The effects of afforestation of agricultural land on the water balance in the Ethiopian highlands

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Effects of afforestation of agricultural land on the water balance in Ethiopian Highlands

Effekter av beskogning av jordbruksmark på vattenbalansen i etiopiska höglandet

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Abstract

In this study, I examined how land use change affects the partitioning of water and how soil-plant interactions are impacted by yearly rainfall at a stand scale. Even though many studies have been conducted to evaluate the extent of land use change and the economic impacts, few have attempted to study the rapid farmer-driven afforestation with *Acacia decurrens* and also disaggregated dry, normal and dry seasons at stand scale. Most of the studies are done on a large scale or capture catchment.

The purpose of this study was to analyse how changes in land use from annual to perennial crops affected water balance at a stand scale in the Ethiopian highlands. A recent change in land use in Fagita Lekoma, Ethiopia, has seen farmers adopt planting *A. decurrens* rather than teff.

To study the impact of changing land use from annual to perennial cropping on the water balance, a crop water productivity model called AquaCrop model 6.1 was used. This study used a long-term climate dataset (1982-2020) to represent, dry, normal and wet Kiremt seasons. In this study, the land use change for *A. decurrens* stands aged 1 to 4 years were compared to annual teff cultivation.

The key findings from this study are that afforestation with *A. decurrens* increases actual evapotranspiration (ETa) and reduces runoff. The estimated annual mean ETa for afforestation with *A. decurrens* from this study was 497 mm/y, 474 mm/y, and 461 mm/y during the dry, normal, and wet Kiremt seasons, respectively. In contrast, the annual mean ETa during teff cultivation ranged from 322 mm/y during the dry Kiremt season to 346 mm/y during the normal Kiremt season and 297 mm/y during the wet Kiremt season. Further, the annual mean runoff for teff cultivation during the dry, normal, and wet Kiremt seasons was 74 mm/y, 330 mm/y, and 636 mm/y, respectively. On the other hand, surface runoff during afforestation with *A. decurrens* was 13 mm/y, 56 mm/y, and 144 mm/y during the dry, normal, and wet Kiremt seasons respectively. Lastly, during this study, results show an unexpected high annual mean drain during afforestation with *A. decurrens*. The drain was 408 mm/y, 1,574 mm/y and 1,171 mm/y during the dry, normal and wet Kiremt seasons respectively. While Teff cultivation had an annual mean drain of 413 mm/y during the dry season, 956 mm/y during the normal Kiremt season, and 1,208 mm/y during the wet Kiremt season.

The results of this study suggest that afforestation with *A. decurrens* in Ethiopian highlands will likely result in a downstream effect of reducing stream flow during dry periods due to increased ETa. However, more information on crop parameters in the model could alter this conclusion.

Keywords: Acacia decurrens, AquaCrop Model, afforestation, water balance, teff

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Abbreviations

A. decurrens	Acacia decurrens
A. mearnsii	Acacia mearnsii
CC	Green canopy cover [per cent or fraction]
CSV	Comma-separated values
CN	Curve Number
CV	Coefficient of Variation
DOY	Day of Year
ETa	Actual evapotranspiration [mm per unit time]
ETo	Reference Crop evapotranspiration [mm per unit time]
FAO	Food and Agriculture Organisation of the United Nations.
FC	Field Capacity
GDD	Growing Degree Days [^{o}Cd]
GDP	Gross Domestic Product
GERD	Grand Ethiopian Renaissance Dam
GMAO	Goddard's Global Modelling and Assimilation Office
$K_{c,\,Tr}$	Crop transpiration coefficient
K_s	Water stress coefficient
K_{sat}	Saturated hydraulic conductivity [mm per unit time]
MERRA-2	Modern Era Retrospective Analysis for Research and Applications
NASA	National Aeronautics and Space Administration
Θ	Volumetric water content [m^3m^{-3}]
Θ_{FC}	Soil water content at FC [m^3m^{-3}]
Θ_{PWP}	Soil water content at PWP [m^3m^{-3}]
Θsat	Soil water content at soil saturation. [m^3m^{-3}]
PWP	Permanent Wilting Point
SLU	Swedish University of Agricultural Sciences
SOC	Soil Organic Carbon

SPI	Standard Precipitation Index
STD	Standard Deviation
TAW	Total Available Water [mm/m]
USDA	United States Department of Agriculture
P	Precipitation or rainfall [mm.d^{-1}]
Wr	Soil water content of the root zone expressed as an equivalent depth [mm]
Zr	Effective rooting depth [m]

1. Introduction

Food production and water use are not separable, given water's role in determining crop yield from an agronomic perspective (Fischer 2019). Around the world, water shortages, unequal rainfall distributions, and limited knowledge of water use are common issues, especially in Sub-Saharan countries such as Ethiopia, where this study was conducted (Abedinpour et al. 2012). A growing population, increased agricultural production, hydropower production, and an increasing need for ecosystem services have increased water demand (ibid.).

In the Ethiopian highlands, the planting of *A. decurrens* is raising interest among stakeholders on its effects on the water resources since it was introduced in the early 1990s to address the problem of urban firewood caused by deforestation. *A. decurrens* commonly referred to as green wattle, is in the family Fabaceae (Witt 2017). Australian Acacia species generally have similar plant and life cycle characteristics (Wilson et al. 2011). *A. decurrens* was also introduced to establish short-cycle forestry and restore a large watershed (Nigussie et al. 2021). In addition, the cultivation of *A.decurrens* is providing farmers with higher incomes than annual crops such as teff (Chanie & Abewa 2021).

Land use change in the Ethiopian highlands has several implications for the Nile basin water balance, both upstream and downstream. In this regard, the Ethiopian highlands are of particular interest, as they serve as a major source of water for the Blue Nile and support the livelihoods of 257 million people (Ter Borg 2020). Furthermore, the Ethiopian highlands and equatorial regions receive high rainfall compared to other areas that experience sub-humid or hyper-arid conditions (ibid.).

Recent studies indicate that the shift from annual to perennial land use in the Fajita Lekoma District impacts the water balance at the headwaters and lower course of the Nile River (Kindu et al. 2016; Ter Borg 2020). Further, Minta et al. (2018) report that between 1957 and 2014, there was an increase of 170% in cultivated land, 13,673% in plantation, and 172% in a settlement in central Ethiopia highlands, while there was a decline in the pasture (67%), forestland (73%) and woodland (100%).

Several studies have examined the effects of land use change on income or extent of land use; however, few have examined the impact of land use change on the water balance at a stand scale.

1.1 Objective of the study

This study uses historical climatic data to examine the impact of changing agricultural land use on water balance at a stand scale. The following are the key questions addressed in this research:

1. How does afforestation with *A. decurrens* affect water balance partitioning compared to annual crops such as teff?

2. Is there any significant impact on water balance by variations in precipitation of dry, normal, and wet Kiremt rainfall?

2. Background

2.1 Agriculture and land use in Ethiopia

Gebreselassie et al. (2015) report that 80% of Ethiopia's population is employed in the agricultural sector, representing the primary source of the country's Gross Domestic Product (GDP). Agriculture in Ethiopia is heavily dependent on rainfall (ibid.). Furthermore, Gebreselassie et al. (2015) report that most farming is subsistence-based. The major challenge is low productivity caused by land and water degradation and a decline in biodiversity.

Ethiopia grows several major crops, including teff, wheat, maize, barley, sorghum, and wheat (Gregory 2013). Many of these crops are produced using rain-fed agriculture, but irrigation has become more common due to droughts and a growing population (Tekleab et al. 2011).

Hurni et al. (2015), suggest that 87% of the Ethiopian population (94 million in 2014) reside in the Ethiopian highlands. This is because the Ethiopian highlands receive a sufficient amount of rainfall compared to the lowlands (Gregory 2013). On the other hand, Ethiopia's highlands has some of the most severe land degradation areas globally (Hurni et al. 2015).

Agriculture activities such as livestock grazing and deforestation reduce soil cover protection, resulting in soil erosion and compaction (Weil & Brady 2017). These findings follow a challenge that has been expressed in the past regarding changes in land-use practices and their impact on hydrology and land degradation, particularly in developing countries such as Ethiopia (Koch et al. 2012).

In some areas in the Ethiopian highlands, plantations are reversing deforestation (Birhane et al. 2019). One of these areas is Fagita Lekoma District, where farmers have planted *A. decurrens* to earn income from charcoal production, conserve water, and improve soil fertility (Nigussie et al. 2017). In the study area, farmers practice agroforestry, planting trees and annual crops. Since then, forest cover has increased annually by 5%, in contrast to cropland shrinking by 1-2% yearly (Wondie & Mekuria 2018).

2.2 Land use and land degradation in Ethiopia

Soil degradation poses a significant challenge to agriculture production in the Ethiopian highlands (Mhiret et al. 2019). Land use change and drought are two leading causes of land degradation and desertification in Ethiopia's highlands (Tesfaye 2021).

Other reasons for land degradation in Ethiopia include rapid population growth and severe soil erosion (Taddese 2001). Furthermore, deforestation, slope terrain, low plant cover, and unsustainable agricultural practices contribute to land degradation in Ethiopia (ibid.). Similar studies by Worku et al. (2021) suggest that between 2010 and 2017, cropland was the dominant land use type in Ethiopia, followed by grazing land, while plantations like *A. decurrens* had the least coverage.

Gebrehiwot et al. (2021) identify the Ethiopian highlands as one of the hot spots of deforestation and afforestation worldwide. In this study, it is reported that an area of 31,000 km^2 of forests was lost between 1990 and 2015, while forest plantations expanded by 4,800 km^2 during the same period (ibid.)

A large area of the Ethiopian highlands has become unproductive because of land degradation caused by soil erosion (Adimassu et al. 2018). Furthermore, Adimassu et al. (2018) report that soil loss occurs most frequently on cultivated land and ranges from 42 $t\ ha^{-1}\ y^{-1}$ to 179 $t\ ha^{-1}y^{-1}$. Meanwhile, Taddese (2001) suggests that Ethiopia's average rate of soil formation is estimated to be less than 2 tonnes per hectare, much lower than soil erosion.

Soil degradation causes a decrease in soil productivity due to physical loss of topsoil, reduced root depth, and loss of nutrients and water (Yesuf et al. 2005). Also, high levels of soil erosion may reduce the hydraulic head of the Great Ethiopia Renaissance Dam (GERD), which could jeopardise energy production.

