RWH) and PWAFS (Poultry litter &RWH) at a significance level of $p < 0.05$. Both PWAFS and AWAFS had similar positive effect on pH. Conversely, WAFS (RWH but no soil aditive) had non-significant effect on pH ($P<0.05$) compared to AFS (neither RWH nor Soil additive). Maximum and minimum SOM (2.26%, 1.21%) were observed under BWAFS and AFS respectively. Both SOC and SOM exhibited significant variations among all the treatments. BWAFS, PWAFS, AWAFS increased SOM by 86%, 27.2%, 16.5% and 5.7% respectively in comparison with AFS (control). Treatments involving only RWH (WAFS) had a slight effect on SOM (5.8% increase) but a non-significance effect on SOC compared to the control.

Similar to SOM, treatments involving soil amendment and RWH had higher TN and Av. P compared to treatments with no soil amendment nor RWH. Particularly, total nitrogen -TN was maximum in PWAFS and minimum in AFS (control). There was no statistically significant variation observed between BWAFS and PWAFS with TN 2.9% and 2.7% respectively. Maximum Av.P was observed under BWAFS and minimum under AFS. BWAFS and PWAFS had significant effect on Av.P with increases of 78.1% and 63% relative to the control plots. AWAFS (wood ash &RWH) and WHAFS (only RWH) treatments had no statistically significant difference at $p < 0.05$. Maximum Ca and Mg were obtained under BWAFS (biochar &RWH) with increases of 35.5% and 19.2% respectively while AWAFS exhibited minimum Ca and Mg levels. Conversely, both BWAFS and AWAFS treatments exhibited a reduction on potassium level –K. Only PWAFS treatments (poultry litter & RWH) slightly increased K level by 5.2%. BWAFS had maximum Manganese -Mn (10.5% increase) followed by PWAFS. AWAFS and AFS had no significant variation in Mn. Similarly, BWAFS treatments substantially increased copper-Cu by 67% followed by AWAFS (53%), and PWAFS (42%) compared to the control-AFS.

PWAFS and BWAFS significantly increased Iron (Fe) by 16% and 10.5% respectively. AWAFS treated soils had no significant effect on Fe. Molybdenum (Mo) and Zinc (Zn) did not exhibit any significant changes among all the treatments.

Table 7.2 some characteristics of poultry litter, poultry litter bio char and wood ash

Parameters	Raw PL	PL Biochar	WA
pH	6.90	8.70	9.70
EC (dsm^{-1})	0.21	0.23	0.29
Organic carbon (%)	16.43	21.29	2.28
Organic matter (%)	28.32	36.71	3.94
Total nitrogen (gKg^{-1})	22.63	13.76	$45*10^{-3}$
Av.p(gKg^{-1})	18.70	26.37	9.15

*EC= electrical conductivity, Av.p = available phosphorus, (% = 10 * g/*Kg DM*)*

Table 7.3 effect of treatments on selected soil fertility indicators

Treatments	**pH**	**SOM (%)**	**SOC (%)**	**TN (g/Kg)**	**Av.p (mg/kg)**
PWAFS	5.77 ± 0.06^{a}	1.54 ± 0.00^{a}	0.88 ± 0.01^{a}	2.9 ± 0.03^{a}	21.40 ± 0.00^{a}
BWAFS	6.32 ± 0.14^{b}	2.26 ± 0.01^{b}	1.31 ± 0.00^{b}	2.7 ± 0.04^{a}	23.26 ± 0.01^{b}
AWAFS	5.76 ± 0.18^{a}	1.41 ± 0.02^{c}	0.66 ± 0.00^{c}	1.7 ± 0.02^{b}	19.06 ± 0.01^{c}
WAFS	5.36 ± 0.25^{c}	1.28 ± 0.08^{d}	0.74 ± 0.06^{d}	1.1 ± 0.03^{c}	18.45 ± 0.06^{c}
AFS	5.29 ± 0.03^{c}	1.21 ± 0.00^{e}	0.71 ± 0.01^{d}	$.59 \pm 0.04^{d}$	13.14 ± 0.05^{d}

