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Department of Land Resources Management and Environmental Protection

Simulating development, biomass and yield of tef (Quncho variety) using FAO's AquaCrop model: a case study in Mekelle area.

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This is to Certify that this thesis entitled "***Simulating development, biomass and yield of tef (Quncho variety)using FAO's AquaCrop model: a case study in Mekelle area***" submitted in partial fulfilment of the requirements for the award of MSc, degree in "***Tropical Land Resources Management*"** to the Department of Land Resources Management and Environmental Protection (LaRMEP) Mekelle University, done by Mr. **Hailay Haileselassie Gebregzeabher ID CDA/PR002/2004** is an authentic work carried out by him under our guidance. The matter embodied in this project work has not been submitted earlier for award of any degree or diploma to the best of our knowledge and belief.

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Dedication

This work is dedicated to my beloved mother (W/ro Hagosa Abraha and my wife Bisrat Haileselassie) who supported me to join this program and to complete this work with invaluable patience, memorable love, moral and continuous support.

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Acronyms

ANOVA	Analysis of Variance
AGB	Above Ground Biomass
Av.K	Available Potassium
Av.P	Available Phosphorus
AWC	Available Water Capacity
B	Biomass
BD	Bulk Density
CC	Green canopy cover
CEC	Cation Exchangeable Capacity
CM	Centimeter
CO_2	Carbon dioxide
CSA	Central Statistics Authority
CWR	Crop Water Requirement
DAP	Diammonium Phosphate
DAS	Days After Sowing
ET_c	Evapotranspiration
ETo	Reference Evapotranspiration
FC	Field Capacity
GDP	Gross Domestic Product
GPS	Global Positioning System
GY	Final Grain Yield
Ha	hectare
HI	Harvest index
IWUE	Irrigation Water Use Efficiency
K_c	Crop coefficient factor
Kg	Kilo gram
K_s	Stomata Conductance

Ksat	Hydraulic conductivity
LAI	Leaf Area Index
LAP	Leaf area per plant
LS	Loamy sand
m.a.s.l	Meter Above Sea Level
Mg	Exchangeable Magnesium
ME	Model Efficiency
MS	Mean Squares
Na	Exchangeable Sodium
NFUE	Nitrogen Fertilizer Use Efficiency
NMSA	National Meteorology Service Agency
NS	Non significant
NT	Number of tillers
^oC	Degree Celsius
OM	Organic Matter
ppm	Parts per million
PWP	Permanent Wilting Point
R^2	Coefficient of Determination
RAW	Readily Available Water
RMSE	Root Mean Square Error
SCL	Sandy Clay Loam
Si	Silt
$\sum$	Summation of observations
SS	Sum of Squares
SY	Straw Yield
TAW	Total Available Water
TCL	Textural Class
TLA	Total leaf area
TN	Total Nitrogen

T	Crop transpiration
WP*	Normalized crop water productivity
WUE	Water use efficiency
Z_r	Root zone

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Abstract

The experiment was carried out in the northern Ethiopia at Mekelle University Main campus in 2012. The objectives were to evaluate the effect of fertilizer and water level on yield and yield component as well as to simulate, development, biomass and yield of improved tef (Quncho) variety under different levels of water and fertilizer. The experimental design was arranged in a Randomized Completely Block Design (RBCD) in two factorial with fertilizer treatments of 0, 32 and 64 kg.ha^{-1} of N; and 0, 23, 46 kg.ha^{-1} of P in N-P combinations, respectively; and water treatments: deficit irrigation(two irrigation and four irrigation) and full irrigation (nine irrigation) after cessation of rainfall and rainfed (control). The experimental crop was sown by broadcasting at a seeding rate of 25kg.ha^{-1} and the plot size was 4 mx3 m. The highest (LAI=4.77) was recorded for high fertilizer treatment N-P combination (with 64 kg.ha^{-1}N and 46 kg.ha^{-1}P with deficit irrigation (four irrigation) after the cessation of rainfall whereas the lowest (LAI=2.27) was recorded for zero fertilizer treatment (zero NP kg.ha^{-1}) under rainfed condition. Results showed that the highest leaf area index (LAI=4.77) was recorded between 63 and 73 after sowing (DAS) for all treatments. The result of the research showed that the highest aboveground biomass (10416.7 kg. ha^{-1}) and grain yield (2190.8 kg. ha-^{1}) were obtained from treatments that received relatively high fertilizer (64 kg.ha^{-1}N and 46 kg.ha^{-1} P) with full irrigation (nine irrigation) whereas the lowest aboveground biomass (4375 kg. ha^{-1}) and grain yield (1008.1 kg. ha^{-1}) were obtained from treatments that received zero NP kg ha^{-1}under rainfed condition. During the experiment the water productivity of tef was 30 g.m^{-2}. The model efficiency (ME) values for canopy cover (CC) simulation over the growing season were between 0.94 and 0.98 whereas the root mean square of error (RMSE) for CC ranged between 1.72 and 2.67%. The simulated tef grain yield deviated from the observed value with a range of -20.92% to 10.21%. Similarly, the model efficiency (ME) for grain yield and biomass simulation was 0.81 and 0.74, respectively. The root mean square error (RMSE) for grain yield and aboveground biomass were 0.77 and 0.18 t ha^{-1}, respectively. Therefore, the result of this research showed that AquaCrop model was able to adequately simulate the canopy cover, development, aboveground biomass and grain yield of tef under different irrigation managements.

Keywords: *AquaCrop model, Quncho tef, fertilizer, supplementary irrigation, and simulation.*

CHAPTER I: INTRODUCTION

1.1. Background

Ethiopia has 85% of the population living in the rural areas majority of which depend on agriculture for their livelihood. Agriculture is the most important sector which is sources of income as export and even as means of living in day to day life of the people of Ethiopia. The agricultural sector accounts for more than 40% of national GDP, 90% of exports, and provides basic needs and income to more than 90% of the poor (Diao,*et al* ,2010). A better performed agricultural sector has provided growth to the overall economy, improved the food security and reduced poverty in the recent years **(**Diao,*et al.,* 2010).

Ethiopia is the second most populous country in Africa with an estimated population of *85* million (CSA, 2010). Over the past few years, the Ethiopian government has designed and implemented several economic development plans, notably the Sustainable Development and Poverty Reduction Plan (SDPRP), which covered the years 2002/03 to 2004/05 and a Plan for Accelerated and Sustainable Development to End Poverty (PASDEP) that ran from 2005/06 to 2009/10. Over those years, agriculture remained the main sector of the economy accounting for about 45% of the GDP of the country on average whereas the average contributions of the industry and service sectors were about 13% and 42%, respectively (MoFED, 2011).

Tef [Eragrostis tef (Zucc,) Trotter] is endemic to Ethiopia and its major diversity is found only in that country as with several other crops. The exact date and location for the domestication of *tef* is unknown. It is believed that *tef is* a very ancient crop in Ethiopia, where domestication took place before the birth of Christ (Piccinin, 2010).

Tef is the major staple cereal to Ethiopia. The common name of *tef* is written in three forms, namely ***Teff, Tef*** and ***Te'f,*** but the form "*Tef*" is the most widely used. Its scientific name is *Eragrostis tef (Zucc.) Trotter*. It is the only cereal cultivated in the genus Eragrostis, which contain about 350 species (Piccinin, 2010). *Tef* may have been domesticated in the highlands of

Ethiopia by pre-sematic people, but it is not certain for how long it was under cultivation (Tefera and Ketema, 2001).

1.2. Justification and Problem statement

Tef is adapted to dry land farming in Ethiopia and is considered as a drought-resistant crop. Despite its adaptation to dry land conditions, one of the major yield-limiting factors in *tef* production is water shortage. *Tef* production is expected to lower due to water stress if the current climate change persists. Inappropriate fertilizer applications and recommendations decreases potential yield and returned value from application are one of the key bottlenecks constraining the *tef* value chain (ATA, 2012).

Availability of water is crucial in life of plants, often constitutes the primary limiting factor in the production of crops. To grow successfully, each plant must achieve a water economy such that the demand made up on it is balanced by the supply available to it. The problem is the evaporative demand of the atmosphere is generally continuous, where as the supply of water by natural precipitation is only occasionally, and irregular. To survive during dry spells between rains, the plant must rely up on limited reserves contained in its own tissues. Even temporal depletion of the latter may cause impairment of normal physiological functions. Prolonged dehydration of plants generally causes irreversible damage and even wilting and drying (Wild, 1993).

Water is among the limiting factors for crop production in much of the world where rainfall is not ample. The recent increase in demand of agricultural commodities and the ensuing food crisis in poor developing countries, the need to improve the efficiency of water use in crop production are never more apparent. Based on these efforts toward this goal, the Food and Agricultural Organization (FAO) of the United Nations came with a crop simulation model known as AquaCrop. The model simulates a balance between accuracy, simplicity, robustness, and ease of use, and is aimed at practical end users such as extension specialists, water managers, personnel of irrigation organizations, and economists and policy specialists who use simple models for planning and scenario analysis (Hsiao *et al.*, 2009).

According to Yumbya *et al.,* (2011) small scale farmers have first-hand knowledge of climate change impacts due to their long-term observation and engagement with their environments. Their study confirmed that farmers have adapted to climate change and responded by developing efficient environmental management practices such as soil and water conservation, and adoption of early maturing and drought tolerant varieties.

The variability of rainfall in space and time is such that, even in climates that are classified as humid, crop yield losses due to limited water availability can occur. In these circumstances the effect of dry spell can often be minimized through the use of supplementary irrigation, however, in semi-arid regions not only rainfall is limited, but also supplementary water resources are often absent, too, and irrigation of agricultural crops is possible in restricted areas. Thus agricultural production in these areas is based on mainly rainfed agriculture (Parry and Carter, 1988). Hence one means of enhancing *tef* yield is through improving water management and appropriate fertilizer application doses in *tef* fields. This would benefit not only the smallholders who grow it but would also improve food security in the country and bring in revenue from international sales. Understanding *tef* yield water relations and calibrating a model for quantifying *tef* yield under various water availability and fertilizer levels could enhance adaptation to climate change there by contributing to livelihood food security in the region, However, such data lack in the region.

1.3. Objective

1.3.1. General objective

- To calibrate and validate the FAO AquaCrop model for simulating dry aboveground biomass and yield of *tef* under various water and fertilizer availability scenarios.

1.3.2. Specific objectives

- To evaluate the effect of different rates of fertilizers (Nitrogen and Phosphorus) on the development, yield, and biomass production of tef.
- To evaluate the interactive effect of supplementary irrigation and fertilizers on yield and yield component of tef.

- To quantify tef water relationships.
- To calibrate and validate AquaCrop model for predicting yield of tef.

1.4. Research Hypothesis

- The optimal fertilizer for rainfed tef growers is below the currently recommended NP rates in the region.
- It is possible to optimize the NP fertilizer rate for the different levels of water availability conditions in tef.
- AquaCrop model could be used for simulating tef yield under different water and fertilizer levels.

CHAPTER II: LITERATURE REVIEW

2.1. *Tef* crop description, origin and distribution

Tef [*Eragrostis tef* (Zucc,) Trotter (Ketema, 1997,: Alemayehu, 2001,: and Miller, D., 2008) is a C_4 plant (self-pollinated and annual crop). It has a fibrous rooting system with mostly erect stems, although some cultivars are bending or elbowing or bending types. The sheaths of *tef* are smooth, glabrous, open and distinctly shorter than the internodes. Its ligule is very short and ciliated but its lamina is slender, narrow and nearly linear with elongated acute tips. *Tef* has a panicle type of inflorescence ranging from very loose, loose, semi loose, semi-compact to compact forms while the spikelet have 2-12 florets with each floret containing lemma, palea, three stamens, an ovary and mostly two, in exceptional cases three and feathery stigmas (Ketema, 1997, Alemayehu, 2001).