Several organisations, including the government, have implemented several soil and water conservation initiatives to improve land productivity in the Ethiopian highlands (Adimassu et al. 2018). Ethiopia's soils and water conservation (SWC) initiatives include farmland and hillside terraces, tree planting, soil bunds, and sediment storage dams (ibid.). In addition to terracing land and building land bunds, Ethiopia's Ministry of Agriculture has implemented programs to encourage agroforestry among communities (Megerssa & Bekere 2019).

In Fagita Lekoma district, *A. decurrens* plantations have expanded over the years due to economic benefits such as jobs, charcoal sales, as well as the ability of *A. decurrens* to grow alongside other crops for the first two years (Wondie & Mekuria 2018). Aside from reversing land degradation, *A. decurrens* has shown to be adaptable to acidic conditions and offer local farmers short-term economic benefits in fuelwood selling (ibid.).

Other benefits of *A. decurrens* include a reduced rate of soil erosion due to a lack of soil disturbance after planting (Chanie & Abewa 2021).

2.3 Land use and water balance

The water balance of a region or area is determined by the relation between precipitation, evapotranspiration, groundwater recharge, and runoff (Nugroho et al. 2013). Furthermore, the water balance of an area is affected by various anthropogenic factors such as human settlements, agriculture, logging, and others (ibid.). A simplified equation (1) describes the water balance relationship above (Weil & Brady 2017). In this study, the water input is through rainfall, and it is assumed that there is no input from irrigation and groundwater.

$$P = ET + SS + RO + D \qquad (1)$$

Where, P= precipitation ET= evapotranspiration, SS= Change in soil storage, RO = runoff, and D= discharge

The conversion from perennial to annual land use may result in a rise in flood frequency but mainly a reduction in flood discharges during dry periods (Koch et al. 2012). In addition, intensified agricultural land use due to population growth and water abstraction for irrigation practices are causing water shortages (ibid.).

Xu et al. (2012) report that plant cover acts as a rainfall shield, capturing rain and can also cause soil to dry out. Most farming activities in the Ethiopian highlands involve clearing vegetation, which increases surface runoff and decreases ETa, resulting in reduced precipitation, especially in semi-arid regions (Tesfaye 2021). High runoff is caused by high rainfall on the steep slope of the Ethiopian highlands (Woldesenbet et al. 2018).

In a study on vegetation restoration in the Chinese Loess, forest trees have been linked to soil drying and ecological degradation in arid and semi-arid areas (Jian et al. 2015).

Analysis of the storage-discharge relationship by Gebrehiwot et al. (2021), reports an increase in water storage as natural forest cover decreases in the Woshi-Dimbira and Upper Didesa watersheds. While results from the Sokuru watershed which was afforested with Eucalyptus spp, fruit trees and Grevilia spp show high drainage and reduced soil water storage (ibid). A similar study on the water balance by Nugroho et al. (2013) in the Goseng catchment, Indonesia, reports increased surface runoff and river discharge due to decreased vegetation coverage.

Recent studies have also shown that Eucalyptus afforestation uses a lot of water and outcompetes other plants for soil nutrients (Minta et al. 2018). Also, studies in the loess plateau of China show that arid and semi-arid regions suffer from soil desiccation and ecological degradation caused by excessive water use by different types of trees (Chen et al. 2008 see Jian et al. 2015).

3. Methodology and materials

3.1 Study Area

The plot for this study is located in Fagita Lekoma District, which is located approximately at 36 °40′ to 37° 06′ E longitude and 10 °5"6′ to 11°12′ N latitude (Wondie & Mekuria 2018). The study area is surrounded by a watershed of about 31.6 km^2, with an elevation range of 2,390 m to 2,915 m (Ter Borg 2020).

A study by Nigussie et al. (2021) suggests that the population density for the surrounding study area is 224.7 people per km^{2,} and 90% of the population lives in rural areas.

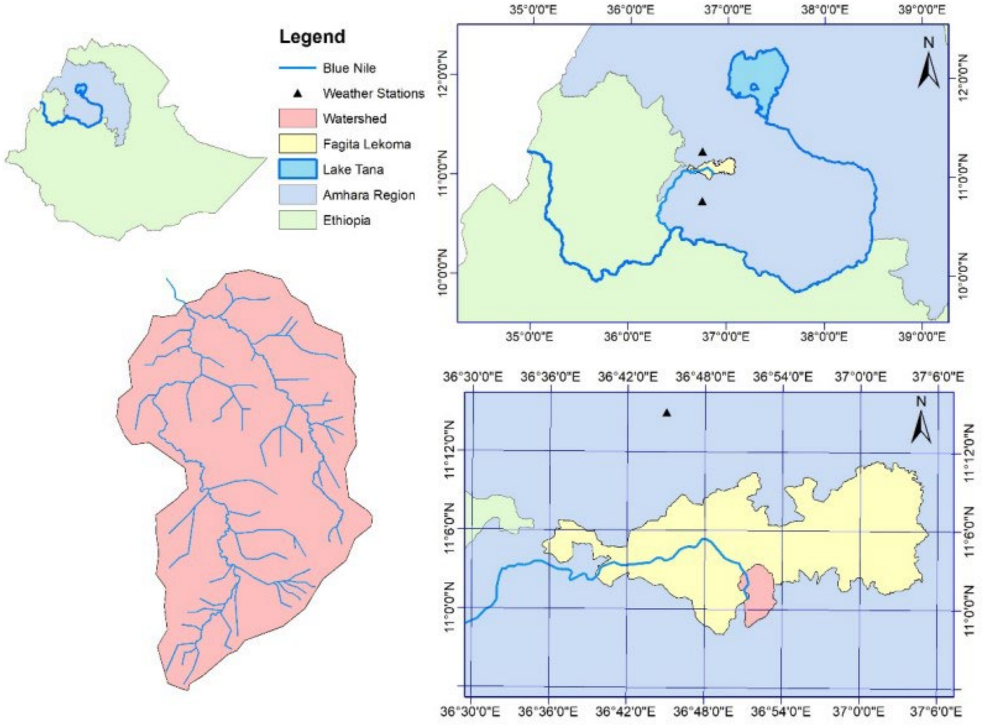

Figure 1. Map of the study area Fagita Lekoma (Ter Borg 2020).

In Fagita Lekoma District, temperatures range between 15 °C and 21 °C, except in valleys and marginal areas, which tend to be warmer (Ayalew et al. 2012). However, NASA's 2020 climatic data analysis in Figure 2 reveals that the mean maximum temperature in the region is 28 °C while the mean minimum temperature is 9 °C.

The study area experiences two distinct seasons of rainfall. The Belg season runs from March through May, and the Kiremt season runs from June to September (Ayalew et al. 2012). In addition, there is the dry period, locally referred to as the Bega, which lasts from October to February (Mekonen & Berlie 2020). The Kiremt rainfall is generally more stable than Belg season rainfall in most parts of the country (ibid.). Figure 2 shows average monthly precipitation, Reference crop evapotranspiration (ETo), and maximum and minimum temperatures from 1990 to 2020.

The predominant soil types in this region are Humic Nistisols, followed by Eutric Fluvisols and Luvisols (FAO et al. 2012 see Ter Borg 2020).

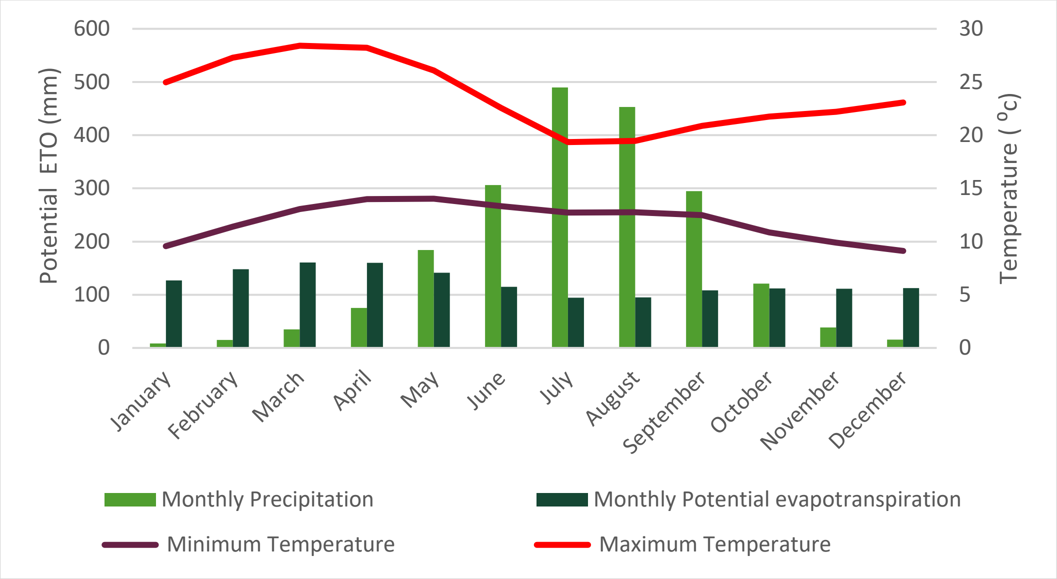

Figure 2. Average monthly potential Evapotranspiration, precipitation, and maximum and minimum temperature from 1990 to 2020. Data source NASA 2020.

3.2 AquaCrop 6.1 Model

AquaCrop 6.1 model simulates crop development, transpiration, biomass production, and yield formation (Raes et al. 2018b). This study focuses on how land use change impacts water balance due to crop development and crop transpiration (ibid).

AquaCrop 6.1 model simulates the amount of canopy cover and above-ground biomass plants produce when they transpire (Jin et al. 2018). The four groups of variables in the AquaCrop 6.1 model are historical climate data, plant and soil parameters and field management practices (Raes et al. 2018b).

Raes et al. (2018a) show that Aquacrop 6.1 model calculates the Actual evapotranspiration (ETa) by multiplying the crop transpiration Coefficient ($K_{c,\,Tr}$) by the ETo and the water stress factor (Ks). A crop's transpiration coefficient in AquaCrop 6.1 model depends on the green canopy cover (CC), and the soil water evaporation coefficient varies with bare soil (Raes et al. 2018a). This relationship is given in equation (2).

$$ETa = Ks*CC*Kc_{,\,Tr}*ETo \qquad (2)$$

Several studies have used AquaCrop 6.1 model on annual crops such as teff, but relatively few have been conducted on perennial tree species such as *A. decurrens* (Heng et al. 2009; Ismail et al. 2015; Paff & Asseng 2018).