Data are means ± SE, n = 3, means followed by the same letter with in a column are not significantly different at $p<0.05$ where PWAFS – (poultry litter & rainwater harvesting,), BWAFS (biochar & rainwater harvesting,), AWAFS (wood ash, rainwater harvesting,), WAFS (rainwater harvesting with no soil additive), AFS (agroforestry system with no rainwater harvesting nor soil amendment)

7.3.2 Crop Yield and Biomass

Soils treated with a combination of organic amendments and RWH under *eucalyptus globulus* based agroforestry systems had significant increases in crop yield and biomass. Maximum maize biomass was observed under BWAFS (56.5% increase) while minimum maize biomass was observed in WAFS (16.2% increase) relative to AFS- the control. Both PWAFS and AWAFS had a similar effect on maize biomass with non-significant variation between the treatments. There was significant variation in barley biomass among the treatments compared to the control. BWAFS had maximum barley biomass (61.5%) and minimum biomass was found in WAFS (28.5%).There was no significant differences between PWAFS and BWAFS as well as between AWHAS and WAFS at $p<0.05$. Similar to maize biomass, both BWAFS and PWAFS treatments increased maize yield by 74% and 36% respectively. Minimum maize yield was found under WAFS (2.08 ton/ha) with 6.7% yield increase. There was no significant changes observed between AWAFS and WAFS. Barley yield was highly influenced by the combination of biochar and RWH-BWAFS resulting in yield increase by 89.6% followed by AWAFS - 62.2% and PWAFS- 57%.

7.3.3 Correlation between crop yield, Crop biomass and soil parameters

Positive and strong correlation was observed between crop yield, crop biomass and selected soil properties ($P< 0.05$ and $P< 0.01$). Yield and Biomass of maize/ barley was strongly and positively correlated with pH, TN and Av.p (Table 7.5); Positive and moderate correlation was found with SOM. Conversely, Maize yield was less strongly correlated with EC and SOC relative to other parameters.