The panicle of *tef* ranges from a very loose to compact. The flowers of *tef* are hermaphroditic with both the stamens and pistils being found in the same floret. Florets in each spikelet consist of three anthers, two stigmas and two lodicules that assist in flower opening (Ketema, 1997).*Tef* is a fine stemmed, tufted annual grass characterized by a large crown, many shoots and a shallow, diverse root system. Its inflorescence is a loose or compact panicle. The extremely small grains are 1 – 1.5 mm long, and a gram of seeds teff crop contains 2,500 – 3,000 seeds. The plants germinate quickly and are adapted to environments ranging from drought stressed to water-logged. Tef's 1000 weight averaging 0.3–0.4 grams equivalent to 150 grain weight of wheat. In Ethiopia it is considered as a reliable, low-risk crop (Ketema, 1997). *Tef* has different names however, the accepted synonyms of Eragrostis *tef* (Zucc.) Trotter, are *E. pilosa* (L.), *P. Beauv* sub-sp. a*byssinica* (Jacq.) Aschers et Garebn. *E. abyssinica (*Jacq.), Link, *Cynodon abyssincus (*Jacq.) Rasp, *Poa cerealis* Salisb, *P. abyssinica* Jacquin, *P. Tef* Zuccagni, the common vernacular name of the crop in Ethiopia is *tef*. This is also known by the vernacular name *Tafi* in Oromigna and "*Taff*" in Tigrigna (Alemayehu, 2001).

2.2. Importance of Tef (Eragrostis Tef)

Tef (*Eragrostis Tef)* is an indigenous cereal to Ethiopia. When compared with other food crops grown in the country, it is highly-valued by farmers and consumers. This is because of its importance in the national diet of most Ethiopians. *Enjera* (thin, flat and pancake-like bread with evenly distributed openings), which is a staple diet of most Ethiopians is made of *tef* flour. Its special adaptation to diverse biotic and abiotic stresses has made it ‘’low-risk’’ crop for cultivation. Farmers’ preference to grow *tef* and the sustained demand from urban consumers have increased the production to an average of 2 million ha a year, setting in the forefront of cultivated area (Tefera and Ketema, 2001).

2.3. Advantage of tef to farmers

The area devoted to *tef* cultivation is increasing mainly due to the versatility of the crop to the Ethiopian farmers. Some of the specific merits of *tef* that make it important and preferred cereal by farmers are the following (Ketema, 1997):

- *The prices for its grain and straw are higher compared to other cereals;*
- *It performs better than other cereals (maize, sorghum) under low moisture stress conditions. Often it is sown as a rescue crop as it survives and produces grain when planted after other cereals that have failed because of moisture shortage;*
- *Tef performs better than maize and, wheat or sorghum in the high moisture (water logged) conditions. Flat and depressed lands that have a drainage problem are usually reserved for tef planting;*
- *The grain can be stored in any kind of locally available material without being attacked by weevils;*
- *No disease epidemic has threatened its performance;*
- *‘’Enjera’’(bread made of tef flour) is the main stay of Ethiopian diet and*
- *The straw is a nutritious and highly preferred feed for cattle compared to other cereals;*

2.4. Production and productivity of *tef*

In Ethiopia over 2.5 metric tons of *tef* grain is produced per year; and a staple food for over 50 million people in the country (Berhe, 2009). According to Alemayehu, *et al* (2012) the cereal crops growth increased to 7% from 1999/2000 to 2008/2009 with *tef*, wheat and sorghum showing the fastest annual growth rates. An increase in Ethiopian restaurants (in Europe, US and other countries), and the increased familiarity with Ethiopian cuisine,

- health food trade due to good balance of amino acids, is high in iron and calcium and is low in gluten (suitable for people with allergies to wheat flour);
- *Tef's* straw is used for livestock feed and construction for plastering houses (Ketema, 1997).

According to CSA (2011) report, out of the total grain crop area, 79.34% (9,588,923.71 ha) was under cereals. *Tef*, maize, sorghum and wheat took up 22.6% (about 2,731,111.67 ha), 17% (2,054,723.69 ha), 15.92% (1,923,717.49 ha) and 11.89% (1,437,484.73 ha) of the grain crop area in Ethiopia, respectively (Fig 2.1).The total land area covered by grain crops; cereals, pulses and oil crops was 12,086,603.89 ha. The productivity of selected field crops in 2004 and 2011 is summarized in Table 2.1.

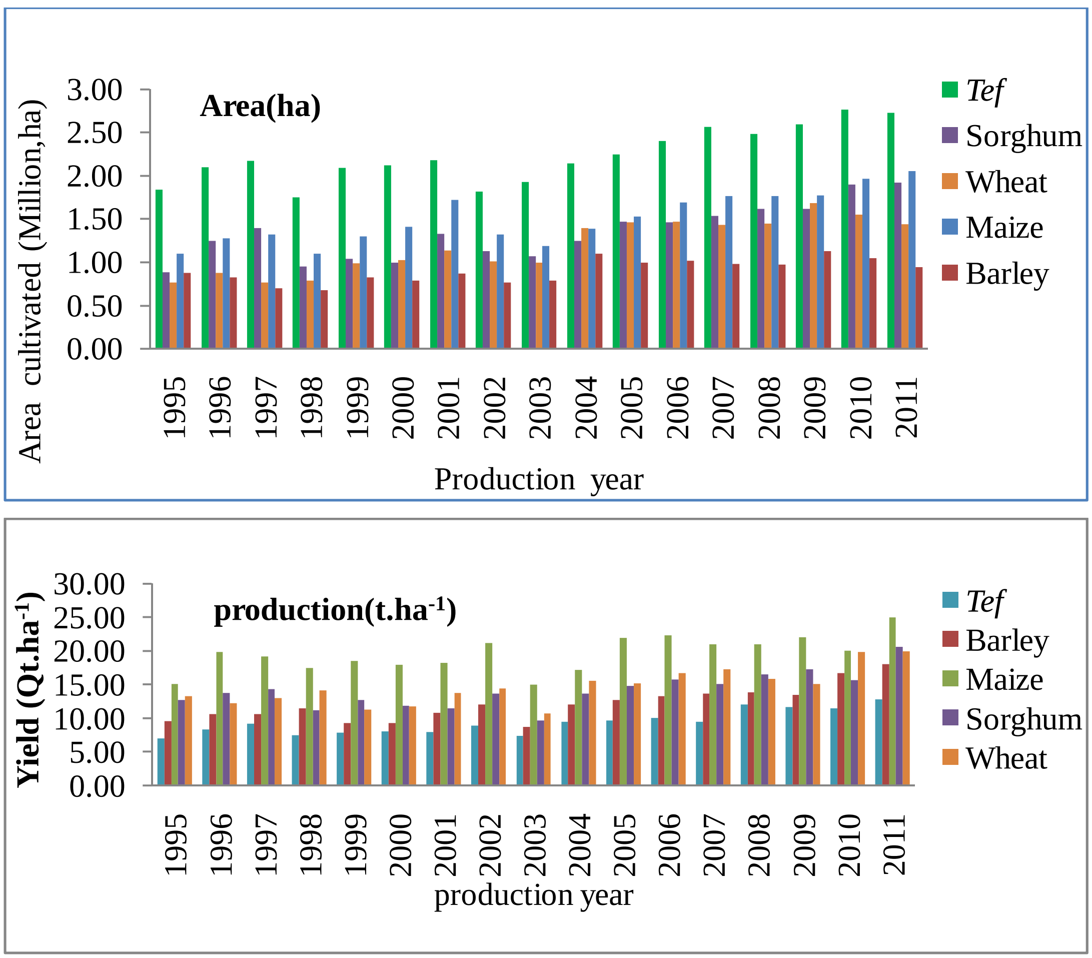

Figure 2. 1: *Tef* area coverage compared to other cereals in Ethiopia (1995-2011)

Table 2. 1: Production and productivity of *tef* in Ethiopia (2004-2011)

Year	Total area(000 ha)	Production (000 Qt[*1])	Yield ($Qt.ha^{-1}$)
2004/2005	2136	16773	7.9
2005/2006	2246	20255	9.0
2006/2007	2405	21756	9.0
2007/2008	2565	24377	9.50
2008/2009	2481	29929	12.10
2009/2010	2589	30280	11.70
2010/2011	2761	34977	12.61
2011/2012	2731	34835	12.81
Change b/n 2004 and 2011(%)	27.9	107.70	62.40
Average Annual % change	3.5	13.50	7.80

*(**Source**: CSA 2004- 2011 and Author's calculation)*

According to CSA (2011/12) out of the total grain crop area, 79.34% (9,588,923.71 hectares) were under cereals. *Tef*, maize, sorghum and wheat took up 22.6% (about 2,731,111.67 hectares), 17% (about 2,054,723.69 hectares), 15.92% (1,923,717.49 hectares) and 11.89% (1,437,484.73 hectares) of the grain crop area, respectively. From table 2.1 the national average yield of *tef* was 1261 and 1281 $kg.ha^{-1}$ in the production year of 2010 and 2011, respectively.

2.3. Agro-ecology

Crop production patterns in Ethiopia differ from place to place due to agro-ecological variations; hence there are five agro-ecological regions; moisture reliable cereal based highlands. Moisture reliable enset based highlands, humid lowlands, drought prone highlands, pastoralist areas (Alemayehu, *et al.*, 2012). In Ethiopia, *tef* is mainly produced in Amhara and Oromia, with smaller quantities in the Tigray and SNNP regions. There are 19 major *tef* producing zones in the country. The Central and South Tigray zones are the major *tef* producing zones in Tigray. Within

[*1] 1Qt=0.10ton

the Amhara region, East Gojam, West Gojam, North Gonder, South Gonder, North Wollo, South Wollo, North Showa and Awi zones are the major producers of *tef*. Finally, in Oromia region the major Tef producing zones include the East Showa, West Shoa, South West Shoa, North Shoa, East Wallaga, Horo Guduroo Wallaga, Jimma, Illubabor and Arsi zones (Bekabil *et al,* 2011). According to Ketma (1997), tef can be grown from sea level up to 2800 m.a.s.l, under various rain falls, temperature and soil conditions. It grows suitably at an altitude of 1800-2100 m, annual rainfall of 750-850 mm, growing season rainfall of 450-550 mm, though it can grow with 300 mm rain fall; and a temperature range of 10-27°C. *Tef* is widely grown in both high potential and marginal production areas. These areas include most parts of the Vertisols that suffer from water logging, and other soil types in different parts of the country that suffer from low moisture stress (Ayalew *et al*., 2011; Piccinin, 2010).

2.4. Agronomic practices

Tef yield is affected indispensably by several factors, such as land preparation, soil moisture or rain fall, nutrient availability, insect pests and diseases. Cropping system, land preparation, weeding, fertilizer application, planting methods, harvesting and postharvest techniques, e.g. row planting and transplanting have paramount importance in increasing yield of *tef*. Some of the important management practices in *tef* production are discussed below.