In AquaCrop 6.1 model, ETo is derived from air temperature, humidity, solar radiation, and wind speed using the Food and Agriculture Organisation (FAO) Penman-Monteith method (Allen et al. 1998).

AquaCrop 6.1 model simulates the water balances by considering all the water flowing in and out of the root zone (Wr). Similarly, the equivalent depths represent the soil water content in the Wr. The water content in the Wr is calculated by multiplying volumetric water content (Θ) by the effective rooting depth (Zr). In equation (3), the conversion factor of 1000 converts meters to millimetres (mm). (Raes et al. 2018a).

$$Wr = 1000 * \Theta * Zr \tag{3}$$

At Field Capacity (FC), absorption and capillary forces predominate the gravitation forces. Furthermore, gravitational forces dominate when the soil layer is saturated and small, and bigger soil pores are filled with water. Water flows from one layer to the next until it reaches groundwater (Weil & Brady 2017). Water movement from one layer to the next depends on the soil saturated hydraulic conductivity (K_{sat}). AquaCrop 6.1 simulates water content in the Wr at FC by multiplying soil water content at Field capacity (Θ_{FC}) and the Zr, as shown in equation 4 (Raes et al. 2018a).

$$Wr = 1000 * \Theta_{FC} * Zr \tag{4}$$

The lower limit of water content in the root zone is known as the permanent wilting point (PWP), and at this stage, water in the soil matrix is held so strong by capillary and absorption forces that the plant cannot extract it (Weil & Brady 2017). AquaCrop 6.1 model calculates water content at PWP using equation 5 (Raes et al. 2018a).

$$Wr = 1000 * \Theta_{PWP} * Zr \tag{5}$$

The difference between the water content at FC and PWP is the plant's Total Available soil Water (TAW)(Raes et al. 2018a).

In AquaCrop 6.1, the drainage characteristic tau (τ) is used to model drainage (Raes et al. 2018a). Typically, the tau value varies from 0 to 1, with 0 representing complete drainage and 1 representing an impermeable layer. Equation 6 shows how AquaCrop 6.1 model simulates drainage. Increasing tau will generally cause the soil layer to reach FC faster.

$$\frac{\Delta\Theta i}{\Delta t} = \tau(\Theta_{SAT} - \Theta_{FC})\frac{e^{\Theta i-\Theta FC}-1}{e^{\Theta SAT-\Theta FC}-1} \tag{6}$$

Where $\frac{\Delta\Theta i}{\Delta t}$ decrease in soil water content at depth i, during a time step

Δt [$m^3.m^{-3}.day^{-1}$];

τ drainage characteristic;

Θ actual soil water content at depth i [$m^3.m^3$];

Θ_{SAT} soil water content at saturation [$m^3.m^3$];

Θ_{FC} soil water content at field capacity [$m^3.m^3$];

Δt time step [day]

The AquaCrop 6.1 model estimates tau in relation to K_{sat}, and equation 7 depicts this relationship (Raes et al. 2018a).

$$0 \leq \tau = 0.0866\ K_{sat}^{0.35} \leq 1 \qquad (7)$$

Full details on the operation of the AquaCrop 6.1 model is found in (Steduto et al. 2012; Raes 2015).

3.3 Data

3.3.1 Climate

Daily climate measurements from 1982 to 2020 were downloaded using weather station coordinates. A National Aeronautics and Space Administration (NASA) POWER project model uses Goddard's Global Modeling and Assimilation Office (GMAO) modern Era Retrospective-Analysis for Research and Applications (MERRA-2) assimilation model products to access and process climatic data from weather stations across the world.

Long-term climatic data from the same weather station used by (Ter Borg 2020) is used in this study. The latitude and longitude for the two weather stations are 10.75 and 36.75 for station 1 and 11.25 and 36.75 for station 2 respectively (ibid).

The six climatic parameters downloaded were solar radiation, minimum and maximum temperatures at 2 meters, relative humidity at 2 meters, precipitation and wind speed at 2 meters. The climatic data used in this study was from weather station 1.

The output data comma-separated values (CSV) file from the NASA POWER project model was converted into a text file. A default carbon dioxide concentration measured at the Mauna Loa observatory created a climate file saved in the Aqua Crop input climatic database (Raes et al. 2018b).

To statistically compare land-use changes in this study, a t-test was conducted with Microsoft excel.

3.3.2 Rainfall

Downloaded data from weather stations 1 and 2 were transformed into an excel sheet to analyse descriptive statistics for annual Belg and Kiremt rainfall seasons (Ter Borg 2020). The coefficient of variation for yearly, Belg and Kiremt seasons was calculated to provide insights into variation in rainfall (ibid.).

To determine the degree of drought for the Belg and Kiremt seasons, the Standard Precipitation Index (SPI) given in equation 8 was used (World Meteorological Organization 2012). Following this, Table 1 with five drought classes was used to find the degree of drought during each season. As shown in equation 8, x represents annual or seasonal precipitation, $\bar{x}$ is the mean rainfall for the period, and $\boldsymbol{\sigma}$ is the standard deviation (Shadeed & Almasri 2007).

$$\text{SPI} = \frac{X-\bar{x}}{\sigma} \tag{8}$$

Table 1. Standard Precipitation Index classes(Kurniasih 2017; Elkollaly et al. 2018).

SPI range	Drought class
1.5 to 2	Severely wet
1 to 1.49	Moderately wet
-0.99 to 0.99	Normal
-1 to -1.49	Moderately dry
-1.5 to -2	Severely dry

3.3.3 Vegetation parameters

To determine plant parameters for *A. decurrens* and teff to use in the model, I reviewed several kinds of literature from online sources such as, Google Scholar, Scopus, and botanical websites and also consulted subject experts.[1]

Plant parameters such as rooting depth not available for *A. decurrens* were taken from species in the Acacia family such as *Acacia mearnsii* (Ter Borg 2020). *A. decurrens* can grow to 5-10 meters but sometimes grow as tall as 22 meters in the right environmental conditions (Boland 1987).

In general, Acacia plants flower annually after they have reached the juvenile stage (Cossalter 1986). Water availability is a significant factor influencing whether or not an acacia will flower in arid regions (ibid.).

In addition to moderate root depth and drought tolerance, *A. decurrens* also fix nitrogen in the soil, control soil erosion, and serve as a windbreak (Chanie & Abewa 2021a). In AquaCrop 6.1 model, phenology events such as time for flowering, canopy senescence, and physiological maturity were used as input plant parameters (Raes et al. 2018b).

This study assumed a typical tree was planted in four stands of *A. decurrens* from the first to the fourth year (Figure 3).

To conduct the simulation, separate files were created for the first four years with corresponding crop parameters. Appendix 1.0 includes Table 9, which has *A. decurrens* plant parameters used in AquaCrop 6.1 model.

Among Ethiopians, teff is highly popular because most people consume it, and it is used for feed and construction purposes (Paff & Asseng 2018).

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[1] Rebecca ter Borg is a researcher at the Swedish University of Agricultural Sciences in Uppsala, Sweden.

Teff is generally sown by hand between mid-July and early August in Ethiopia (Steduto et al. 2012a). Teff is not planted from the second to the fourth year due to dense canopy cover caused by afforestation with *A. decurrens*, which prevents it from gaining light (Chanie & Abewa 2021). Teff can grow in various soil types, is drought-tolerant and tolerant to waterlogging conditions (Paff & Asseng 2018). Table 10 of Appendix 1 shows detailed teff crop parameters used in the model. A crop file was created in Growing Degree Days (GDD) to calculate plant growth as a function of temperature (Raes et al. 2018b).

For this study, the growing season I am using to compare land use change from teff to afforestation with *A. decurrens* is from 1st July to 27th November of each year, as illustrated in figure 3.

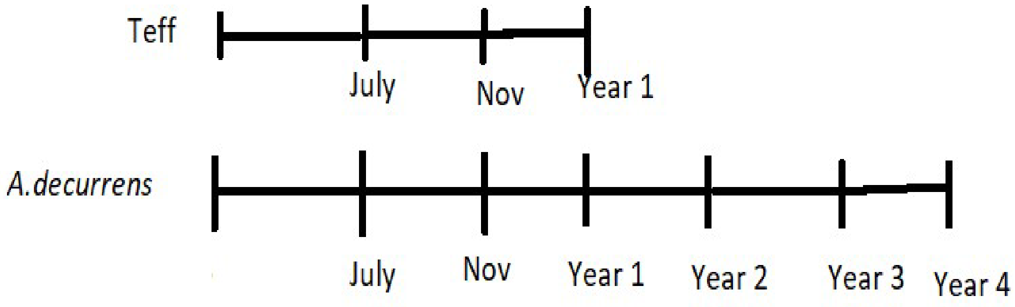

Figure 3. The schematic diagram for land use change from teff to afforestation with A. decurrens in the Ethiopian highlands.

3.3.4 Soil

The soil data used in this study is from ongoing field measurements in Fagita Lekoma by Getachew G Tiruneh.[2] There were two soil depths (Table 2), each 0.5 meters thick. The topsoil was textured as loam, while the subsoil was textured as silt loam.

Using soil properties in Table 11 of Appendix 2, soil hydraulic properties such as PWP, FC, and K_{sat} in Table 2 were calculated using a hydraulic calculator developed by the United States Department of Agriculture (USDA) (Raes et al. 2018b). Using soil properties in Table 11 of Appendix 2, soil hydraulic characteristics such as PWP, FC, and K_{sat} in Table 2 were calculated using a hydraulic calculator developed by the United States Department of Agriculture (USDA) (Raes et al. 2018b).

The calculated soil hydraulic characteristics for the two textural classes were compared to the indicative values in AquaCrop 6.1 model Reference Manual to

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[2] Getachew G Tiruneh is a PhD student at the Swedish University of Agricultural Sciences in Uppsala, Sweden.

confirm if they fall within the accepted range (Raes et al. 2018b). The AquaCrop 6.1 model calculated the TAW based on the input soil hydraulic characteristics.