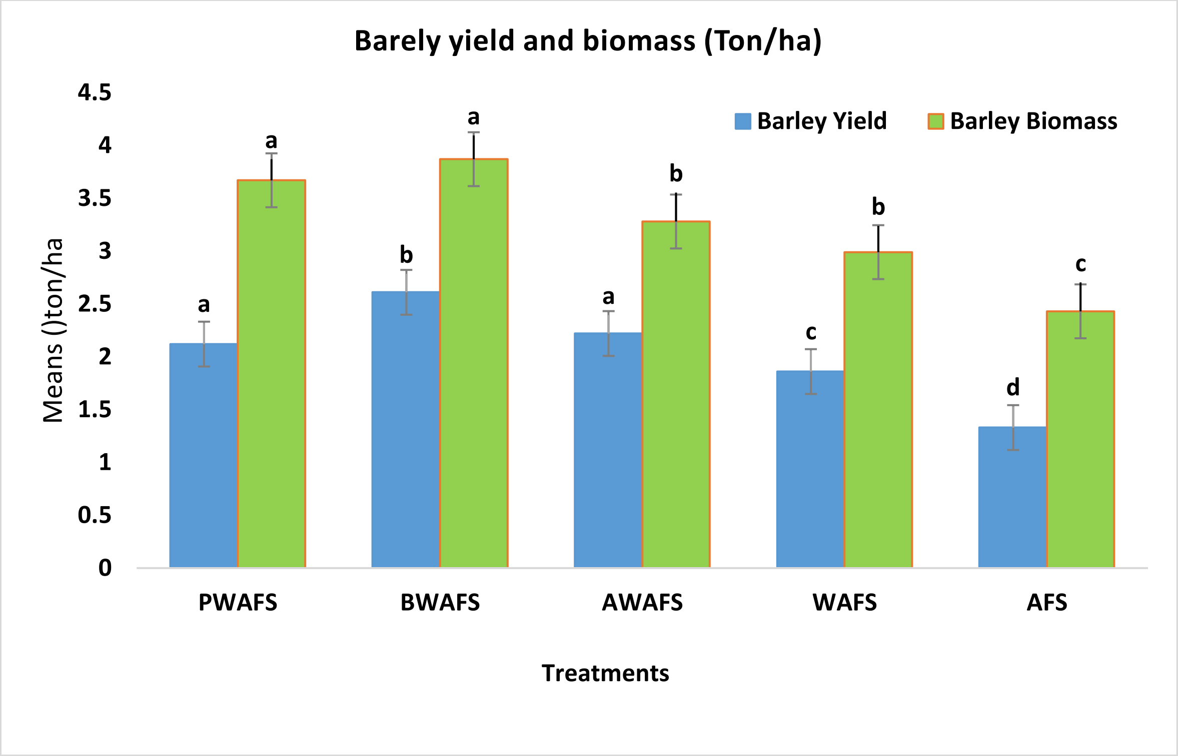


Figure 7.7 Effect of the treatments on barley (Hordeum vulgare L) yield & barley biomass Data are means ± SE, n= 3 means followed by the same letter with in a column are not significantly different from each other at $p<0.05$, PWAFS = poultry litter & rainwater harvesting, BWAFS= poultry biochar & rainwater harvesting, AWAFS = wood ash &rainwater harvesting, AFS = Agroforestry system with neither rainwater harvesting nor soil amendment

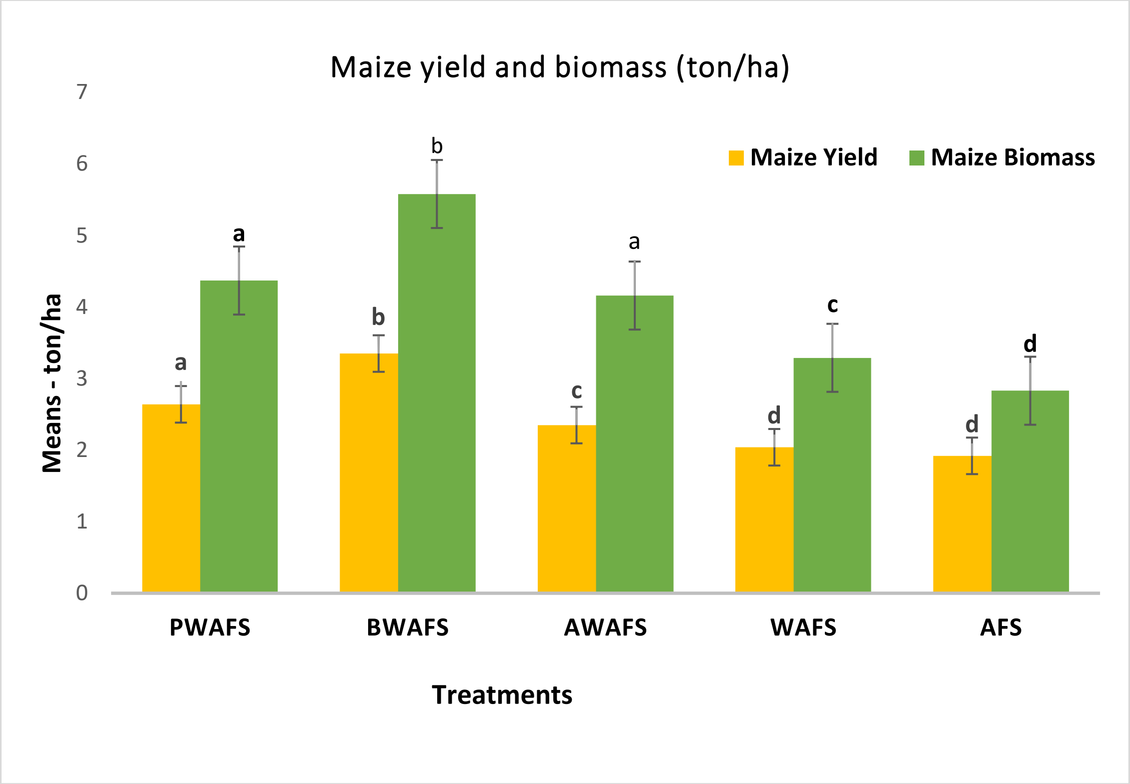


Figure 7.8 Effect of treatments on Maize (Zea Mais) yield and biomass, Data are means ± SE, n= 3 means followed by the same letter with in a column are not significantly different from each other at p<0.05, PWAFS = poultry litter & rainwater harvesting, BWAFS= poultry biochar & rainwater harvesting, AWAFS = wood ash &rainwater harvesting, AFS = Agroforestry system with neither rainwater harvesting nor soil amendment