2.4.1. Sowing

Tef is one of the small seeded crops. Even though it is a long stay and traditional crop to Ethiopia, there are no improved planting techniques yet. The farmers' experience of sowing *tef* crop is by broadcasting the seeds on top of the soil after sowing and preparing seed beds very fine for the seed to land over, after the seeds are spread over and the farmers apply fertilizer they cover the seeds as well as the fertilizers by pulling woody tree branches (Ketema, 1997). In the traditional way of *tef* production under farmers experience, it has been observed that covering *tef* seeds thinly or pressing them lightly just after sowing or packing the seedbed before sowing under moisture stress conditions has vital role; in ensuring good crop establishment, promotes germination and increases grain yield through increasing stand establishment on both Andosols (light clay loam soils) and Vertisols (heavy clay soils). Especially, when there is moisture stress or rainfall interruption incidence at the beginning of the growing season, moderate packing of the seedbed is useful to enhance stand establishment on Vertisol that suffer from soil crusting (Ketema, 1997). This practice of packing the field is known as "**mintiqtak"** (in local language, Tigrigna), where it is carried out by using oxen, donkeys, goats, sheep and other farm animals. Seedbed packing is done before sowing *tef* to make the seedbed firm, prevent the soil surface from drying quickly, assist germination of seeds and minimize the damaging effect of low moisture during late onset of rain (Ketema, 1997).

According to Hailu and Edwards (2011) the experiences by farmers around Aksum Central zone of Tigray, *tef* seeds are mixed or coated with cattle dung or matured compost besides it can serve as a source of nutrient during germination, it can also be carried out by mixing with sand; and drilled to rows on nursery beds; water will be sprayed either by hand or watering can evenly, and continues until transplanting, after seedlings reach transplanting stage usually when they bear two to three leaves, they are uprooted and planted carefully to reduce root trauma and transplanting shock. The seed rate of the *tef* crop varies from 25-30 to 2-2.5 Kg/ha for broadcasting and transplanting respectively (Yoseph, 2010). According to Ketema (1997), the farmers' experience of seeding rate for one hectare of land is 40-50 kilogram, however, the recommended seed rate is to use 25-30kg/ha. Due to the small size of the seeds it is difficult to drill the seeds.

2.4.2. Varieties

There are a lot of improved and land race cultivars under cultivation in the country, the distribution and accessibility is not uniform for all farmers growing *tef*. Local cultivars such as Gea-Lamie, Dabi, Shewa-Gimira, Beten and Bunign, which are early maturing varieties (less than 85 growing days), are widely used in areas that have a short growing period due to low moisture stress or low temperature. In the highly productive and major *tef* producing regions of Gojam and Shewa, and in other regions where environmental stress is not severe, the local cultivars such as Alba, Ada and Enatit are used. Improved varieties are being used in many regions but in very small areas within each region. In the areas of Gojam and Shewa, which are located in the central highlands of Ethiopia and are also the largest and major *tef* production areas in the country modern varieties are used as well as traditional landraces and local cultivars. The most widely used modern varieties in these areas are depicted in Table 2.2.

Table 2. 2: Tef varieties and their distinct characteristics in Ethiopia

Variety	**Characteristics**
DZ-01-196	It is not as widely adapted and high yielding as DZ-01-354 but is very popular with farmers because of its very white seed color which fetches the highest market price for its grain-quality in the country
DZ-01-787	It has specific adaptation, cream-white seed color, better tolerance to rust and high grain yield
DZ-Cross-37	It has wide adaptation, cream-white seed color, and medium maturity (less 90 days). It is suitable to areas having a short growing period. In the region of Wello, Tigray, many areas of the rift valley and other areas that suffer from low moisture stress is used (Ketema, 1997).
DZ-01-974	This is high yielding, but because of the seed color (pale white) its preference by farmers was limited. On the other hand, the variety DZ-01-196 has been popular for its very white seed color, but its productivity has been relatively low (1.6–1.8t/ha). It has white seeds, very loose panicle, plant height of 102cm, and matures at 116.5 days, and grain yield of 2.461 and 1.271 t/ha on station and on-farm respectively (Kebebew et al, 2012).
*Qunch*o [(974 × 196)-HT′-387 (RIL355)]	It was developed by Debrezeit Agricultural Research Center (DZARC). The variety was released in 2005 (Bekabil, *et al*, 2011 and Kebebew, *et al*., 2011).

Table 2. 3: Distinguishing features of *tef* variety **Quncho** as compared to the parental lines

Characters/traits	**DZ-01-974**	**DZ-01-196**	**Quncho**	**Farmers 'variety**
Panicle form	very loose	Fairly loose	Very loose	Mixture
Lemma/ glumes color	yellowish green	yellowish green, and variegated with red tips and margin	yellowish green, and variegated with red tips and margin	Mixture
Seed color	Pale white	Very white	Very white	Mixture
Plant height (cm)	107.12	97.00	102.00	103.00
Days to mature	107.00	96.50	116.50	117.00
On- station grain yield($t.ha^{-1}$)	2.4-3.4	1.8-2.2	2.461	2.254
On- farm grain yield($t.ha^{-1}$)	2.0-2.5	1.4-1.6	1.271	1.188
On- station biomass ($t.ha^{-1}$)	12.00	9.60	10.11	10.09
On-farm above biomass ($t.ha^{-1}$)	10.00	8.10	8.10	6.18

(***Source:*** Adapted from Kebebew, *et al.*, 2011**,** 26 pp***)***

2.4.3. Fertilizer application

In Ethiopia, Urea (CO $(NH_2)_2$ and Diammonium phosphate, (DAP), $(NH_4)_2HPO_4$ are the manufactured fertilizers widely imported and used as a source of nitrogen and phosphorus respectively. The N content in Urea and DAP is 46 and 18 %, respectively are currently used. The optimal recommended doses[2] of N and P were used as a basis for the different application rates used during the experiment. Systematic studies on the fertilizer requirements of tef under varying conditions and in various regions need further investigation. However, currently the following recommendations from Debre Zeit Agricultural Research Centre are 60 kg N and 26 kg P_2O_5 per ha on heavy clay soils (Vertisols) and 40 kg N and 26 P_2O_5 per ha on sandy clay loam soils (Andosols). Urea is generally recommended to be applied in split applications (Ketema, 1997).

Table 2. 4: National N and P recommendations in Ethiopia for different soil types

Soil Type	N(kg. ha^{-1})	P(Kg.ha^{-1})
Andosols	45	21.9
Cambisols	50	21.9
Luvisols	45	21.9
Red soils	40	21.9
Nitosols	40	24.0
Vertisols	80	26.2

Source: National Fertilizer and Input Unit (NFIU, 1993)

[2] *The optimal recommended doses are 40 kg N ha^{-1} and 26 kg P ha^{-1} for light soils and 60 kg N ha^{-1} and 26 kg P ha^{-1} for heavy soils (EARO, 2002 as cited in* Tsegay, 2012*).*

Table 2. 5: Comparison of fertilizers on production and yield of *tef* in the study area

Year	Crop type and variety	input application	Production (ha)	Yield (qt.ha^{-1})	Yield Inc (%)
2010	*Tef* (Quncho)	With fertilizer	0.00	0.00	
		Without fertilizer	0.00	0.00	0.0
	Tef(local)	With fertilizer	18224.70	5.99	
		Without fertilizer	37492.00	2.05	192
2011	*Tef (*Quncho)	With fertilizer	202.50	7.36	
		Without fertilizer	0.00	0.00	>100
	Tef(local)	With fertilizer	11305.50	15.16	
		Without fertilizer	10762.50	9.00	68.44

NB: Inc (%), Increase (%), (***Source***: Author's calculation based on woreda Enderta ARD office report, 2010/2011).

2.4.4. The role of Nitrogen and Phosphorus in plant growth

Nitrogen (N)

Nitrogen is one of the most essential elements which are taken by plants in greatest amount after carbon, oxygen and hydrogen. However, it is the most deficit nutrient in crop production (Halvin *et al.*, 2002). It is also one of the most widely distributed elements in nature and Contains 99.8% of the global N (N_2). Atmosphere contains 78% N_2 is the ultimate source for nitrogen Foth and Ellis (1988); Loegreid *et al. (*1999) though it has to be converted to ammonium (NH_4^+) or nitrate (NO_3^-) to be available to the plant. According to Deckers (1998),the main sources of plant available nitrogen are mineralization of organic matter pools, nitrogen fertilizers and decomposition of organic inputs such as plant biomass and animal manures NH_4^+ ions bind to the soil's negative charges (exchangeable cations) and behave much like other cations in the soil. Nitrate ((NO_3^-) ions do not bind to the soil solids because they carry negative charges, but exist dissolved in the soil water, or precipitated as soluble salts under dry conditions (Loegreid *et al.*, 1999). Once the nutrient is taken by the plant, it is a vital component of many important structural, genetic and metabolic compounds in plant cells. It is a major component of chlorophyll, the compound by which plants use sunlight energy to manufacture sugars from water and carbon dioxide (i.e. photosynthesis). Nitrogen is also a major component of amino acids, the building blocks of proteins.

Based on Brady and Weil (2002), some proteins act as structural units in plant cells while others act as enzymes, making possible many of the biochemical reactions on which life is based. Nitrogen is a component of energy-transfer compounds, such as adenosine triphosphate (ATP), which allows cells to conserve and use the energy released in metabolism. In addition, nitrogen is a significant component of nucleic acids like deoxyribonucleic acid (DNA), the seat of genetic inheritance that allows cells (and eventually whole plants) to grow and reproduce (Tsegay, 2012). In addition according to Sinclair (1990), one major consequence of inadequate N is reduced leaf area, thereby limiting light interception, photosynthesis, and finally biomass growth, grain yield, and water productivity.

Phosphorus

Phosphorus is the major essential element next to nitrogen for plants. This element is a component of DNA, ribonucleic acid (RNA) that directs protein synthesis, ATP (the high energy phosphate group that drives most energy driven biochemical process like uptake of nutrients, transportation and assimilation of bimolecular), and also the phospholipids that form all cell membranes. In cereal field crops the nutrient stimulates root and tiller growth, strengthens structural tissue such as those found in stalks, hastens plant maturity and contributes to the production of good quality seed (Brady and Weil, 2002).The major available forms of phosphorus available for plants in the soil solution are the orthophosphate anions (HPO_4^{2-} and $H_2PO_4^-$).

The most important factors controlling the availability of soil P are the concentration of phosphate ions in the soil solution, the ability of the soil to replenish these ions when plant roots remove them (the P-buffer capacity of the soil) and the plant root depth. Similarly, factors that affect crop yield such as soil moisture and plant health status can influence P uptake by the crop and thus the recovery of P and its efficiency (Syers *et al*., 2008). Phosphorus is also known to be the master key to agriculture because lack of available P in soils limited the growth of both cultivated and uncultivated plants (Foth and Ellis, 1988). According to Malhi *et al.*, (2002**),** the efficiency of fertilizer P use by crops ranges from 10 to 30% in the cropping year. The remaining 70 to 90% becomes part of the soil P pool, which is released to the crop over the following months and years where this pool contributes to future crop production.

2.4.5. Weeding

Tef crop requires fine seed bed and free of weeds due to its small sized seeds. Repeated plow not only used to pulverize the soil, but also used to already grown weeds or newly emerging weed seedlings. Working should also start with clean *tef* seeds that are free of weed seeds. Hand-weeding once at early tillering stage (25-30 days after emergence) is ideal and adequate, if the weed population is low. However, if the infestation is high, a second weeding should be done at the stem-elongation stage. On the other hand, hand-weeding after heading is not recommended, since it may result in heavy damage to the plants **(**Ketema, 1997).