Since the initial soil water content was unknown, the assumption was made that soil water content would reach FC at the start of the rainy season. In doing so, the model calculated the soil moisture content for every rain event (Raes et al. 2018b).

In this study, I assumed that the crop was not under stress due to nutrient deficiency and salt (Raes et al. 2018b).

Also shown in Table 2 is tau, a characteristic of soil drainage. In AquaCrop 6.1 model, drainage or tau represents the decline in soil water content of a soil layer saturated on the first day of free drainage (Raes et al. 2018b).

Table 2. Soil hydraulic characteristics at a field scale in Fagita Lekoma.

Textural class	TAW (mm/m)	PWP Vol (%)	FC Vol (%)	Saturation Vol (%)	Ksat Vol (%)	Tau (mm)
Loam	162	17.5	33.7	50.7	311.28	0.65
Silt Loam	167	11.5	29.0	47.1	419.52	0.72

In AquaCrop 6.1 model, the runoff is determined by a curve number (CN) based on the K_{sat} and wetness of topsoil (Raes et al. 2018b). The higher the CN, the more water is lost to runoff (ibid.).

The CN is also influenced by slope, terracing, planting method, soil cover, and field management practices (Raes et al. 2018). The CN in Table 3 was used in AquaCrop 6.1 model to reflect crop cover at various stages of growth.

Table 3. Adjusted curve numbers for different land use(Raes et al. 2018b).

Land use	Year	Curve Number
Teff	1-4	61
A. decurrens	1	45
A. decurrens	2	30
A. decurrens	3	25
A. decurrens	4	21

4. Results

4.1 Rainfall analyses

In Table 4, the descriptive rainfall statistics for station 1 and station 2 are summarized. The average rainfall at station 1 is 2,049 mm/y and at station 2 is 1,829 mm/y.

During the Belg season, station 1 received, on average, 299 mm/y of rainfall, and station 2 received, on average, 242 mm/y of rainfall. During the Belg season, station 1 received, on average, 299 mm/y of rainfall, and station 2 received, on average, 242 mm/y of rainfall. In contrast, the long-term average rainfall during the Kiremt season was 1,436 m/y for station 2 and 1,564 mm/y for station 1.

A small coefficient of variation (CV) between the two weather stations in Table 4 suggests minor variation in rainfall amounts during the Kiremt season.

Table 4. Summary statistics captured by the two weather stations (1990 to 2020).

Weather station	Annual rainfall			Belg season			Kiremt season		
	Mean	Std	CV	Mean	Std	CV	Mean	Std	CV
1	2,049	465	22	299	127	42	1,564	311	19
2	1,829	384	21	242	98	40	1,436	276	19

As shown in Figure 4, the highest annual rainfall is 2,823 mm, and the lowest is 1,163 mm. In addition, Figure 4 indicates that 50% of the annual precipitation is within the range of 1,672 to 2,458 mm.

Figure 4, also shows that the rainfall in the Kiremt season ranged between 975 mm and 2,253 mm. This contrasts with rainfall amounts during the Belg season, where rainfall ranged between 69 mm and 530 mm.

The above rainfall statistics show that the Kiremt season contributes more to the annual rainfall than the Belg season. This suggests a higher crop yield in the Kiremt season than in the Belg season. During the Belg season, farmers may also need to irrigate crops with high water requirements to avoid yield losses caused by water stress.

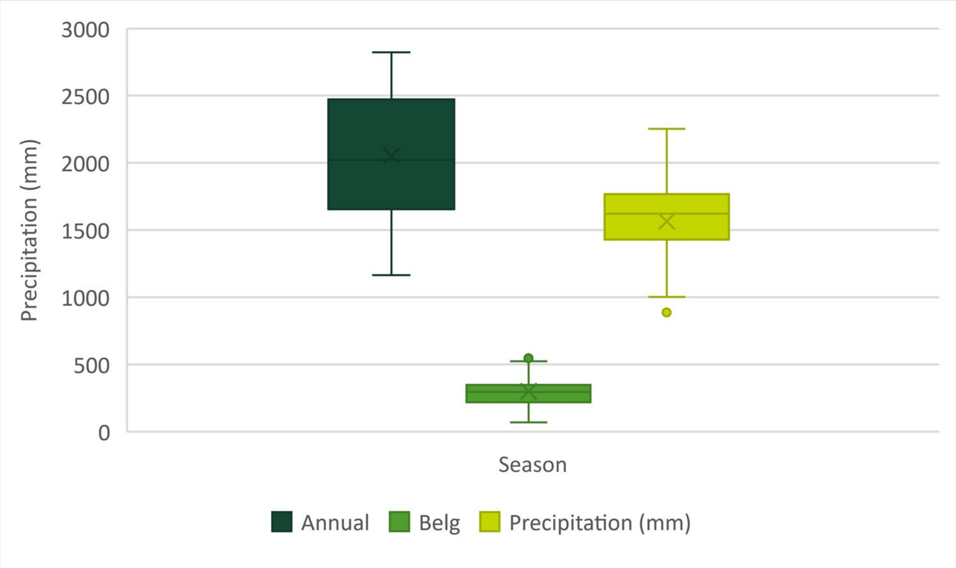

Figure 4. Rainfall distribution during Belg and Kiremt season for station 1.

4.1.1 Standard Precipitation Index analyses

The three wettest Belg seasons were 1996, 2016 and 2017 (Figure 5). The moderate dry years were 1990, 2002, 2009, and 2012 and their SPI index values ranged between -1 and -1.49.

With an SPI of -1.9, 2003 fell into a severely dry year. The result indicates that rainfall fluctuates over the years during the Belg season.

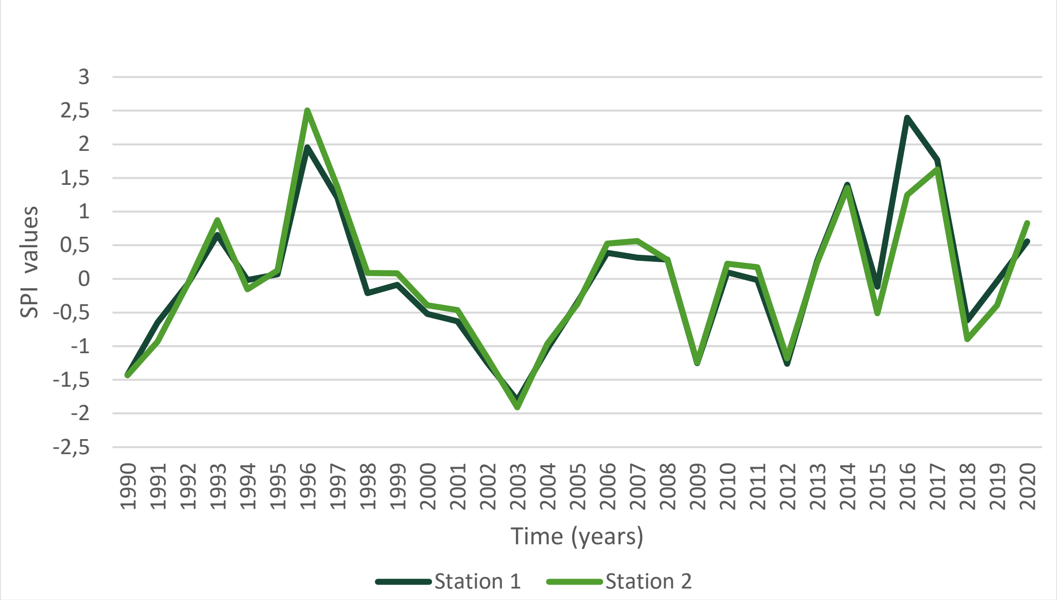

Figure 5. SPI values during the Belg season for stations 1 and 2.

In 1993 and 2020, the Kiremt season was normal and wet, respectively (Figure 6). In contrast, the Kiremt seasons of 2001, 2002, 2004, and 2011 were dry, while the other years had generally normal rainfall.

Based on the above analyses, I chose 2004 to represent the dry Kiremt season, 1993 to represent the normal Kiremt season and 2020 to represent the wet Kiremt season in the study.

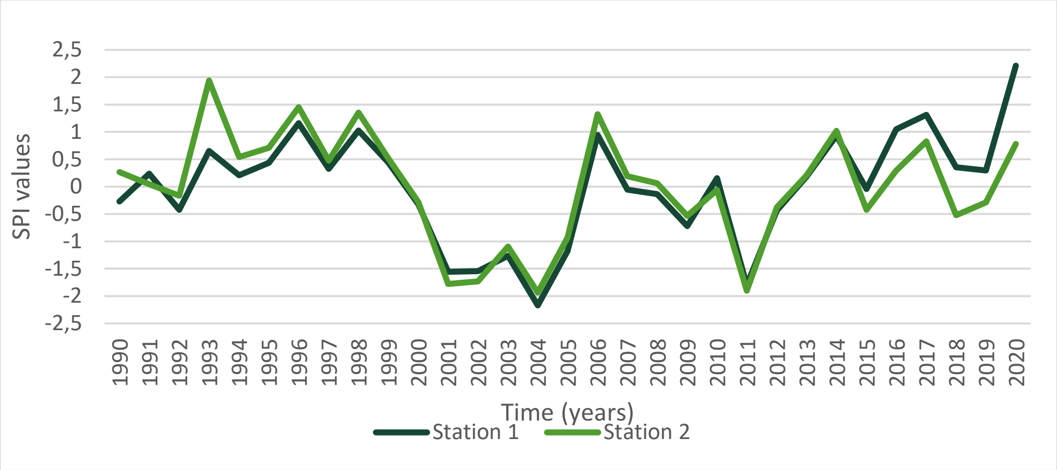

Figure 6. SPI values during Kiremt season for stations 1 and 2.

4.2 Water balance analyses

4.2.1 Teff water balance

During the growing season (1st July to 27th November), the rainfall amounts were 2,120 mm, 1,649 mm, and 825 mm for the wet, normal, and dry Kiremt seasons, respectively (Table 5).

More runoff occurred during the wet Kiremt season (30%) than during the normal Kiremt season (20%) and dry Kiremt season (9%). In addition, evaporation was 26% of dry Kiremt seasonal rainfall, followed by normal Kiremt season (15%) and wet Kiremt season (9%). Results also show that teff transpired more during dry Kiremt season than during normal and wet Kiremt seasons (Table 5).