Table 7.4 means of macro and micro soil nutrients (g/K*g* DM or mg/K*g* DM)

Treatments	macro nutrients - g/Kg			micro nutrients - mg/Kg				
	Ca	**Mg**	**K**	**Mn**	**Cu**	**Fe**	**Mo**	**Zn**
Control	3.25	1.68	9.61	0.238	15.00	10.5	<1.3	<250
BWAFS	5.04	2.08	9.59	0.283	25.00	11.6	<1.3	<250
AWAFS	3.66	1.74	9.06	0.236	23.00	10.7	<1.3	<250
PWAFS	3.56	1.98	10.1	0.263	26.00	12.5	<1.3	<250

PWAFS - poultry litter & rainwater harvesting, BWAFS- poultry biochar & rainwater harvesting, AWAFS - wood ash &rainwater harvesting, AFS - Agroforestry system with neither rainwater harvesting nor soil amendment

Table 7.5 Pearson correlation coeffient between maize and barley yield, biomass and selected soil parameters

Crop Yield and Biomass	Soil chemical properties					
	pH	EC	SOM	SOC	TN	Av.P
Maize Yield	.887**	.496	.501	.478	.904**	.691**
Maize Biomass	.876**	.616*	.541*	.558*	.856**	.756*
Barley Yield	.768**	.692**	.561*	.614*	.709**	.805*
Barley Biomass	.826**	.557*	.492	.503	.885**	.576*

*significant at 0.05 level, ** Significant at 0.01 level

7.4 Discussion

7.4.1 Soil properties

Soil chemical properties including pH, SOM, SOC, TN, AV.P, macro & micronutrients were positively affected by the combined application of RWH and soil organic amendment under *Eucalyptus globulus* agroforestry system. Similar results were found by (Bhardwaj et al., 2017) which reported positive changes in N, P and K under eucalyptus based agroforestry system. SOM and SOC are important soil attributes for higher crop productivity (Lal, 2014). SOM substantially improves soil chemical, biological and physical characteristics via mobilization of nutrients through SOM decomposition(Corral-Nuñez et al., 2014). Value of SOC/SOM is dependent on factors like climatic conditions (precipitation and temperature) and biotic properties such as quantity & quality of carbon inputs (Luo et al., 2017). Higher SOM values under BWAFS, PWAFS and AWAFS could be attributed to presence of more organic matter inputs and root turnover. These results are in agreement with (Singh et al., 2021) which reported higher soil organic matter on eucalyptus tree based intercropping. The values of SOM and SOC were however low for all the treatments except for BWAFS – biochar &RWH compared to SOM values of farmlands and exclosure areas (2.1 to 5.6) % in the highlands of Tigray (Corral-Nuñez et al., 2014). The higher pH value under treatments involving soil amendment might be related to the various soil biogeochemical process such as mineralization of organic matter & metal ions or enzymatic activity that can influence soil pH (Neina, 2019).