2.4.6. Harvesting and post harvest technology

Depending on the variety and location the maturity period of *tef* crop varies. The most commonly used symptom to identify weather the crop reach to harvesting or not, is the yellowish color of the straw. *Tef* is harvested when the vegetative parts turn yellowish. This depends on the maturity period of the varieties, which varies from 60 to 120 days. Harvesting before the plant gets too dry helps prevent losses from shattering (Ketema, 1997). However, late harvest may result in shattering causing a significant yield loss in *tef* production; the crop needs to be harvested on time. Shattering begins right after the crop starts to dry and can still occur during harvesting, gathering, piling and threshing. Due to late harvesting shattering can cause 10-30% yield loss (Bekabil *et al*., 2011).

Threshing of *tef* is done on special flat ground called ‘*awdma*’ or “***Awdi***” in Tigrigna that is usually plastered by dried cattle dung mixed with water. The harvested *tef* is scattered over the ‘awdma’ and cattle/pack animals are driven over to separate the grain from the straw. Sometimes when oxen and mules and/ or horses are not available, threshing is done manually by human by beating the harvested *tef* with a stick. However, significant yield losses are incurred during this process. In addition, as the threshing is done on the ground, the quality of the *tef* grain is affected as it can be mixed with the soil, sand and other foreign matter. This affects the market value of *tef* significantly as *tef* becomes contaminated by the foreign matter, particularly minute grains of sand and soil, which are difficult to clean and cause discomfort during the consumption of ‘Injera’ (Bekabil, *et al.,* 2011).

2.5. Tef- water relationship

2.5.1. Determination of Crop requirement

The amount of water required to compensate the evapotranspiration loss from the cropped field is defined as crop water requirement (Allen *et al.,* 1998). Crop water requirements are essential for any water conservation study in purpose of crop production. This is particularly important in arid and semi-arid regions where water is increasingly becoming scarce (Arku *et al.,* 2011).

2.5.2. Importance of supplementary irrigation

Supplemental or deficit irrigation is used when water supply is not sufficient to meet full crop water requirement or when it is expensive; this type of irrigation is applied to supply small amount of water during water stress conditions to water stress sensitive crop development stages (Jacob, *et al.,* 2009). Application of supplementary irrigation can be use full in establishing good tillers and crown roots, and finally, reduce the ultimate yield failure in dry land areas where there is high evapotranspiration which is higher than the rain fall received.

Supplementary irrigation is the most promising way to minimize drought, resulting from first class short growing seasons and dry spells, indicating that more than 80% of yield reductions is resulted due to water stress, and more than 50% of the crop failures attributed by this stress could have been avoided by irrigating adequately during the periods of rain withdrawals (Araya and Stroosnijder, 2011).

2.5.3. Total Available Water (TAW)

Soil water availability refers to the capacity of a soil to retain water available to plants. After heavy rainfall or irrigation, the soil will drain until field capacity is reached. Field capacity is the amount of water that a well-drained soil should hold against gravitational forces, or the amount of water remaining when downward drainage has markedly decreased. As water uptake progresses, the remaining water is held to the soil particles with greater force, lowering its potential energy and making it more difficult for the plant to extract it and this is called **permanent wilting point**. This is represented by following formula:

$$\text{TAW} = 1000(q\ FC - q\ WP)\ Z_r, \qquad \text{(Eq.1)}$$

Where, TAW = the total available soil water in the root zone [mm],

q FC = the water content at field capacity [$m^3 . m^{-3}$],

q WP = the water content at wilting point [$m^3 . m^{-3}$],

Z_r = the rooting depth [m].

TAW is the amount of water that a crop can extract from its root zone, and its magnitude depends on the type of soil and the rooting depth (Allen *et al.*, 1998).

2.5.4 .Readily available water (RAW)

It is considered that theoretically available until wilting point, crop water uptake is reduced well before wilting point is reached. Where the soil is sufficiently wet, the soil supplies water fast enough to meet the atmospheric demand of the crop, and water uptake equals ETc. As the soil water content decreases, water becomes more strongly bound to the soil matrix and is more difficult to extract. When the soil water content drops below a threshold value, soil water can no longer be transported quickly enough towards the roots to respond to the transpiration demand and the crop begins to under soil water stress conditions experience stress. The fraction of TAW that a crop can extract from the root zone without suffering water stress is the readily available soil water:

$$RAW = p\ TAW \qquad \text{(Eq.2)}$$

Where: RAW the readily available soil water in the root zone [mm],

- ρ average fraction of Total Available Soil Water (TAW) that can be depleted from the root zone before moisture stress (reduction in ET) occurs [0-1] (Allen *et al.*,1998).

2.5.5 .Water balance

The water balance is the difference between precipitation received by the crop and water lost by the crop and soil (Allen *et al*, 1998). The water retained by the soil and available to the crop is also taken into account in the calculation. The Calculation of the water balance is carried out on special form (FAO Agro meteorological rain fed crop monitoring).

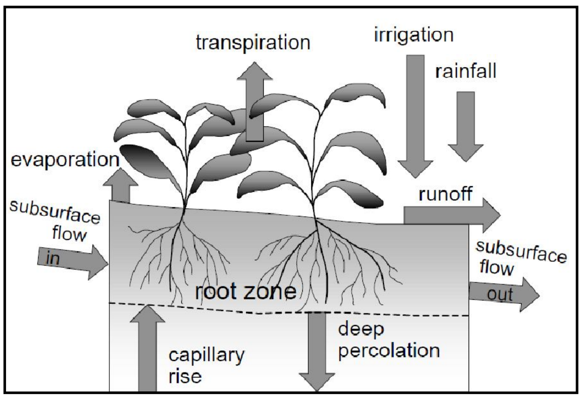

Figure2. 2 : Soil-water balance of a root zone

2.5.6. Crop water productivity

Crop water productivity (WP) or water use efficiency is defined as the yield of plant product (grain or other product of concern) produced per unit of water used (Taylor *et al.,* 1983). The crop water productivity expresses the aboveground dry matter (g or kg) produced per unit land area (m^2 or ha) per unit of water transpired (mm). Many experiments have shown that the relationship between biomass produced and water consumed by a given species is highly linear (Steduto *et al*., 2007). Enhancing water use efficiency in irrigated agriculture includes increasing output per unit of water, reducing water loses and prioritizing water allocation .The sustainable use of water has to consider maximizing yield per unit of water rather than maximum yield per unit of area **(**Howell, 2001). By considering the crop water productivity (WP), the aboveground biomass is derived from the simulated amount of water transpired and the normalized water productivity is calculated by (Eq 3.) as indicated by Steduto *et al.*(2009); Hsiao *et al.*(2009) to make the model applicable at diverse location and seasons including future climate scenario.

$$NCWP = \frac{BY}{\Sigma\left(T/_{ET_o}\right)} \qquad \text{(Eq.3)}$$

Where NCWP= Normalized crop water productivity, $g.m^{-2}$, BY= sequential dry matter accumulation, $kg.ha^{-1}$, T= actual crop transpiration (mm) calculated from the water balance equation, ET_O = reference evapotranspiration (mm).

Water Use efficiency **(**WUE) also refers to the amount or the value of water consumed by crop over the growing period or value of water depleted or diverted (Bessembider *et al.*, 2005). It can be expressed in general physical and economic terms**.** Oweis and Hachum (2006) defines Physical productivity as the quantity of the product divided by the amount of water depleted or diverted ($kg.m^{-3}$). WUE was used as the productivity of both grain and biomass of *tef* per unit amount of water applied in rainfed, and various irrigation scenarios.

2.6. The FAO AquaCrop description

FAO recently developed a water-driven model for use as a decision support tool in planning and scenario analysis in different seasons and locations (Steduto *et al.,* 2009; Hsiao *et al.*, 2009). Once validated, models are easy and need less resource and could be use full to avoid cropping risks (Tsudo *et al.*, 2005; Soltani and Hoogenboom, 2007). The AquaCrop model simulates the variation in attainable crop biomass and harvestable yield in response to variation in soil moisture in the root zone. This is done in daily time steps by considering the incoming and outgoing water fluxes and by taking into account the daily transpiration rate. The increment in yield depends on the normalized transpiration for the local climate and the separation of yield into biomass and grain. Biomass growth is associated with crop parameters such as stomatal conductance, canopy senescence and harvest index (Steduto *et al.*, 2009).

Such a model could have the potential to minimize the risks related to food insecurity in the country because it can be used to explore and evaluate alternative management that improves water productivity and achieves more efficient water use (Bessembider *et al*., 2005). It might also be applied by extension specialists, relief organizations, and policy makers, to predict yields. The model can be used as a decision support tool in planning and scenario analysis **(**Steduto, *et al.*, 2009; Hsiao *et al.*, 2009).The model is recommended for use in optimizing water use including in exploring better options in improving water use efficiency (Araya *et al.*, 2010b). Models that adequately simulate the effects of water stress on yield can be valuable tools in irrigation management. These models can be used to optimize the allocation of irrigation water between different crops and/or the distribution of water during the crop season **(**Cavero *et al.*, 2000).Complete testing of a model is needed before it can be used for irrigation planning in a particular area. This ensures that the model correctly simulates the main physiological processes that affect crop yield under water stress.

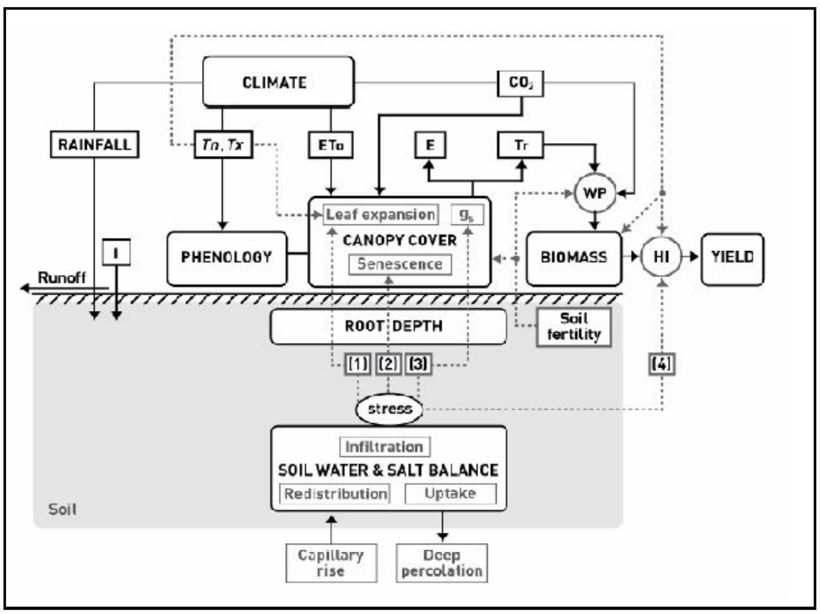

Figure2. 3: Flow chart showing the main component of AquaCrop model.

(***Source****:* Raes, 2009b AquaCrop model version 3.1).