The groundwater recharge from water infiltration was highest during the normal Kiremt season (58%), followed by the wet Kiremt season (57%) and lastly, the dry Kiremt season (50%).

Table 5. Water balances for teff expressed are as a percentage of Kiremt seasonal rainfall.

Kiremt season	Rainfall amount (mm)	Evaporation (%)	Transpiration (%)	ETa (%)	Drain (%)	Runoff (%)
Normal (1993)	1,649	15	6	21	58	20
Dry (2004)	825	26	13	39	50	9
Wet (2020)	2,120	9	5	14	57	30

4.2.2 Acacia decurrens water balances

The results show that transpiration increased from 7% to 12% of the Kiremt seasonal rainfall during the second year (Table 6), then it became stable in the third and fourth cycle of afforestation with *A. decurrens*. On the other hand, evaporation decreased during the first and second cycles of afforestation with *A. decurrens* and then became stable in the third and fourth cycles of afforestation with *A. decurrens*. The mean ETa was 29% of the normal Kiremt seasonal rainfall.

The drainage amount increased from 65% to 74% of the normal Kiremt seasonal rainfall from the first to the fourth cycle of afforestation with *A. decurrens*. On the other hand, runoff decreased from the first to the fourth cycle of afforestation with *A. decurrens*. The average runoff was 3% of the normal Kiremt seasonal rainfall. In other words, there was more runoff in the first cycle of afforestation with *A. decurrens* compared to subsequent years of afforestation.

Table 6. Water balances for A. decurrens are expressed as a percentage of normal Kiremt seasonal rainfall.

Tree stand age	Rainfall (mm)	Transpiration (%)	Evaporation (%)	ETa (%)	Drain (%)	Runoff (%)
1	1,649	7	21	28	65	9
2	1,649	12	17	29	72	3
3	1,649	12	17	29	73	1
4	1,649	12	17	29	74	0.6

The ETa increased from the first to the second cycle of afforestation *A. decurrens* (Table 7). The ETa was 61% of the Kiremt seasonal rainfall in the third and fourth cycles of afforestation with *A. decurrens*. The transpiration rate increased from the first to the third cycles of afforestation with *A. decurrens* before becoming stable in the fourth cycle of afforestation with *A. decurrens* (26%). On the other hand, evaporation decreased from the first to the second cycle of afforestation with *A. decurrens* and became stable in the third and fourth cycles of afforestation with *A. decurrens*. Compared to transpiration, evaporation was the major contributor to ETa during the four cycles of afforestation with *A. decurrens*. The average ETa during the dry Kiremt season was 60% of the Kiremt seasonal rainfall, which was higher than the average ETa during the normal Kiremt season (29%) and wet Kiremt season (22%).

The groundwater recharge increased from the first to the second cycle of afforestation with *A. decurrens* and was stable in the third and fourth cycle of afforestation with *A. decurrens*. In contrast, the runoff was higher in the first year and reduced significantly in the subsequent years. The average drainage and runoff were 50% and 2% of the dry Kiremt seasonal rainfall, respectively. The drainage and runoff during the dry Kiremt season were comparably low to the normal Kiremt season.

Table 7. Water balances for A. decurrens are expressed as a percentage of dry Kiremt seasonal rainfall.

Tree stand age	Rainfall (mm)	Transpiration (%)	Evaporation (%)	ETa (%)	Drain (%)	Runoff (%)
1	825	16	42	58	45	6
2	825	25	36	61	51	0.3
3	825	26	35	61	51	0.1
4	825	26	35	61	51	0.01

The ETa was 22% of the Kiremt seasonal rainfall (Table 8). The ETa during the wet Kiremt season was low compared to the dry and normal Kiremt seasons.

The transpiration rate was between 5% to 13% of the wet Kiremt seasonal rainfall and was highest in the fourth cycle of afforestation with *A. decurrens*. On the other hand, the average evaporation rate was 13% of the wet Kiremt seasonal rainfall, lower than the dry and normal Kiremt seasons.

The drainage into the groundwater increased from the first to the fourth cycle of afforestation with *A. decurrens* and was, on average, 74% of the wet Kiremt seasonal rainfall (Table 8). This result means more groundwater recharge during the wet Kiremt season than during the normal Kiremt season.

There was a decrease in runoff from the first to the fourth cycle of afforestation with *A. decurrens* during the wet Kiremt season (Table 8). On average, a runoff was 7% of the wet Kiremt seasonal rainfall, which is high compared to the normal and dry Kiremt seasons.

Table 8. Water balances for A. decurrens are expressed as a percentage of wet Kiremt seasonal rainfall.

Tree stand age	Rainfall (mm)	Transpiration (%)	Evaporation (%)	ETa (%)	Drain (%)	Runoff (%)
1	2,120	5	16	21	66	16
2	2,120	9	13	22	75	7
3	2,120	9	13	22	77	4
4	2,120	13	9	22	79	0.1

The seasonal cumulative ETa for *A. decurrens* during the third and fourth cycle of afforestation with *A. decurrens* was 475 mm. Furthermore, the average ETa during the third and fourth cycle of afforestation with *A. decurrens* was 3.2 mm/day with a STD of 0.4 (Figure 7). On the other hand, the seasonal ETa for teff during the normal Kiremt season was 341 mm, and the mean ETa was 2.3 mm/day with an STD of 0.8 mm. This result suggests that *A. decurrens* transpired more than teff during the normal Kiremt season. The two-tail test shows $P < 0.05$ ($P = 0.00$), meaning the average ETa for *A. decurrens* for the third and fourth cycles differs from teff.

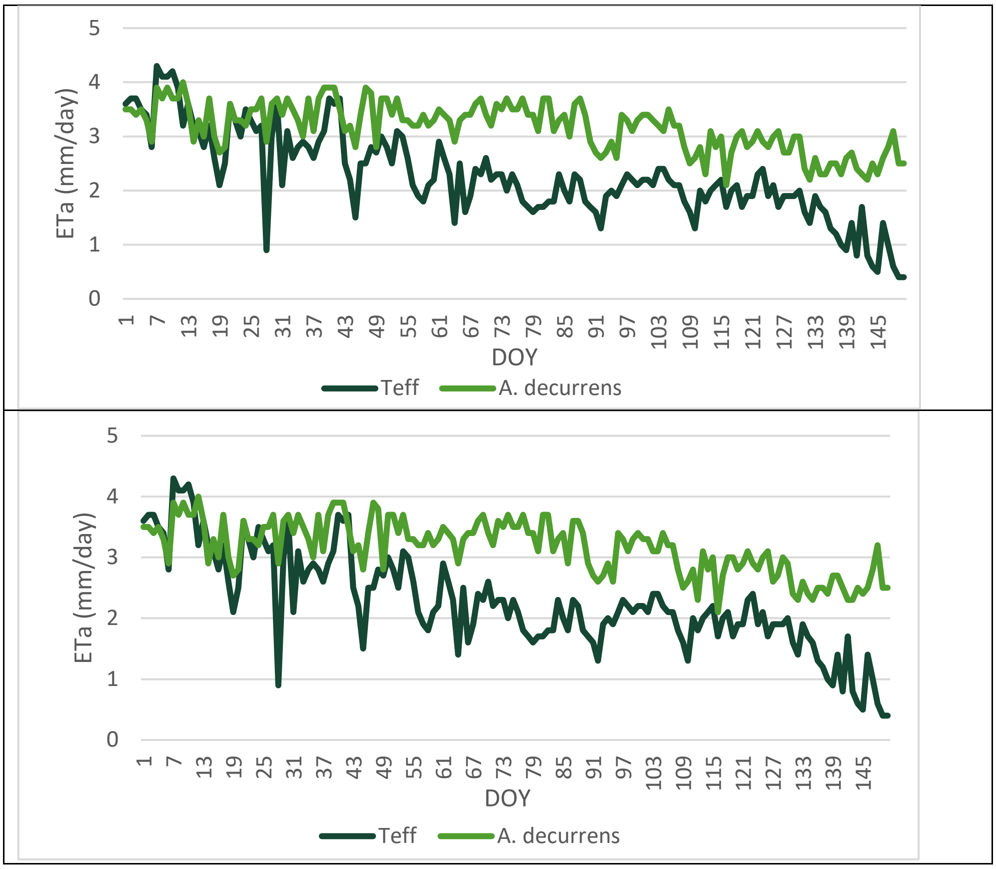

Figure 7. Daily ETa for teff and A. decurrens during normal Kiremt season in third (top) and fourth (bottom) cycles of afforestation.

The cumulative ETa during the dry Kiremt season for the third and fourth cycles of afforestation with *A. decurrens* was 500 mm/y and 501mm/y, respectively. The mean ETa for *A. decurrens* for the third and fourth cycle was 3.3 mm/day with a STD of 0.4 (Figure 8). On contrary, the seasonal ETa for teff cultivation was 320 mm and the mean ETa was 2.1 mm/day with an STD of 0.9 mm. The two-tail test for both cycles show $P < 0.05$ ($P= 0.00$), meaning the average ETa for *A. decurrens* in both cycles of afforestation with *A. decurrens* differs significantly from teff cultivation.