The increase in pH of acidic soils can be associated with the availability of alkaline elements with a potential of neutralizing acidic soils (Zolfi-bavariani et al., 2017). A long-term study on combination of poultry litter and walnut tree based agroforestry system also resulted in higher pH value(Sauer et al., 2015). BWAFS &PWAFS treatments involving poultry litter and poultry biochar exhibited higher soil nutrient such as SOM, TN and Av.P compared to AWAFS - treatments that involve wood ash. This could be associated with availability of high organic matter, total nitrogen and phosphorus on both poultry litter and poultry litter biochar (table 3). According to (Chan et al., 2008), organic soil resources that originated from animal-wastes had higher nutrient amount than their plant derivatives. In addition, the lower TN under AWAFS (wood ash &RWH) could be due related to the very limited nitrogen amount available on wood ash (An & Park, 2021) compared to poultry litter and its biochar. Phosphorus is among the most critical soil nutrients responsible for crop productivity. The combination of soil amendment and RWH had significant positive effect on available phosphorus with higher effects on treatments involving poultry biochar and RWH. This might be attributed to the formation of immobile phosphorus compounds following poultry biochar application and the resulting delayed rapid sorption of phosphorus thus slowly releasing P to the soil (Zhu et al., 2018). Treatments that combined only RWH and agroforestry system (WAFS) also resulted in higher SOC, TN and Av.P compared to treatments with only agroforestry systems- AFS. Similar positive changes in TN and SOC were reported by Salazar et al. (2011) in the drylands of Chile which combined rainwater harvesting and agroforestry systems with similar agroecology. BWAFS treatments had notably higher Ca and Mg ions whereas no significant changes were exhibited between PWAFS and AWAFS. These results are in agreement with (Chandra et al., 2020; Gezahegn et al., 2019) which reported higher Ca and Mg ions following soil biochar application. The observed increase in various soil nutrients discussed above could be attributed to the synergistic effect the combined application of organic resources, rainwater harvesting and the litter falls and root turn over from *eucalyptus globulus* tree. Rainwater Harvesting can favour water retention, facilitate nutrient mobilization and organic matter mineralization (G. Singh, 2012).Besides, instu rainwater harvesting can prevent or reduce massive nutrient losses. A study by Grum et al. (2017) in northern Ethiopia reported up to 80% reduction in soil nutrient losses including TN and Av.P with instu rainwater harvesting. Soil organic amendments are also known to supply essential nutrients to the soil leading to higher crop productivity (Chandra et al., 2020; Z. Liu et al., 2017; Pandit et al., 2018)

7.4.2 Crop yield, biomass & relationship with soil parameters

Yield and biomass of barley (*Hordeum vulgare L*) and maize (*Zea mays)* were positively affected by the combination of RWH and soil organic amendments under *Eucalyptus globulus* agroforestry system. BWAFS (biochar &RWH) showed maximum positive effect on maize yield/biomass (3.39, 5.58 ton ha^{-1}) as well as barley yield/biomass (2.56, 3.86 ton ha^{-1}) respectively. This could be associated to higher positive net effects of PLB on soil nutrients and the role of Instu RWH in preventing crop failure finally resulting in higher crop yield. It has been reported that crop failure due to water shortages can cause up to 50% crop yield losses (Mekdaschi Studer & Liniger, 2013). A similar increase in *Zea mais* yield was found by (Nyaga et al., 2019) under eucalyptus tree based agroforestry system through managing competition. The calculated maize yield was found to be higher when compared to maize yields with only in situ rainwater harvesting (Chiturike et al., 2023; Makhlof et al., 2019). AWAFS (wood ash & RWH) did not significantly increased in both maize and barley yield relative to the other treatments. This might be attributed to the limited nitrogen nature of the wood ash (Romdhane et al., 2021). Similar to maize yield/biomass, BWAFS significantly increased barley yield followed by PWAFS, AWAFS, WAFS and AFS- the control. With WAFS, treatments (RWH & AFS) without soil amendment also increased about 6% maize yield and 36.2% barley yield. Barley yields were much higher compared to treatments which solely depend organic amendment (Makhlof et al., 2019; Mutlu, 2021). PH, TN and Av.P had Strong positive correlations with crop yield and biomass of both crops. Since pH is among the most dominant soil attributes that determine soil nutrient availability (Moral & Rebollo, 2017), its strong association with crop yield could be that more nutrients were readily taken up by plants that lead to higher yields(Neina, 2019). Similarly, the strong correlation of crop yield and biomass with TN and Av.P could be the indication of the positive influence of these nutrients on crop productivity (Soofizada et al., 2023).