AquaCrop, a new version of CROPWAT, is a Windows based software programme designed to simulate biomass and yield responses of field crops to various degrees of water availability. Its application encompasses rain fed as well as supplementary, deficit and full irrigation. It is based on a water-driven growth-engine that uses biomass water productivity (or biomass water use efficiency) as key growth parameter (WP_b).The model runs on daily time-steps using either calendar time or thermal time. It accounts for three levels of water-stress responses (canopy expansion rate, stomatal closure and senescence acceleration), for salinity build up in the root zone and for fertility status. An important peculiarity of the model is that the WP_b parameter is normalized for climatic conditions (specifically, the evaporative demand of the atmosphere (ET_o and the CO_2 concentration) and it simulates biomass and yield also under various global warming and elevated CO_2 conditions. It allows evaluating different water-management strategies, the development of recommendations for improved irrigation practices and the planning of irrigation schedules under varying water availability/supply. It is also a water-driven simulation model that requires a relatively low number of parameters and input data to simulate the yield response to water of most of the major field and vegetable crops cultivated worldwide. Its parameters are explicit and mostly intuitive and the model maintains sufficient balance between accuracy, simplicity and robustness (Bernardi and Michele, 2007).The particular features that distinguishes AquaCrop from other crop models is its focus on water, the use of ground canopy cover instead of leaf area index, and the use of water Productivity values normalized for atmospheric evaporative demand and of carbon dioxide concentration that confer the model an extended extrapolation capacity to diverse locations and seasons, including future climate scenarios and its wide range use of crops including forage, vegetable, grain, fruit, oil and tuber crops **(**Raes *et al*, 2009 and Hsiao *et al*., 2009). Moreover, although the model is simple, it gives particular attention to the fundamental processes involved in crop (Bernardi and Michele, 2007). It is also a tool for:

- *Predicting crop production under different water-management conditions (including rain fed and supplementary, deficit and full irrigation) under present and future climate change conditions, and*
- *Investigating different management strategies, under present and future climate change conditions. Appropriate for risk-management and adaptation-capacity studies of cropping systems. It can be applied at all locations; agricultural sector; site-specific, but can be extrapolated to larger scale by GIS applications* (Bernardi and Michele, 2007).

A detailed description of the model can be found in Steduto *et al.* (2009) and Raes *et al*. (2009a) who describe the underlying principles and distinctive components as well as the structural details and algorithms of the AquaCrop model.

2.6.1. Applications of FAO's AquaCrop model

AquaCrop can be used as a planning tool or to assist in management decisions for both irrigated and rain fed agriculture. The model is particular useful:

- *to develop irrigation strategies under water deficit conditions;*
- *to study the effect on crop yield of location, soil type, sowing date;*
- *to study the effect on crop yield of various land management techniques;*
- *to compare the attainable against actual yields in a field, farm, or a region, to identify the constraints limiting crop production and water productivity (benchmarking tool);*
- *to predict climate change impacts on crop production for scenario simulations and for planning purposes for use by economists, water Administrators and managers* (Raes *et al.*, 2009b).

2.7. Crop parameters simulated by FAO AquaCrop Model

2.7. 1. Biomass production

By considering the crop water productivity (WP), the aboveground biomass is derived from the simulated amount of water transpired. The crop water productivity expresses the aboveground dry matter (g or kg) produced per unit land area (m^2 or ha) per unit of water transpired (mm). Many experiments have shown that the relationship between biomass produced and water consumed by a given species is highly linear (Raes *et al*., 2009a).

2.7.2. Crop Evapotranspiration

There is no easy way of distinguishing between the evaporation and transpiration processes. Apart from the water availability in the top soil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction observed to decrease over the growing period as the crop develops and the crop canopy shades more and more of the ground area. When the crop is at its initial stage, water is predominately lost by soil evaporation, but if the crop is well developed and completely covers the soil, transpiration becomes the main process. At sowing nearly 100% of ET comes from evaporation, while at full crop cover more than 90% of ET comes from transpiration (Allen *et al.*, 1998).

2.7.3. *Tef* actual evapotranspiration

The average potential evapotranspiration of *tef* ranged from 260 to 317 mm. The average crop coefficient (Kc) values of *tef* for the initial, mid and late season stages were also found to be 0.8–1, 0.95–1.1 and 0.4–0.5, respectively. *Tef* shows a moderately sensitive and linear response to water stress (Araya, *et al.*, 2010a).

CHAPTER III: METHODS AND MATERIALS

3.1. General description of the study area

3.1.1. Location and map of the study area

The study area was located in northern Ethiopia at Mekelle University main campus, Enderta *Woreda*[3] ($13^0 48'$ latitude and $39^0 49'$ longitude with elevation of 2225 meters above sea level and slope of approximately 2%, at about 3 km east of Mekelle town.

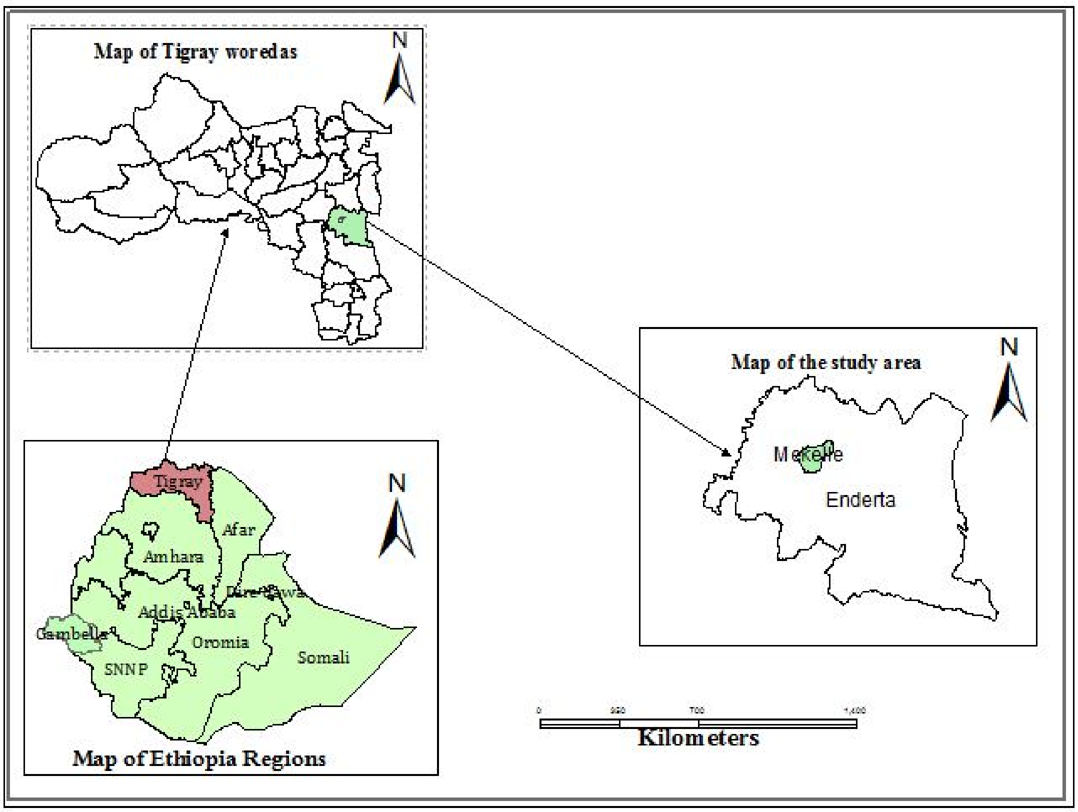

Figure 3. 1: Location of the study area

[3] *Woreda is to mean district*

3.1.2. Climate

The input for the climate data of the experimental season were daily minimum temperature (T_{min}), maximum temperature (T_{max}), daily rainfall, RH, wind speed, sun shine hours and the reference evapotranspiration, denoted by ET_o. ET_o is the rate of evapotranspiration from a reference surface, not short of water, a large uniform grass (or alfalfa) field is considered as reference surface, where the reference crop completely covers the soil, if is kept short, well water and is actively growing under optimal agronomic conditions (Allen *et al.*,1998*)*. The climate data was obtained from National Meteorology agency, Mekelle air port which is 3 km far from the experimental site.

As part of the Ethiopian high lands, Tigray has generally a cool tropical semi-arid climate. In general, two rainfall seasons can be distinguished in Tigray: the" *Belg*" or small rains, which generally occur from March till May and the "*Kremt*" that take place from July to September. The yearly average rainfall ranges from 511 to 656 mm with more than 85% of it received within a period of four months from June to September. The annual temperature in the high lands and low lands is about 26^0C and 22^0C respectively. While the highest and lowest average minimum temperature occurs in June (28^0C) and December (9^0C) respectively (Ahmed, 2001). Similarly the annual rainfall for the growing period 2012 of the study area was 559.33 mm (Table 3.1). The long term climatic data of the study area as shown in Fig. 3.2 indicated that the highest mean monthly rainfall and ET_o evapotranspiration occurs in August and May respectively.

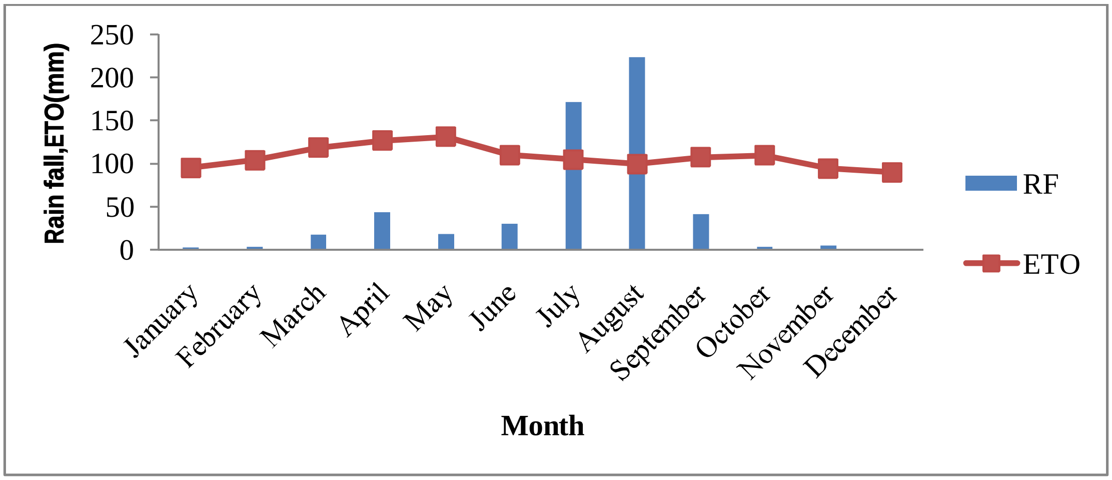

Figure 3. 2: Average RF versus ETo of long term data (1992-2012) of the study area.

Table 3. 1: Monthly climatic data of the study area during the experimental season in 2012.

Month	Average temperature (°C)		Average RH (%)	Total rain fall (mm)
	Max	Min		
July	22.38	13.41	81.03	84.00
August	29.81	12.96	79.39	210.00
September	24.29	11.14	57.93	57.50
October	23.69	9.60	44.10	0.00
November	23.37	10.56	46.89	0.00
			Total	**351.50**

(***Source:*** National Meteorological Agency)

3.1.3. Soils

The soil at the experimental site (Mekelle) is mainly Cambisol (Atakure, 2001; Habtegebrial and Singh, 2006) with a Sandy Clay loam (Table 4.1) texture up to 0.45 m deep**.** Soil depth is approximately 1 m, with white calcareous rocks (limestone) beneath this depth. The slope uniformly ranges from 2- 2.5%. Soil organic matter content ranges from 0.21 – 0.36%, total N is from 0.005 – 0.017 % available P and K ranges from 1.92 to 3.13 and 137.66 to 272.47 mg.kg^{-1} (Table 4.2) ,respectively.