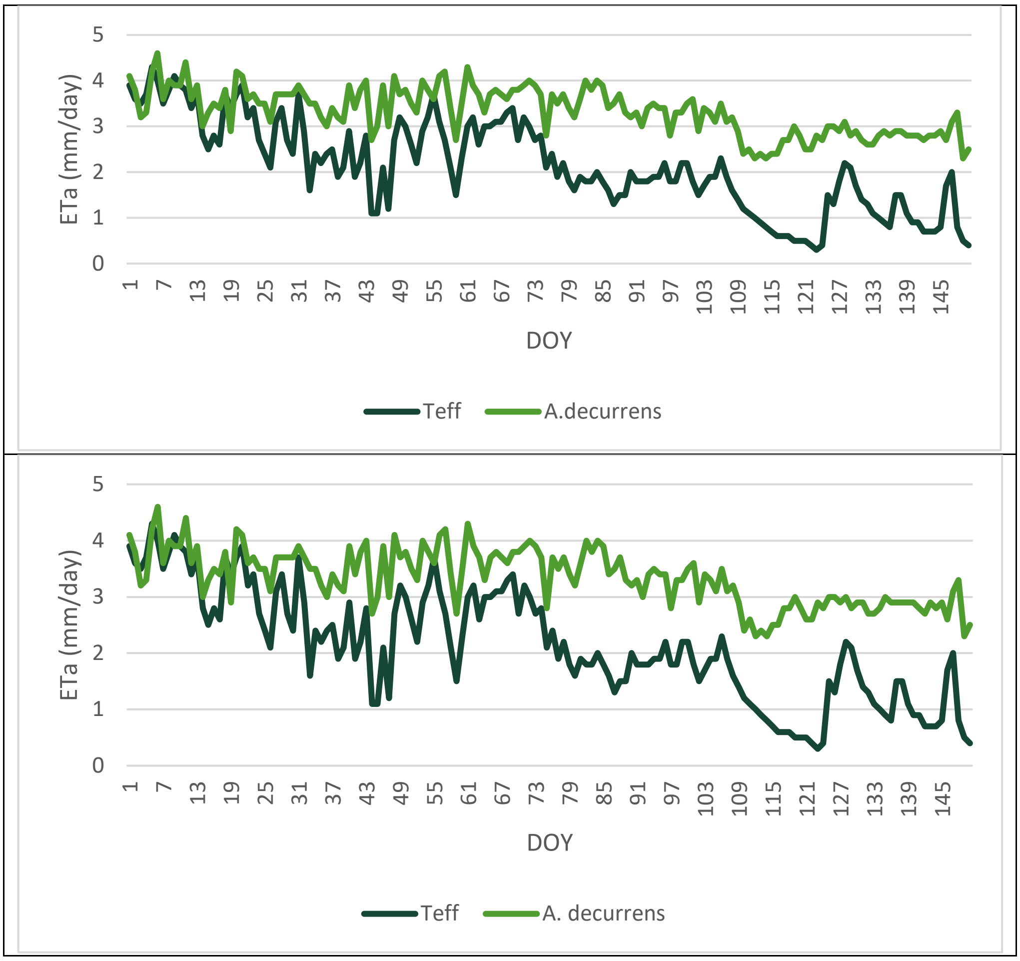

Figure 8. Daily ETa for teff and A. decurrens during dry Kiremt season for third (top) and fourth (bottom) cycles of afforestation.

The ETa during the wet Kiremt season was 468 mm and 469 mm for the third and fourth cycle of afforestation with *A. decurrens*, respectively. The average ETa for the third and fourth cycle of afforestation with *A. decurrens* was 3.1 mm/day with a STD of 0.5 mm (Figure 9). While teff's seasonal ETa was 293 mm, the mean ETa was 2 mm/day with a STD of 0.8 mm. In both cycles of afforestation with *A. decurrens*, the two-tail test shows that the ETa in *A. decurrens* differs significantly from teff $P < 0.05$ ($P = 0.00$).

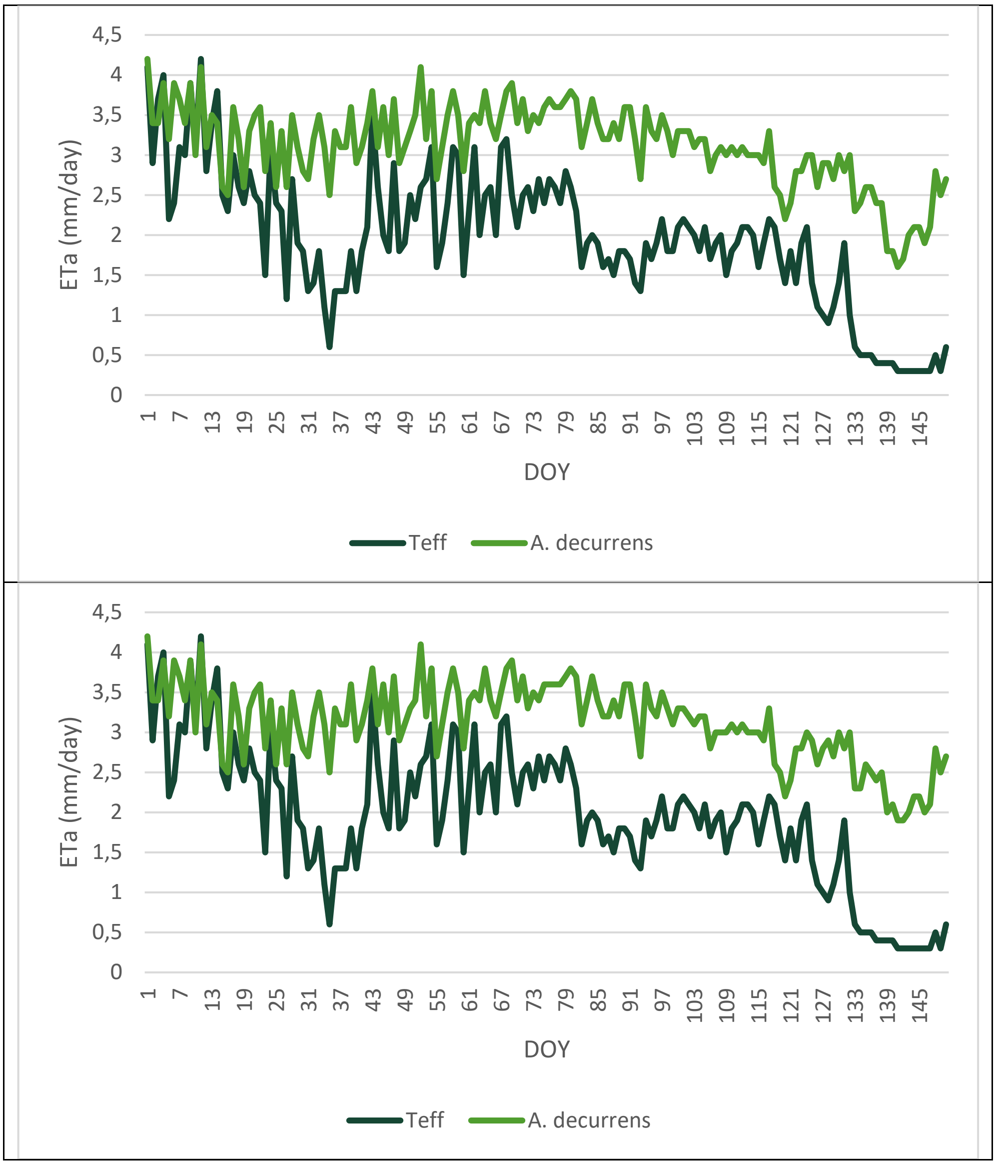

Figure 9. Daily ETa for teff and A. decurrens during wet Kiremt season for third (top) and fourth (bottom) cycles of afforestation.

During the fourth cycle of afforestation with *A. decurrens*, 1,174 mm of water was drained into groundwater, compared to 958 mm when teff was grown during the normal Kiremt season (Figure 10). This represents 10% more groundwater recharge in *A. decurrens* than in teff cultivation.

There was 331 mm of runoff from teff cultivation compared to only 11 mm during the fourth cycle of afforestation with *A. decurrens* (Figure 10). This represents 94% more runoff compared to afforestation with *A. decurrens*.

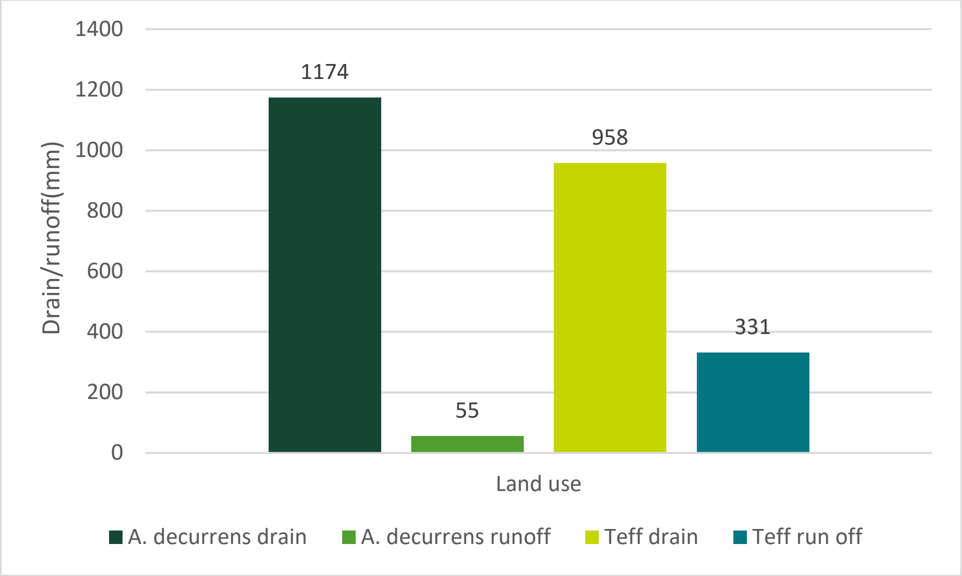

Figure 10. Drain and runoff for different land use during normal Kiremt season.

During the dry Kiremt season, teff and afforestation with *A. decurrens* had relatively small drainage differences (Figure 11). 422 mm of water was drained in the fourth cycle of afforestation with *A. decurrens*, compared to 413 in teff cultivation. The amount of drainage in afforestation with *A. decurrens* is only 4% higher than in teff cultivation.

The fourth cycle of afforestation with *A. decurrens* had very little runoff (0.1mm) compared to 71 mm under teff cultivation (Figure 11).