7.5 Conclusion and Recommendation

To summarize, the combination of RWH and soil organic amendments under *eucalyptus globulus* tree based agroforestry system positively influenced pH, SOM, TN and Av.P compared to AFS treatments with neither soil amendment nor RWH. BWAFS significantly increased pH, followed by AWAFS and PWAFS. Soil organic carbon SOM significantly varied among all treatments, with the highest values observed under BWAFS and the lowest in AFS. Similarly, higher TN and Av.P values were observed under BWAFS followed by PWAFS and WAFS. In terms of soil microelements, BWAFS had higher Ca, Mg, Mn and Cu. Potassium–K and Iron-Fe levels were however higher under PWAFS treatments. As with soil chemical properties, soils treated with a combination of organic amendments and RWH in the agroforestry system exhibited significant increases in crop yield and biomass. Maize (*Zea Mais*) and barley (*Hordeum vulgare L*) yield & biomass were positively correlated with pH, TN, and Av.P. Overall, the study indicated that combining rainwater harvesting and soil organic amendments to a *eucalyptus globulus* based agroforestry system has the potential to improve soil fertility, crop yield, and biomass. These findings have implications for sustainable organic agricultural practices in the region and beyond. However, further research is needed to measure the long-term interaction effects of *Eucalyptus globulus* tree on crop yield & biomass of Zea *mais* and *Hordeum vulgare L* at different seasons prior to upscaling the system. Besides, future studies on agroforestry should prioritize on tree –crop complementarity with a particular emphasis on leguminous trees due to their role in nutrient acquisition.

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Appendix

Table A.

weighted overlay method (Debebe et al., 2023)

Criteria	Weight (% influence)	Sub criteria	Score [1-10]
Slope-0^0	9	0-5	9
		5-10	8
		10-15	7
		15-25	6
		>25	5
Aspect- 0^0	8	Flat,North	9
		East	8
		SE,SW	6
		West	5
		N.West	5
Annual Rainfall(mm)	31	497-532	7
		532-552	7
		552-565	8
		565-775	9
		575-587	9
LULC	7	built-up area	1
		Dense. Vegitation	2
		Pasture	7
		Crop land	8
		Mountainous	6
		Water bodies	9
Soil texture	20	Loam	7
		Sandy loam	6
		Clay loam	8
		Clay	9

Moisture Index	14	Very dry Dry Moderate Wet Very wet	3 4 5 7 7
Stream order	5	1st 2nd 3rd 4th 5th	3 3 5 6 7
Dist to Road (Km)	3	0-2 2-4 4-6 6-8 >8	9 8 6 3 2
Dist to River(Km)	3	0-1.5 1.5-3 3-4.5 4.5-6 >6	7 5 5 3 3

Table B. Run off depth estimation using soil conservation service – curve number (SCS-CN)

DoY = days of the year

DoY	**Rainfall (mm/day)**	**(P-0.2S)**	**(P-0.2S)^2**	**(P+0.8S)**	**Run off depth (mm)**	**Run off Volume(m^3)**
08/02/2021	27.38	13.05	170.3025	84.68	2.01113	2,000,000
26/04/2021	18.35	4.02	16.16	75.65	0.21	210,000
07/05/2021	15.74	1.41	1.98	73.04	0.027	27,000
08/05/2021	23.42	9.09	82.6	80.72	1.02	1,020,000
09/05/2021	18.04	3.71	13.76	75.3	0.18	180,000
10/05/2021	20.87	6.54	42.77	78.21	0.54	540,000
14/05/2021	37.51	23.18	537.3	94.84	5.66	5,660,000
01/07/2021	17.82	3.49	12.18	75.1	0.162	162,000
03/07/2021	18.3	3.97	15.76	75.6	0.208	208,000
04/07/2021	14.87	1.03	1.076	72.17	0.014	14,000
07/07/2021	16.19	1.86	3.46	73.49	0.047	47,000
08/07/2021	17.03	2.7	7.29	74.33	0.098	98,000
09/07/2021	18.8	3.75	14.06	76.1	0.184	184,000
13/07/2021	32.97	18.64	347.4	90.27	3.848	3,848,000
14/07/2021	23.65	9.32	86.86	80.95	1.07	1,070,000
21/07/2021	27.27	12.94	167.4	84.57	1.947	1,947,000
28/07/2021	28.26	13.99	194.04	85.56	2.26	2,260,000
01/08/2021	21.34	7.01	49.14	78.64	0.62	620,000
05/08/2021	15.49	1.16	1.346	72.79	0.018	18,000
06/08/2021	17.53	3.2	10.24	74.83	0.13	130,000
07/08/2021	22.84	8.51	72.42	80.14	0.9	900,000
08/08/2021	18.29	3.96	15.68	75.59	0.207	207,000
26/08/2021	44.58	30.25	915.06	101.88	8.98	8,980,000
05/09/2021	24.42	10.09	101.88	81.72	1.246	1,246,000
22/09/2021	24.61	10.27	105.47	81.91	1.287	1,287,000
29/12/2021	43.83	29.5	870.25	101.13	8.6	8,600,000