Soil samples were taken from experimental site of observation 0-0.15, 0.15-0.30, and 0.30-0.45 m for analyzing physical and chemical characteristics such as bulk density, field capacity, permanent wilting point and texture. Bulk density and field capacity (%, w/w) were analyzed as described in Rawls *et al*. (1991). Permanent wilting point (%, w/w) was analyzed by Pressure plate apparatus (Richards, 1954). Soil texture was analyzed using hydrometric method before sowing. The soil chemical characteristics and the methods followed to analyze them are shown in

Table 3. 2 : Different methods used for soil chemical analysis

Parameter	**Method**
Organic matter (%OM)	Walkley and Black (1934)
Total nitrogen (TN %)	Modified kjedhal (Bremmer and Mulvaney,1982)
Cation Exchangeable capacity (CEC)	Measured after saturating the soil with 1N ammonium acetate (NH_4OAC) and displacing it with 1N NaOAC Landon (1991)
Exchangeable bases	
✓ Na^+ and K^+	Flame photometer
✓ Mg^{++} and Ca^{++}	Atomic Absorption Spectra photometry (AAS)
Available phosphorus	Olsen *et al,(*1954) method due to pH is alkaline
Available potassium	Morgan solution
Soil pH(1:2.5)	pH meter with glass electrode (Richards, 1954)
Electric conductivity(EC)(ds/m)	Ec meter (Sahelemedhin and Taye,2000)
Available Nitrogen(N)	Alkaline permanganate method

3.1.4. Irrigation water quality assessment

A water sample (of one liter) was taken to Geochemistry laboratory at the Department of Earth Science (Mekelle University) to analyze the water quality used for the irrigation treatments in the experimental site and the methods are listed here in Table 3.3.

Table 3. 3: Different methods used for irrigation water quality analysis

Parameter	Method
Na^+ and K^+ cations	Flame photometer
Mg^{++} and Ca^{++} cations	Atomic Absorption Spectra photometry (AAS)
pH	pH meter
Electric conductivity, EC (ds/m)	Ec meter (Sahelemedhin and Taye,2000)
Cl^-, SO_4^{-2} and HCO_3^-	Ultraviolet spectrometer, titration and turbid methods

3.1.5. Land use and cropping pattern

The agriculture practice of the study area is characterized by rainfed small-scale subsistence mixed farming. Majority of the farmlands are cultivated to annual food crops, including wheat (*Triticum aesticum),* Tef *(Eragrostis tef)*, barley (*Hordeum, Vulgare. L),* Maize (*Zea mais L.)*, pulses (*faba bean, chick pea*), and lentils and some vegetables and fruits in the irrigated lands of Enderta woreda. The area, production and yield of major crops grown in the area are presented in Table 3.4.

Table 3. 4**:** Area, production and yield of major cereals in the study area

Production year	Cereal type	Area cultivated (ha)	%	Production ($qt.ha^{-1}$)	%	Yield ($qt.ha^{-1}$)
2009/10	Wheat	10428	42.20	335646	66.63	32.19
	Barley	9312.98	37.69	278759	55.34	29.93
	Tef	4873.60	19.72	55916.7	11.10	11.47
2010/2011	Wheat	10709.18	43.34	220275.01	68.43	20.57
	Barley	6385.505	25.84	121694.4	37.80	19.06
	Tef	2113.45	8.55	22095.5	6.86	10.45

(Source: Author’s calculation based on woreda Enderta ARD office report, 2010/2011)

3.2. Treatments and experimental set up

3.2.1. Treatments

The treatments of the experiment were:

- **Water levels**
  - Optimal water(supplementary irrigation)=I_f
  - Deficit with four irrigation days = DI_4
  - Deficit with two irrigation days = DI_2
  - Rainfed = R
- **Fertilizer level**
  - NP_0 = zero NP fertilizer (0 kg.ha^{-1} N and P)
  - NP_{50} = 50% of the regional recommended doses of NP fertilizer (32 kg.ha^{-1} N and 23 kg.ha^{-1}P).
  - NP_{100} = 100% of the regional recommended doses of NP fertilizer (64 kg.ha^{-1}N and 46kg.ha^{-1}P).

Treatment Combinations

The experiment had **12** combinations in two factors (**water availability and fertilizer levels**) in factorial design as:

T_1= RNP_0, T_2= DI_2NP_0, T_3= DI_4NP_0, T_4= I_f NP_0, T_5= RNP_{50}, T_6= DI_2NP_{50}, T_7= DI_4NP_{50}, T_8= I_f NP_{50}, T_9= RNP_{100}, T_{10}= DI_2NP_{100}, T_{11}= DI_4NP_{100}, T_{12}= I_f NP_{100}

3.2.2. Randomization and field layout

Randomization

The treatments were assigned to the experimental units at random using random numbers as described in Gomez and Gomez (1984). All the treatments were replicated three times. Hence all plots in the experimental season were aligned in a randomized complete block design (RBCD). The plot size was 3.0 m x 4.0 m with 1.5 m between plots and 2.0 m between blocks buffer areas around the experimental plots and passages between the experimental units was made to avoid border and interaction effects. The plots were separated from each other using soil bunds of about 0.20 m high and were made uniformly at a slope of 2 % (Fig 3.3).

Field layout

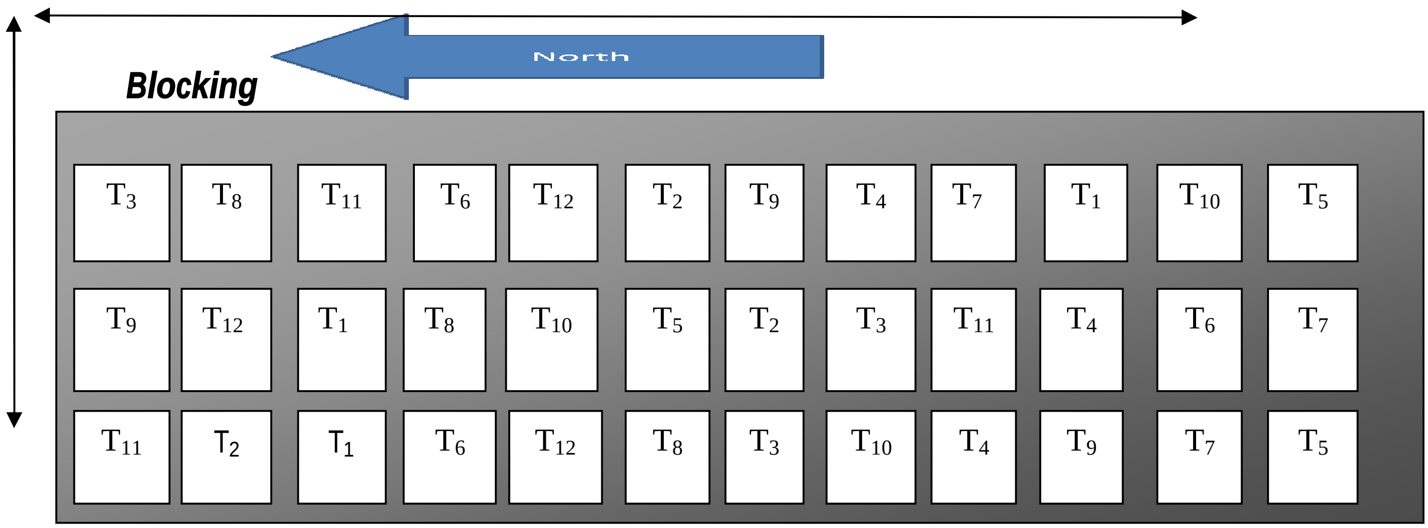

Figure 3.3: Field layout and randomization of the experiment.

3.2.3. Water levels

The irrigation amount and frequency was predetermined as calculated with the help of CROPWAT8 software program. Irrigation was applied when 25% of the field capacity has depleted. Irrigation was applied as predetermined based on CROPWAT 8 program (8-17 mm at 3 to 4 days interval, (Appendix 27). depending on the climate, crop stage and soil .Then irrigation was stored in known volume container and the water was applied manually using a pipe.

3.2. 4. Fertilizer application

The sources of N and P fertilizers used for research were urea ($CO(NH_2)_2$ and DAP $(NH4)_2HPO_4$), respectively. In this research the NP fertilizer treatment combinations were: NP_0 (0 kg ha^{-1} N and 0 kg ha^{-1} P); NP_{50} (32 kg ha^{-1} N and 23 kg ha^{-1} P) and NP_{100} (64 kg ha^{-1} N and 46 kg ha^{-1} P).Note that the NP_{50} and NP_{100} treatments were named after the NP regional recommendation where NP_{100} is the regional recommended fertilizer rate whereas the NP_{50} indicates just half of the recommended rate. The N fertilizer was applied in split application (half during sowing and the rest after 35 days after sowing) to reduce loss of N.

3.3. Land preparation and crop management

Land was ploughed three times; it was free of clods and weeds. Sowing was carried out by broadcasting at a rate of 25 $kg.ha^{-1}$ as described in Yoseph (2010). Top soil was at field capacity when sowing.

3.3.1. Crop management

Weeding was carried out five times. Weeds were removed regularly by hand. In addition, minor shoot fly (*Hylemya arambourgi*), (common insect pest in tef field) attacks were observed during the experimental season and was controlled by spraying pesticides. Harvesting was carried out manually using sickle from center (2 m x 2 m) of each plot. Each harvested crop was bundled, spread on Sun and left for two days to dry out the harvested crop and threshed manually on a smooth plastic sheet. After threshing the grains were labeled and weighed.

3.4. Data collection

3.4.1. Crop parameters

The following crop parameters were measured during the research:

Days to emergence (DE): was recorded when 50% of seeds emerge.

Sequential biomass: dry matter accumulation was measured by taking three samples from an area of 40*40 cm^2 or (0.16 m^2) from each treatment every 10 days. This biomass was dried in an oven drier for 48 hr at 65^0C and then weighed.

Canopy cover (CC): Canopy cover was taken using a digital camera as described in Nielson *et al. (*2012) every 10 days. The camera was placed in a locally made mast with horizontal extension which attaches the digital camera at right angle. The Photos were subsequently analyzed using 'SamplePoint' measurement software version 1.55 (Booth *et al*., 2006). The

SamplePoint software was set to select 64 randomly located points in each image. The software operator classified each of the 64 points as either grass or soil. Then each picture element (**pixel**) was classified as **grass** and **soil** and 8 x 8 grid cells were selected and the percentage classification was summarized in Ms-excel. The canopy cover percentage was calculated as the fraction of sampled points that contacted the crop canopy. Accordingly, the observed canopy cover were taken then regressed with the simulated canopy cover. The results from the three replications photographed in each plot were averaged to give the average CC per plot at each sampling time.

Leaf area index and plant population: leaf area and plant population were taken every 10 days from an area of 40 x 40 cm^2.This was carried out by selecting 3 plants at random from the area and then measure the leaves of these plants using CI-202 L portable laser leaf area meter and counting plant population was carried out manually from the same area at the same day. Then Leaf area index was calculated using equation (4).

$$Total\ Leaf\ area\ of\ a\ plant(TLA) = \sum_{i=1}^{n}(LA_1 + LA_2 + LA_3 + \cdots + LA_n) \qquad \text{(Eq.4)}$$

Where LA_1, LA_2, LA_3 are the leaf area of a plant (cm^2)

$$\text{Leaf area per plant(LAP)} = \frac{(\sum_{i=1}^{n}(LA_1 + LA_2 + LA_3 \ldots + LA_n))}{\text{number of plants taken for measurement}} \qquad \text{(Eq. 5)}$$

$$\text{Leaf Area Index(LAI)} = \frac{(\text{plant population per area}) \times (\text{Leaf area per plant})}{\text{Area of the sampled size}}$$

$$= \frac{\text{Plant population } \times \text{LAP}}{\text{Area}(m^2)} \qquad \text{(Eq. 6)}$$

Where the size of the area is 0.16m^2, number of plants in this case the number of plant is **3** and the unit for LAI is ($m^2.m^{-2}$).