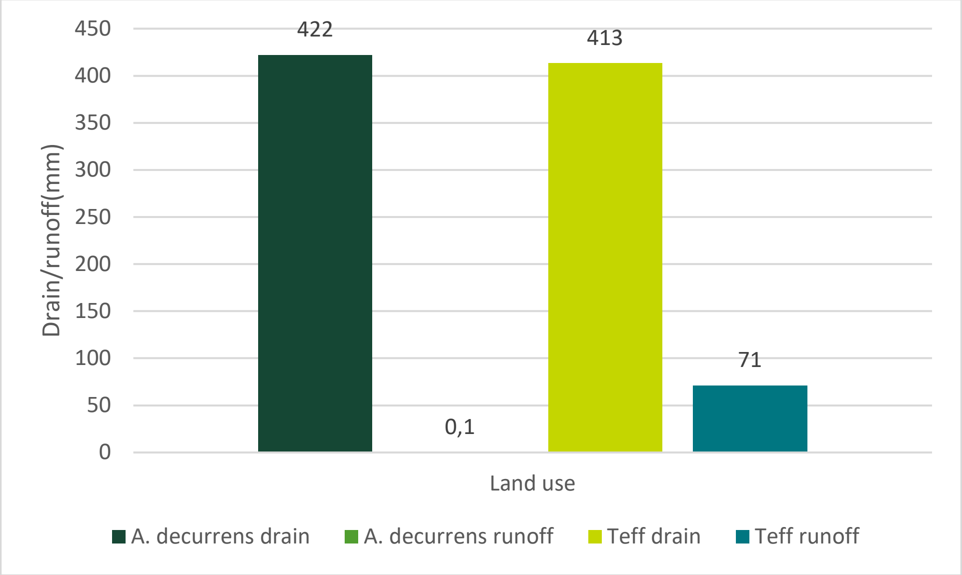

Figure 11. Drain and runoff for different land use during dry Kiremt season.

Figure 12, suggests drainage in the fourth cycle of afforestation with *A. decurrens* was 12% higher than in teff cultivation. Further, Figure 12, also shows that teff cultivation had 60% more runoff than in the fourth cycle of afforestation with *A. decurrens*.

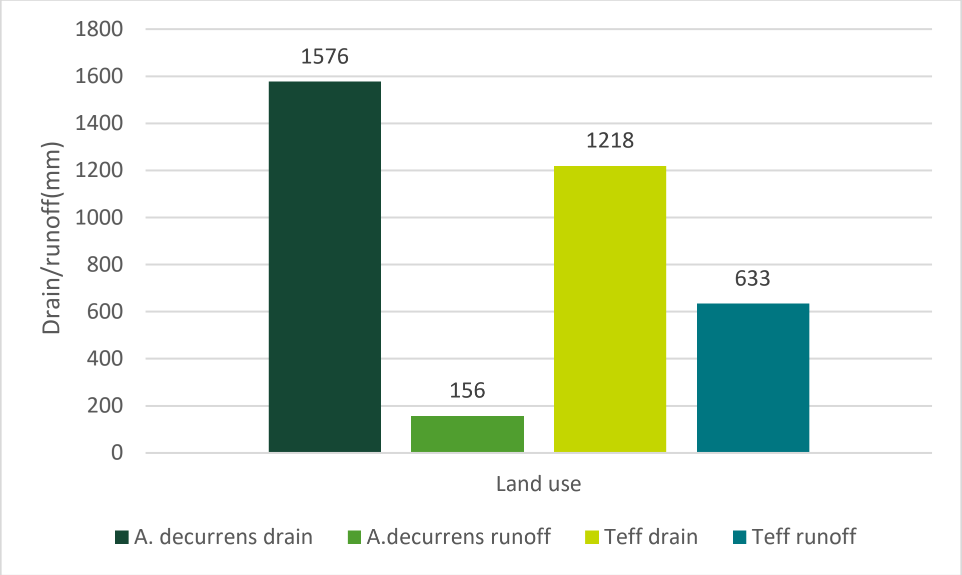

Figure 12. Drain and runoff for different land use during wet Kiremt season.

5. Discussion

This study suggests that rainfall distribution in Fagita Lekoma is uneven across the year and is mainly received from July to September, as shown in previous studies (Ademe et al. 2020). Due to this, farmers tend to grow high moisture demanding crops such as teff during the Kiremt season rather than during the Belg season since there is more rain and less water stress. This study also found that the Belg season is characterised by low rainfall accompanied by high temperatures and ETo (Figure 2).

Considering the results from this study in (Tables 5, 6,7, and 8), high ETa is observed in both teff cultivation and afforestation with *A. decurrens* during dry Kiremt season, followed by normal and wet Kiremt seasons. ETa is a function of gradients in vapour pressure between the soil, plant, atmosphere, and leaf surfaces. These gradients are influenced by solar radiation and climatic variables such as temperature and relative humidity (Weil & Brady 2017). High rainfall conditions, such as those that occur during the wet Kiremt season, lead to increased relative humidity, thereby reducing the evaporative demand of the atmosphere or vapour pressure gradient. ETa is stable under moderate rainfall conditions because the humidity is stable and water stress by plants is reduced for stomatal closure (ibid.).

The study results also show that ETa increases from the first to fourth cycles of afforestation with *A. decurrens*. This observed upward trend in ETa is because of an increase in green canopy cover from the first to fourth cycles of afforestation with *A. decurrens* (Figure 3).

Based on the study results (Figures 7, 8 and 9), there is a significant difference ($P< 0.05$) in ETa between teff and afforestation with *A. decurrens* in the third and fourth cycle of afforestation with *A. decurrens*. This is because *A. decurrens* has a more extensive green canopy cover and a deeper rooting system that can access water in the deeper soil layers increasing the transpiration component of ETa than teff. Changing ETa as a result of land use is consistent with observations made by (Nugroho et al. 2013; Jian et al. 2015).

The study results (Tables 5, 6,7, and 8) show that runoff is higher in teff cultivation than in four cycles of afforestation with *A. decurrens* during all Kiremt seasons. This is due to higher canopy interception in the four cycles of afforestation with *A. decurrens* compared to low rainfall interception by teff. The intercepted water is lost through leaf surfaces by evaporation before it reaches the soil surface (Jian et al. 2015). On the other hand, canopy cover in teff cultivation is small compared to afforestation with *A. decurrens* to intercept much rainfall. Since there is less water loss through evaporation on leaf surfaces in teff cultivation, most precipitation ends up as runoff (Huffman et al. 2013; Le Maitre et al. 2015). Furthermore, this study found unexpected results for high drainage in the fourth cycle of afforestation with *A. decurrens* than teff cultivation in all Kiremt seasons (Tables 6, 7 and 8). This is because there was supposed to be less water drained since most of it is lost through evaporation after canopy interception.

The results for teff cultivation show unexpected high groundwater recharge under normal Kiremt season (58%) conditions compared to the wet Kiremt season (57%). This is because of increased runoff due to increased soil water content in the topsoil layer during the wet Kiremt season. The results show high runoff (30%) during the wet Kiremt season compared to the normal Kiremt season (2%).

5.1 Study limitations and future considerations

AquaCrop 6.1 model determines the ETo by considering climatic factors such as radiation, temperature, humidity, and wind speed (Allen et al. 1998). Despite having most of the weather data for this study, the relative humidity data was sometimes missing. In this study, the dewpoint (Tdew) was assumed to be at a near-daily minimum, according to (Allen et al. 1998). However, this assumption is valid in locations where the cover crop is well irrigated, which might not be the case for stations 1 and 2. This is because the field scale where this study is situated has semi-arid climate conditions (ibid.). There is a need, therefore, to improve the accuracy of capturing climatic data to improve the estimation of water balance results. This can be achieved by increasing the number of weather stations and having weather stations near the study areas, especially at the field scale where high-resolution data is required.

This study used plant parameters such as canopy cover, seedling canopy size, rooting depth, canopy senescence, Harvest Index, and other phenological events for accurate water balance results. However, this was not the case in some situations where plant parameters such as rooting depth for *A. mearnsii* were used due to limited studies on plant parameters and phenological events, especially from the study area. To improve the accuracy of the results, it is necessary to carry out a study that compares or blends simulated results with field observations.

In this study, ETa was considered during the Kiremt growth season when teff was also cultivated. However, if the study was done on a calendar year, the annual total ETa for *A. decurrens* would be higher. On the other hand, ETa for teff is for a defined period during the Kiremt growing season.

5.2 Comparison with other studies

This study aimed to determine how afforestation with *A. decurrens* affects water balance partitioning compared to annual crops such as teff at a field scale. In the second part of my study, I sought to determine if climatic differences affected water balance. According to a verbatim by Jennie Barron:[3]

> "There are few studies available on rapid farmer-driven afforestation with green wattle and few that look at the disaggregated dry, normal, and wet seasons at stand scale compared to catchment or large scale."

Furthermore, most studies on land use change from annual cropping to afforestation with trees focus on the extent of land use change and its impacts (Nigussie et al. 2017; Wondie & Mekuria 2018). There are also relatively few studies on full water balance components given in equation 1.

In addition to the general land use and water balance studies highlighted in section 2.3 from different parts of the world, this study is similar to that by (Ter Borg 2020). Both studies are based on the effect of land use change from teff to afforestation with *A. decurrens* on water balance in the Ethiopian highlands, which is in the same geographical area where this study was conducted. Furthermore, Ter Borg (2020), studied the impact of land use change on sediment yield. Ter Borg (2020) used similar climate data to this study such as rainfall, temperature, humidity, and wind speed to estimate ETo. However, the scales on which the two studies were conducted differ. In this study, the water balance was investigated on a field scale. While the water balance, in Ter Borg (2020) was studied at a watershed level.

In both studies harvesting of A. *decurrens* was done in the fourth year, however, different models were used in both studies to determine the water balances. In this study, the AquaCrop 6.1 model was used, while Ter Borg (2020) used the soil and water assessment tool (SWAT) _2012.10_ 5.21 model.

The CN which determines the runoff was different in both studies. CN ranged from 61 to 21 in this study (Table 3) for the various growth cycles, whereas in Ter Borg (2020), the CN was lowered from 87 to 79. Refer to section 3.3.4 for a detailed explanation of how CN affects runoff.

There was also a slight difference in the growing season between the two studies. In this study, the Kiremt growth season was from 1st July to 27th November for both afforestation with *A.decurrens* and teff cultivation, while in the study by Ter Borg (2020), the growth season for afforestation with *A. decurrens* was from 1st July to 1st November and 1st July to 1st December for teff.

During normal, dry, and wet Kiremt seasons, the annual mean ETa for teff cultivation in this study was 346 mm/y, 322 mm/y, and 297 mm/y, respectively.

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[3] Professor Jennie Barron is a Lecturer of Agriculture Water Management at the Swedish University of Agricultural Sciences in Uppsala, Sweden.

While in the study by Ter Borg (2020), the annual mean ETa for teff was 954 mm/y. Further, Ter Borg (2020) suggests that the annual mean ETa for afforestation with *A. decurrens* was 803 mm/y. On contrary, this study estimates annual mean ETa during afforestation with *A. decurrens* to be 474 mm/y, 497 mm/y and 461 mm/y during normal, dry and wet Kiremt seasons respectively.