30/12/2021	31.59	17.26	297.91	88.89	3.35	3,350,000
Total						49,374,000
29/04/2020	21.40	7.07	50	78.7	0.64	640,000
01/05/2020	41.62	27.29	745	98.9	7.53	7,530,000
23/05/2020	21.94	7.61	58	79.2	0.73	730,000
16/07/2020	14.75	0.42	0.18	72.1	0.0025	2500
20/07/2020	16.54	2.21	4.8	73.8	0.065	65000
26/07/2020	31.92	17.59	308.4	89.2	3.46	3,460,000
5/08/2020	31.58	17.25	297.6	88.9	3.45	3,450,000
10/08/2020	21.75	7.42	55.1	79.1	0.704	704,000
15/08/2020	21.23	6.9	47.6	78.54	0.61	610,000
16/08/2020	23.27	8.94	79.9	80.6	0.99	990,000
Total						18,181500
15/02/2019	14.62	0.29	0.08	71.9	0.001	1000
1/04/2019	14.79	0.46	0.21	72.1	0.003	3000
13/04/2019	14.37	0.04	0.002	71.7	0.00	0.00
9/06/2019	23.89	9.56	91.4	81.2	1.13	1,130,000
11/08/2019	15.07	0.74	0.55	72.4	0.008	8000
29/09/2019	15.23	0.9	0.81	72.5	0.011	11000
1/10/2019	58.46	44.13	1,947.50	115.8	16.81	16,810,000
13/10/2019	18.59	4.26	18.15	75.8	0.24	240,000
22/11/2019	24.68	10.35	107.1	82	1.31	1,310,000
Total						17,963000
31/01/2018	23.4	9.07	82.26	80.7	1.56	1,560,000
15/03/2018	16.48	2.15	4.62	73.78	0.062	62,000
14/08/2018	48.13	33.8	1142.4	105.43	10.84	10,840,000
15/08/2018	14.67	0.34	0.12	71.97	0.002	2000
16/08/2018	31.35	17.02	289.6	88.65	3.26	3,260,000
09/09/2018	89.57	75.24	5661.1	146.87	38.54	38,540,000
Total						54,264000
27/04/2017	49.78	35.45	1256.7	107.8	11.65	11,650,000

29/04/2017	39.38	25.05	627.5	96.68	6.49	6,490,000
14/05/2017	15.52	1.19	1.41	72.82	0.02	20,000
16/07/2017	18.94	4.61	21.25	76.24	0.28	280,000
02/08/2017	16.95	2.62	6.86	74.25	0.1	100,000
15/08/2017	24.87	10.54	111.1	99.12	1.12	1,120,000
24/08/2017	28.51	14.18	201.07	88.88	2.26	2,260,000
25/082017	27.34	13.01	169.26	84.64	1.99	1,990,000
Total						21,790,000
22/03/2016	21.24	6.91	47.48	78.7	0.087	87000
29/04/2016	19.95	5.62	31.58	77.25	0.41	410,000
30/04/2016	37.3	22.97	527.62	94.6	5.57	5,570,000
01/05/2016	20.14	5.81	33.75	77.44	0.43	430,000
07/05/2016	21.99	1.53	2.35	79.29	0.03	30,000
08/05/2016	15.06	0.73	0.533	72.9	0.007	7000
11/07/2016	17.52	3.19	10.17	74.82	0.135	135,000
16/07/2016	18.85	4.52	20.43	69.58	0.065	65,000
21/07/2016	39.68	25.35	642.6	96.98	6.626	6,626,000
31/07/2016	36.03	21.7	470.89	93.3	5.04	5,040,000
11/08/2016	30.95	16.62	276.2	88.25	3.12	3,120,000
12/08/2016	30.01	15.68	245.8	87.31	2.81	2,810,000
04/09/2016	27.32	12.99	168.74	84.62	1.99	1,990000
Total						26,320,000
28/06/2015	28.26	13.93	194.04	85.56	2.27	2,270,000
29/06/2015	58.63	44.3	1962.5	115.9	16.92	16,920,000
01/08/2015	29.26	14.93	222.9	86.56	2.57	2,570,000
14/08/2015	14.73	0.4	0.16	72.03	0.002	2000
25/08/2015	14.47	0.14	0.012	71.77	0	00
26/08/2015	72.79	58.46	3417.6	130.1	26.27	26,270,000
Total						48,032000
06/04/2014	25.27	10.94	119.68	82.57	1.45	1,450,000
08/07/2014	15.82	1.49	2.22	73.12	0.03	30,000