Days to booting or heading: the number of days to booting was recorded when 90% of the population start booting.

Days to flowering: - the number of days to flowering was recorded when 50% the population reach flowering.

Days to maturity: the number of days to maturity was recorded when the 90% population reach maturity.

Plant height: It was measured from ground level to the tip of the panicle by selecting 10 random plants from each plot at maturity.

Panicle length: panicle length was measured from 10 randomly selected plants per plot. It was measured from the base of panicle up to apex of the terminal panicle at maturit**y**.

Final grain yield: matured plants were harvested from the middle plot area of 2 m x 2 m, then, they were dried, threshed, and, winnowed to separate the chaffs from the grain, and finally weighed.

Final aboveground dry biomass: was obtained by harvesting matured and dried tef total aboveground biomass (grain +other part of the plant except the root) from the middle plot area of 2 m x 2 m. The dry biomass was then weighed using sensitive balance.

Straw yield: Straw yield was obtained by subtracting grain yield from the dry aboveground biomass yield.

Harvest index (HI): the ratio of grain yield to the total aboveground dry biomass

$$\text{HI} = \frac{\text{Grain yield}(\text{kg.ha}^{-1})}{\text{Total dry weight}(\text{kg.ha}^{-1})} \qquad \text{(Eq.7)}$$

Where **the total** dry weight = total final aboveground dry biomass which is the sum of grain yield and straw yield.

Lodging: Lodging can be defined as the permanent displacement of a plant from the vertical (Berry *et al*., 2004). Lodging is often a problem for *tef*, especially if the grain is bountiful and when there is strong wind and heavy rain. To study the effect of fertilizer and water (irrigation) on tef lodging percent of lodging was estimated by simple observation at maturity.

Nitrogen fertilizer use efficiency: nitrogen use efficiency (NFUE) is the ability of crop to translate the applied nutrients into grain yield. NFUE was calculated using (Eq.8):

$$\text{NFUE} = \frac{GY_f - GY_0(\text{kg.ha}^{-1})}{N_f} \qquad \text{(Eq.8)}$$

Where:

GY_f and GY_0 are final tef grain yields (kg.ha^{-1}) with nitrogen fertilizer and without nitrogen fertilizer, respectively. N_f is the amount of nitrogen applied (kg.ha^{-1}).

Difference (percentage)

Difference percentage (increase %) on B, GY, water use efficiency (WUE) and Nitrogen fertilizer use efficiency (NFUE) as a result of water and fertilizer management were computed using (Eq.9-12).

- $$\%\text{increase in B} = \frac{\text{B}-\text{B from control treatment}}{\text{B from control treatment}} \times 100 \qquad \text{(Eq.9)}$$
- $$\%\text{increase in GY} = \frac{\text{GY}-\text{GY from control treatment}}{\text{GY from control treatment}} \times 100 \qquad \text{(Eq.10)}$$

Where B is final aboveground biomass production at harvest and GY is the final grain yield ($kg.ha^{-1}$).

- $$\%\text{increase in WUE} = \frac{\text{WUE}-\text{WUE from control treatment}}{\text{WUE from control treatment}} \times 100 \qquad \text{(Eq.11)}$$
- $$\%\text{increase in NFUE} = \frac{\text{NFUE}-\text{NFUEfrom control treatment}}{\text{NFUE from control treatment}} \times 100 \qquad \text{(Eq.12)}$$

3.4.2. Irrigation data

During the experimental season the following irrigation data were measured for analysis.

- Soil moisture was measured every 10 days at soil depths of (0 – 0.15, 0.15 – 0.3 and 0.3 – 0.45 m.
- Daily rain fall was measured by installing a rain gauge and it was recorded carefully after every rainfall session.
- Daily runoff was measured manually at the experimental plots by installing drums (barrels installed) and these barrels were used to collect only the runoff by protecting the sediments by sieving and placing material that hinder the entrance of sediment. Then, these barrels were emptied to known volume of cans every rainy events and that volume of water was converted into depth (mm) by the following relationship:

$$1\text{mm} = 1\frac{\text{litter}}{\text{m}^2} = \frac{1\text{lt}}{\text{m}^2} \qquad \text{(Eq.13)}$$

3.4.3. Agronomic data collected from Farmers' managed fields

Field assessments and interview were carried out from randomly selected woredas of in Tigray namely: from La'elay Maichew woreda, (*Hatsebo kebele*[4]), and Enderta woreda (*Shibta* and *Aynalem, kebeles*) *woredas*[5] of Tigray, in northern Ethiopia, where *tef* is grown dominantly. Selection of farmers was done randomly based on (Eq.14) as described by Yeshey (2010).

$$n = \frac{N}{1+(N*d^2)} \qquad \text{(Eq.14)}$$

Where n = sampling size, N = total population and d = level of precision (it was $taken\ as \pm 5$) Accordingly, the total numbers of interviewees were 30 and 15 farmers for *La'elay Maichew* and *Enderta* woreda from 40 and 20 population sizes, respectively. During the assessment yield measurements were carried out from the farmers plot using 1x1 m quadrant. Three samples were taken per farmer's field and a total of 30 and 15 fields were assessed for La'elay Maichew and Enderta woreda respectively. In addition, farmers were interviewed about overall crop and soil management practices (crop cultivar, fertilizer application rate (N and P), and soil management and land preparation practices. The collected data was used for comparison purposes.

3.5. Calibration and validation of AquaCrop model

3.5.1. Model Calibration

The model was calibrated with the collected data from the experimental plot grown under very minimal water and fertilizer stress condition (treatment, T_{12}). The climate, crop and soil data was then entered into the model. The model was then calibrated and recalibrated to reproduce the canopy cover, aboveground biomass, grain yield of the calibration crop data sets.

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[4] *Kebele= smaller district than woreda*

[5] *woreda= district*

3.5.2. Model validation

Model validation was performed to verify if the calibrated model could give an acceptable simulation output of an independent data set (data which were not used for calibration process). Accordingly, the data collected from experimental plots (T_2, T_3, T_4, T_6, T_7, T_8, T_{10} and T_{11} treatments) were used for the FAO AquaCrop model validation purpose. The model simulation or performance was evaluated based on four statistical techniques: RMSE, ME, R^2 and % deviation The first one is the root mean square errors (RMSE) as used by Hsiao *et al. (* 2009; Nash and Sutcliffe (1970):

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \qquad \text{(Eq.15)}$$

Where S_i and O_i are the simulated and observed values, respectively, and n is the number of observations. The unit for RMSE is the same as that of S_i and O_i; and a model's fit improves as RMSE approaches zero. The second one is the model efficiency (ME), which was also used by Yang *et al.(* 2004) for similar model performance assessment purpose

$$\text{ME} = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad \text{(E.q.16)}$$

Where $\bar{O}$ is the mean of the *n*, number of observations.

The model efficiency (ME) expresses how much the overall deviation between observed and simulated values from the overall deviation between observed values (O_i) and their mean observed value ($\bar{O}$). It is a measure of the robustness of the model. The value of ME ranges from negative infinity to positive 1; the closer to 1, the more robust of and efficient the model to explain the deviation between measured and predicted values. The third one is the coefficient of determination (R^2) value which is obtained from the regression 1:1 line. The higher the R^2 values, the stronger relationship between the observed and simulated values.

Percent deviation

Percent deviation was used to evaluate the deviation of the simulated from the observed as described in (Hsiao *et al.*, 2009).

$$D\ (\%) = \frac{(\mathrm{Sim}-\mathrm{Obs})}{\mathrm{Obs}} \times 100 \qquad \text{(Eq.17)}$$

Where D (%) is the percent of deviation from the observed; Sim. is simulated; Obs. is observed

3.6. Materials

The following materials were used for the research

- Oven drier machine, core samplers, spring and sensitive balances, augur, plastic bag, core samples, plate cups, seed (Quncho variety tef),Fertilizer (Urea and DAP), pegs, hoe ,spade, tape meter, leaf area meter, tension meter and manual rain gauge, GPS, Arc GIS 9.3 software, AquaCrop software, canopy cover estimating software ,statistical soft ware(JMP5),camera carrier mast, digital camera, barrels, ropes, pesticide chemicals, plastic pipes and watering can, plastics mats for threshing, quadrants (both 0.50 and 1 m^2).

3.7. Data Analysis

3.7.1. Analysis of Variance

To assess if there was significant variation among treatments, data collected from each plots were subjected to Analysis of Variance (ANOVA) based on Gomez and Gomez (1984). The statistical software employed for the analysis of variance was SAS JMP version 5 **(**Proust, 2002**).** Differences between the treatments means were computed by means of the Least Turkey's HSD 5% level of significance. Minitab14 was also used for normality testing of the data sets using probability plots and to explore the relationship between the independent variables (fertilizer rates and water level). The data collected from experimental site was also analyzed graphically to compare the treatments. In addition, correlations analysis was carried out by **S**tatistical and **P**resentational **S**ystem **S**oftware (SPSS, statistical software).

3.7.2. Irrigation data analysis

Soil water balance

Soil moisture content was measured using gravimetric method every 10 days from planting to maturity. Drainage was ignored as it is difficult to measure.

- Daily *tef* evapotranspiration was computed and averaged using the water balance equation for the weeks during the experimental seasons to give the weekly ET_c based on Allen *et al.* (1998) equation 17.

$$ET_c = I + P - D - Ro \pm \Delta S \qquad \text{(Eq.18)}$$

Where:

ΔS =the change in soil moisture storage between soil moisture measurements (mm).

I = irrigation (mm).

P = rainfall (mm).

D = drainage (mm).

Ro = runoff (mm).

ET_O (mm/days) was calculated using Penman-Monteith Method Allen *et al*. (1998) with the help of ET_O calculator software (FAO, 2009). Kc values 0.7,1, and 0.5 were used respectively for the initial, mid and late season stage of crop (Araya *et* al, 2011a). Crop water requirement and irrigation scheduling was calculated using CropWAT8 software. Supplementary irrigation was applied when the soil water was below 25% of field capacity. The first irrigation was applied 56 days after sowing. The irrigation amount and its schedule are described in (Appendix 27).

Water Use Efficiency (WUE)

To compare the productivity of the water supplied to the crop in the growing period (rainy season or supplementary irrigation) in terms of water consumed per unit of water supplied. This is known as green water use efficiency (Stroosnijder, 2009). As Bessembider *et al*. (2005) suggested it was used as a validated water response model to estimate the transpiration for computation of water use efficiencies and these equations (Eq.18-20) were used by Araya, *et al.*, (2010a).

1. Grain Water Productivity (Grain -WUE) was calculated using Eq.19:

$$\text{Grain} - \text{WUE} = \left[\frac{\text{GY}}{\sum \text{T}}\right] \qquad \text{(Eq.19)}$$

Where GY is the grain yield measured (kg.ha^{-1}) and T is the transpiration simulated by a calibrated AquaCrop model was converted into m^{3} ha^{-1}

2. Biomass water use efficiency (Biomass-WUE) was calculated using (Eq.20)

$$\text{Biomass} - \text{WUE} = \left[\frac{\text{BY}}{\sum \text{T}}\right] \qquad \text{(Eq.20)}$$

Where BY is the final above ground biomass (measured) in Kg.ha^{-1}

3. Green water use efficiency (Green-WUE) was computed as described by Stroosnijder (2007) and Stroosnijder (2009) based on (Eq.21)

$$\text{Green} - \text{WUE} = \left[\frac{\sum \text{T}}{\text{P+I}}\right] \times 100 \qquad \text{(Eq.21)}$$

Where P, is the seasonal rainfall from sowing to maturity (mm) and *I* is the total depth of applied irrigation (mm) Green-WUE is usually expressed in percent.