In this study, the annual mean runoff for teff cultivation is 330 mm/y, 74 mm/y and 636 mm/y during normal, dry and wet Kiremt seasons respectively. While Ter Borg (2020) reports 637 mm/y annual mean runoff during teff cultivation. Further, this study estimates annual mean runoff for afforestation with *A. decurrens* to be 56 mm/y, 13 mm/y and 144 mm/y during normal, dry and wet Kiremt seasons respectively. While Ter Borg (2020) reports 650 mm/y annual mean runoff during afforestation with *A. decurrens*.

Ter Borg (2020) suggests that the annual mean drain for teff cultivation was 15 mm/y, while this study estimates the mean annual drain for teff to be 956 mm/y, 413 mm/y and 1,208 mm/y during normal, dry and wet Kiremt seasons respectively. In addition, this study estimates annual the mean drain during afforestation with *A. decurrens* to be 1,171 mm/y, 408 mm/y and 1,574 mm/y during normal, dry and wet Kiremt seasons respectively. While Ter Borg (2020) reports a mean annual drain of 21 mm/y during afforestation with *A. decurrens*.

This study differs from Ter Borg (2020) in its estimation of water balance, due to the differences highlighted above as well as the way the calculations were performed. The study by Ter Borg (2020) calculated mean annual water balances from long-term annual averages (1990 to 2019), whereas this study calculated annual mean water balances based on disaggregated normal, dry, and wet Kiremt seasons.

The other similar study is by Ilstedt et al. (2007) which was conducted to assess the effect of afforestation on water infiltration in the tropics. Ilstedt et al. (2007), conducted a meta-analysis study that compared 14 different afforestation treatments. Three African studies and one Asian study were included in the meta-analysis. According to Ilstedt et al. (2007), the infiltration of soil water and subsequent recharge of groundwater in intensified agriculture systems are affected by low organic matter input and surface soil sealing, both of which lead to high runoff and low infiltration. However, the reverse happens when land use changes from annual cropping to afforestation with trees due to high organic matter input. This causes improvements in soil structure that increase infiltration and groundwater recharge (ibid.).

For studies in Africa and Asia, rainfall ranges were 850-2500 mm, which was similar to the rainfall in this study, which was 825 mm, 1,649 mm, and 2,120 mm for the dry, normal, and wet Kiremt seasons, respectively. The soil type in the study by Ilstedt et al. (2007) was largely Anfisol and also some Ultisol. While the soil type in this study was predominant Nistisols, followed by Eutric Fluvisols and

Luvisols. The soil texture for the study by Ilstedt et al. (2007) was largely clay and a little loamy. While in this study the soil texture was loam and silt loam.

Different vegetation types were used in the study by Ilstedt et al. (2007), including Acacia species like *Acacia angutissima* and *Acacia magium* which are in the same family Fabaceae as *A. decurrens* used in this study.

The results suggest that infiltration increased from 3 to 47 mm/h under normal rainfall intensities to 2 to 5 times after land use changed from annual crops to afforestation with trees (Ilstedt et al. 2007). Despite rainfall interception and loss of water on leaf surfaces as a result of increased canopy cover in afforestation with trees, there is increased groundwater recharge due to improved soil structure, which was the case in this study. The expected reduction in runoff in the study by Ilstedt et al. (2007) due to land use change from annual cropping to afforestation with trees is similar to the results shown in this study (Figures 10,11 and 12).

Ilstedt et al. (2007) acknowledge the limitations in accessing the information on edaphic factors, climate, and field management and also estimate the amount of runoff. This study on the other hand has information on soil's physical, biological and chemical properties in the study including climatic information and field management practices applied.

6. Conclusion

In this study, the water balance was examined on a field scale on how it is impacted by land use change. Further, the study investigated the influence of different local climatic conditions on the water balance. This study made the following observations:

1. The annual mean ETa for teff in absolute amounts (mm) was significantly higher during the dry (39%) Kiremt season than during the wet (14%) and normal (21%) Kiremt season. Dry weather conditions create a high vapour gradient between the soil, plant, and atmosphere, allowing for more ETa.
2. In absolute amounts (mm), annual mean ETa for afforestation with *A. decurrens* was considerably higher in the dry Kiremt season (60%) than in normal (29%) or wet (22%) Kiremt seasons during the third and fourth cycles of afforestation with A. *decurrens*. A high ETa rate in the dry Kiremt season is due to increased evaporative demand of the atmosphere that is influenced by high solar radiation and low humidity conditions.
3. Changes in land use from teff to afforestation with *A. decurrens* have significantly affected ETa. In the study, higher ETa rates were evident in afforestation with *A. decurrens* compared to teff. This is because *A. decurrens* has a large green canopy cover than teff. The rate of transpiration increases with the size of the green canopy cover, as observed from equation 2.
4. In the study, unexpected results of increased water drainage were observed in the four cycles of afforestation with *A. decurrens* compared to teff. These results could be attributed to missing relative humidity data, and AquaCrop 6.1 model had to estimate the relative humidity from weather station location and temperature data.
5. The study results show that runoff in teff is higher than in the fourth cycle of afforestation with *A. decurrens*. This is because teff has a smaller canopy cover than *A. decurrens*, so there is less rainfall interception than *A. decurrens*, resulting in increased runoff downstream.

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Popular science summary

Changes in land use substantially impact the partitioning of water balance components like runoff, drain, crop evapotranspiration, and precipitation. Agricultural productivity can also be affected by land use type as a result of water stress by crops.

As more water is stored in the soil, water available during the off-season for agriculture production increases while less water storage reduces it. In addition, groundwater recharge is essential in supporting ecosystems during dry periods of the year. Groundwater recharge also contributes to river flow and hydropower generation both upstream and downstream of the river Nile given the transboundary nature of the Nile River.

Despite the Ethiopian highlands being the primary source of the Nile River, water is scarce due to the growing population and demand for agriculture, hydropower generation and other uses. Water use in the Ethiopian highlands is, therefore, a crucial issue for many stakeholders beyond Ethiopia.

Field management practices can cause excessive runoff downstream, resulting in floods and affecting water quality by transporting diffuse pollutants and sediments. Furthermore, the climate conditions of an area can also impact the water balance partitioning. Depending on the type of land use and climatic conditions it may lead to water losses through increases or decreases in ETa, runoff and soil water storage.

A crop model, such as AquaCrop 6.1, can determine the impact of land use on water balance at a field scale given local climatic conditions, plant and soil parameters, and field management practices. The model results, can help farmers estimate crop water needs and plan for water conservation strategies to sustain agricultural production when the water supply is limited.

The results from this study suggest that land use change from annual cropping to afforestation with *A. decurrens* reduces groundwater storage through increased ETa. The consequence is a reduction in stream flow during dry periods and a limitation of water use for other purposes such as agriculture, hydropower generation, domestic use and support to ecosystem services

This study, therefore, informs farmers, policymakers and other water resources stakeholders on the implication of land use change on sectors that depend on water and analyse the long-term cost benefits of afforestation with *A. decurrens*.

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Appendix 1. Vegetation parameters for *A. decurrens* and teff

Table 9. Plant parameters for Acacia decurrens.

Crop parameter	Unit	Value	GDD	Reference
Leaf Area Index		0.05 2.0 3.5 4.0		(Le Maitre et al. 2015b; Ter Borg 2020)
Spacing		1m x 0.75 m		(Chanie & Abewa 2021b)
Planting density	Plants/Ha	16,000-18,000		(Chanie & Abewa 2021b)
Initial canopy cover	Percentage	1.5		(Raes et al. 2018b)
Maximum canopy cover	Percentage	40 50 5 4		(Raes et al. 2018b)
Time for budbreak recovery	days	2	20	(Raes et al. 2018b)
Time to reach maximum canopy cover	days	120	949	(Clemson 1985a) www.cabi.org/isc.
Time to start flowering	days	120	949	(Clemson 1985a) www.cabi.org/isc.
Duration of flowering	days	65	426	(Clemson 1985a) www.cabi.org/isc.

Time to reach maturity	days	365	2876	(Er-Raki et al. 2021) www.cabi.org/isc.
Time to start canopy senescence	days	190	1403	(Clemson 1985a) www.cabi.org/isc
Maximum root depth	Meter	1.0		(Ter Borg 2020)
Average root expansion	cm/day	1		(Raes et al. 2018b)
Reference Harvest Index	Percentage	76		(Ter Borg 2020)
Base temperature	^{0}C	8		(Ter Borg 2020)
Optimal temperature	^{0}C	20		(Ter Borg 2020)

Table 10.Crop parameters for teff (Eragrostis Tef)

Crop parameter	Unit	Value	GDD	Source
Canopy size per seedling at 90%	cm^2/Plant	1.5		(Araya et al. 2010 see Paff & Asseng 2018)
Initial canopy cover	Percentage	2.30		(Raes et al. 2018b)
Plant density	Plants/m^2	923		(Araya et al. 2010 see Paff & Asseng 2018)
Time for 90% seedling emergency	Days	7	43	(Araya et al. 2010 see Paff & Asseng 2018)
Maximum canopy cover	Percentage	80		(Araya et al. 2010)
Time to reach maximum cover	Days	55	340	(Steduto et al. 2012a)
Time to reach maximum root depth	Days	55	340	(Steduto et al. 2012a)
Time to start flowering	Days	55	340	(Steduto et al. 2012a)
Duration of flowering	Days	16	99	(Araya et al. 2010)
Time to reach maturity	Days	150	1151	(Getu 2012 see Paff & Asseng 2018)
Time to begin canopy senescence	Days	60	370	(Steduto et al. 2012a)
Maximum rooting depth	Meters	0.75		(Ter Borg 2020)
Harvest reference Index	Percentage	25		(Araya et al. 2010)
Length of building up HI	Days	91	560	(Steduto et al. 2012a)

Appendix 2. Soil parameters

Table 11. Soil textural classes and chemical properties from a plot in Fagita Lekoma, Ethiopia.

Textural classes	Thickness (m)	Sand (%)	Clay (%)	Silt (%)	SOC (%)	pH
Loam	0.0-0.5	28.56	26	45.44	3.8	5.56
Silt Loam	0.5-1.0	28.56	16	55.44	2.5	3.58

Appendix 3. Publishing and archiving consent

Publishing and archiving

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