17/07/2014	16.12	1.79	3.204	73.42	0.04	40,000
20/07/2014	37.19	22.86	522.57	94.49	5.53	5,530,000
22/07/2014	20.74	6.41	41.08	78.04	0.52	520,000
30/072014	14.49	0.16	0.025	71.79	0	00
31/07/2014	22.29	7.96	63.36	85.65	0.74	740,000
03/08/2014	24.49	10.16	103.2	81.79	1.26	1,260,000
24/08/2014	34.4	20.07	402.8	91.7	4.39	4,390,000
26/08/2014	16.44	2.11	4.45	73.74	0.06	60,000
06/09/2014	19.75	5.42	29.4	77.05	0.38	380,000
Total						14,400,000
17/07/2013	22.09	7.76	60.21	79.31	0.76	76000
22/07/2013	15.05	0.7	0.49	72.35	0.006	6000
28/07/2013	15.35	1.02	1.04	72.65	0.013	13,000
29/07/2013	17.35	3.02	9.12	74.65	0.122	122,000
30/07/2013	30.11	15.78	249	87.41	2.84	2,840,000
01/08/2013	16.06	1.73	2.99	73.36	0.04	40,000
03/08/2013	46.69	32.36	1047.2	103.9	10.07	10,070,000
04/08/2013	25.71	11.38	129.5	83.01	1.56	1,560,000
05/08/2013	19.49	5.16	26.62	76.79	0.35	350,000
07/08/2013	14.46	0.13	0.017	71.76	0	0
12/08/2013	28.83	14.4	207.36	86.13	2.41	2,410,000
21/08/2013	16.27	1.94	3.76	73.57	0.05	50,000
05/10/2013	20.55	6.22	38.66	77.85	0.49	490,000
06/10/2013	18.56	4.23	17.89	75.86	0.23	230,000
Total						18,257000
19/07/2012	22.19	7.76	60.2	79.39	0.75	750,000
01/07/2011	35.22,	20.89	436.4	92.52	4.71	4,710,000
05/07/2011	18.39	4.06	16.48	75.69	0.22	220,000
Total						4,930,000
18/07/2010	17.53	3.2	10.24	74.83	0.136	136000
20/07/2010	25.84	11.51	132.48	83.14	1.59	1590000

07/08/2010	19.88	5.55	30.8	77.18	0.399	399,000
12/08/2010	15.52	1.19	1.41	72.82	0.02	200,000
24/08/2010	18.08	3.75	14.06	75.38	0.186	186,000
25/08/2010	14.34	0.01	0.0001	0	0	0
26/08/2010	19.26	4.93	24.3	76.56	0.317	317,000
27/08/2010	22.58	8.25	68.06	90.64	0.75	750,000
28/08/2010	27.42	13.09	171.34	84.72	2.02	2,020,000
29/08/2010	15.15	0.82	0.67	72.45	0.009	9000
30/08/2010	17.27	2.94	8.64	74.57	0.115	115,000
Total						6,762,000

Table C. Pearson correlation between soil chemical properties

Pearson Coefficient (r)	pH	SOC	SOM	TN	Av. P
pH	-	.65*	.65*	.48	.64*
SOC		-	.98**	.91**	.95**
SOM			-	.907**	.953**
TN				-	.971**
Av. P					-

**Correlation is significant at the 0.05level, **Correlation is significant at the 0.01 level where EC- electrical conductivity, SOC –soil organic carbon, SOM – soil organic matter, TN – total nitrogen, Av.P –available phosphorus*