Irrigation Water Use Efficiency (IWUE):

Irrigation water use efficiency (IWUE) was estimated based on and Howel1 (2001) and Araya *et al.* (2011) using Eq.22.

$$\text{IWUE} = \frac{\text{GYI} - \text{GYR}}{\text{IR}} \qquad \text{(Eq.22)}$$

Where:

IWUE= Irrigation water use efficiency, GYI= grain of yield irrigated tef (g.m^{-2}), GYR= grain yield of rainfed tef (g.m^{-2}), IR is applied irrigation (mm).

3.7.4. Questionnaires

The collected questionnaires from farmers' managed field (final aboveground biomass, grain yield, plant height and panicle length) and some agronomic data were analyzed by using tables and SPSS 16.0 software (Shown in Table 4.11; Appendix 29 and 30).

CHAPTER IV: RESULTS AND DISCUSSIONS

4.1. Soil-water characteristics

4.1.1. Soil physical characteristics

The soil physical characteristics of the study area were analyzed and are presented in (Table 4.1).

Table 4. 1: Results of soil physical characteristics of the study area (before sowing)

Depth (cm)	BD	Moisture Content (Vol %)			Ksat (mm/day)	S (%)	Si (%)	Cl (%)	TC
		FC	PWP	TAW					
0-15	1.49	26.13	16.22	9.91	125	55	24	21	SCL
15-30	1.37	28.96	17.63	11.33	125	50	26	24	SCL
30-45	1.49	25.19	15.52	9.67	250	68	18	14	LS

NB: BD= Bulk density, (g.cm^{-3}), FC= Field Capacity, PWP= Permanent wilting Point, TAW=Total Available water, K_{sat} = Saturated hydraulic conductivity, S= Sand, Si= Silt, CL= Clay, TC= Textural class, SCL= Sandy Clay loam, LS= Loamy Sand.

Bulk density

The bulk density of the study area ranges from1.37 to1.49 g.cm^{-3}(Table 4.1). This result agrees with the general bulk density for sandy clay loam soils presented in Youdewie *et al. (*1986). Similarly the bulk density at depths of 0-15 and 30-45 cm was the same (1.49 kg.cm^{-3}) but differ in soil texture (Sandy Clay loam and Loamy sand), respectively. This was due to the compaction and tillage in the top soil (0-15) practiced in study area and sand dominated texture in lower depth (30-45) cm.

4.12. Soil chemical characteristics

The soil chemical characteristics of the study area are shown in Table 4.2.

Table 4. 2: Results of soil chemical characteristics of the study area (before sowing)

Soil chemical parameter		Unit	Depth (cm)		
			0-15	**15-30**	**30-45**
pH(1:2.5)			7.2	7.4	6.9
OM		(%)	0.36	0.64	0.21
EC		($ds.m^{-1}$)	0.03	0.05	0.18
TN		(%)	0.01	0.02	0.01
Av.P		($mg.kg^{-1}$)	3.13	1.92	2.42
Av.K		($mg.kg^{-1}$)	272.5	202.6	137.7
CEC		($Cmol_{(+)}.kg^{-1}$)	6.11	5.03	5.03
Exchangeable bases	Na^+	($Cmol_{(+)}.kg^{-1}$)	0.58	0.29	0.25
	K^+	($Cmol_{(+)}.kg^{-1}$)	0.07	0.02	0.01
	Ca^{++}	($Cmol_{(+)}.kg^{-1}$)	3.11	3.00	2.99
	Mg^{++}	($Cmol_{(+)}.kg^{-1}$)	0.21	0.13	0.09

NB: OM= Organic matter, EC= Electric conductivity, TN= Total nitrogen, Av.P =Phosphorus, K= potassium, CEC= Cation Exchangeable Capacity, Na = Sodium K= Potassium, Ca= Calcium, Mg= Magnesium

Soil organic matter content ranges from 0.21 - 0.36%, total N is from 0.005 - 0.017 % available P and K ranges from 1.92 -3.13 and 137.66-272.47 $mg.kg^{-1}$ respectively. The soil analysis result agrees with the findings by Habtegebriel and Singh (2006). According to Landon (1991) the total N (%) of the study area is rated as very low. Similarly the available K and P at the top 30 cm is rated as adequate and low respectively (Landon,1991). Therefore the soils of the study area could be classified as soils with very low N content and deficient in P respectively.

Soil Cation Exchangeable capacity (CEC) is the sum total of the exchangeable cations that a soil can adsorb. Cation exchange capacity is an important parameter of soil because it gives an indication of the type of clay mineral present in the soil and its capacity to retain nutrients against leaching. Landon (1991) rated soils with CEC of 5-15 Cmol $_{(+)}$ kg^{-1} as low. Hence, the soil of the study site is classified as low in its CEC. According to USDA soil classification soils showing electrical conductivity values <4ds/m (at 25^{o}C and pH <8.5 are classified as normal. Therefore the soils of the experimental site are categorized as normal.

Soil pH

The soil pH of the study area ranges from 6.9 to 7.4. According to Tan (1996) the soil is in the range alkaline to normal.

4.1.2. Irrigation water quality

The water quality of the irrigation water of the study area is depicted in Table 4.3. The result showed, the chloride values are < 4 mg/l and is well within the acceptable limits for irrigation (FAO, 1985) and since the type of irrigation application is surface irrigation and the SAR values is <13, the water is normal. Accordingly, the water quality results compared to the FAO (1989) standard, the water in the study area is suitable for irrigation practices.

Table 4. 3: Results of irrigation water quality analysis of the study area

Parameter	**Unit**	**Value**
Electric Conductivity	ds.m^{-1}	1.338
pH		7.56
Na^{+}	mg.l^{-1}	26
Mg^{++}	mg.l^{-1}	19
Ca^{++}	mg.l^{-1}	196
K^{+}	mg.l^{-1}	0.45
Chloride (Cl^{-})	mg.l^{-1}	24
Carbonate	mg.l^{-1}	0.043
Bicarbonate	mg.l^{-1}	212.73
Sulphate	mg.l^{-1}	367.50
Phosphate	mg.l^{-1}	0.954
Total Iron	mg.l^{-1}	0.09

Irrigation water with EC values of 0.70 to 3.0 ds.m^{-1} and values below 4 are considered safe for irrigation (FAO, 1989). Accordingly, the water in study area is suitable for irrigation practices.

4.2. Crop responses to water and fertilizer levels

4.1.3. Leaf Area index (LAI)

Leaf area index (LAI), is the ratio of projected leaf area to ground area. It is an important indicator of an annual crop's development, light interception, water use, productivity, and pollutant deposition.

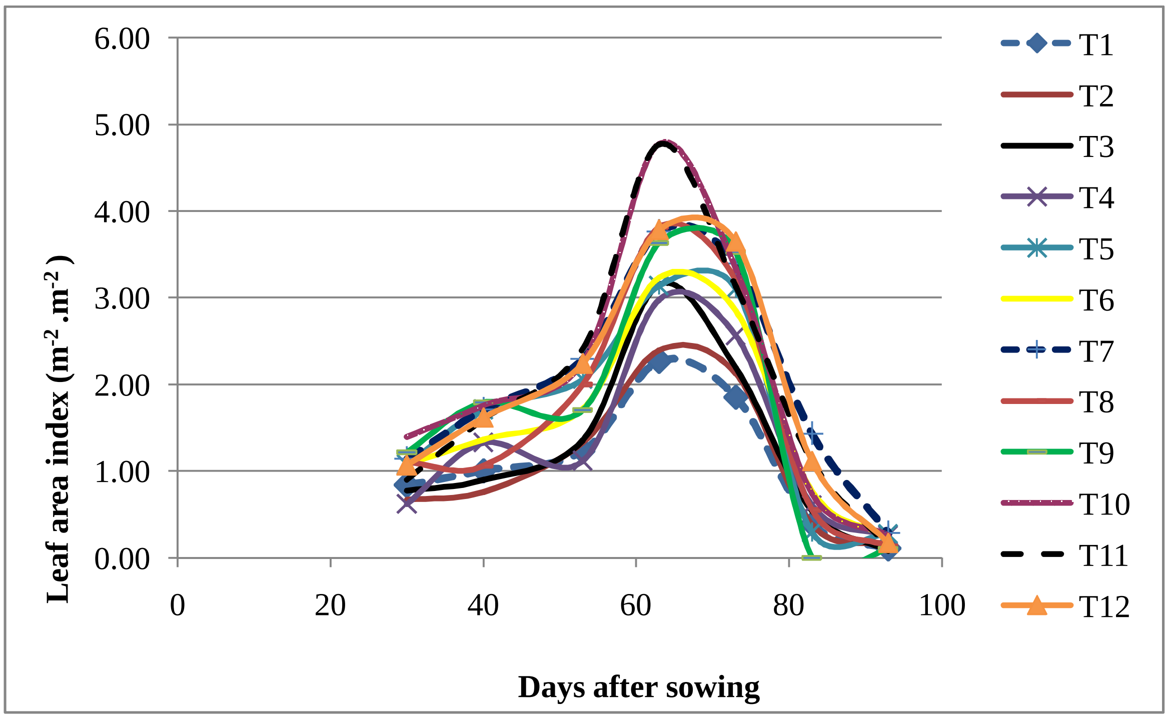


Figure 4. 1: Average Leaf Area Index (LAI) of *tef* trends during the growing period of 2012

Leaf area index showed a parabolic change over time. The Maximum values for LAI were recorded between 63 and 73 DAS for all treatments. The maximum and minimum LAI values of 4.78 and 2.27 m^2.m^{-2} were recorded for T_{11} and T_1, respectively. The end of the growing season was characterized by lower LAI values (Fig 4.1).This was because of the start of senescence.

Table 4. 4: ANOVA analysis of yield component of *tef*

Description	Crop parameters									
	LAI	NT	Lodging	PH	PL	AGB	GY	Straw	NFUE	IWUE
R^2 -square (%)	64.79	69.21	88.04	35.92	34.88	86.87	88.88	81.97	74.50	53.33
R-adj. (%)	43.99	51.03	80.97	-1.95	-3.61	79.11	82.32	71.32	59.43	25.79
Root Mean Square Error	0.73	1.15	13.27	11.44	4.62	1088.6	174.00	1106.90	5.45	0.37
Mean of Response	3.46	6.08	24.14	94.57	31.82	7863.56	1672.33	6191.23	10.00	0.41
F-ratio										
Water level	2.19^{ns}	1.08^{ns}	7.23**	0.465^{ns}	0.2309^{ns}	5.1**	11.82**	2.86^{ns}	0.4864^{ns}	3.63*
Block	1.30^{ns}	8.08^{ns}	0.36^{ns}	0.46^{ns}	0.3797^{ns}	4.65^{ns}	1.58^{ns}	5.2642^{ns}	0.4940^{ns}	1.33^{ns}
Fertilizer Level	12.72**	12.59**	62.61**	4.41*	3.8128*	59.07**	66.22**	39.466**	28.89**	3.88*
Water*Fertilizer	0.98^{ns}	0.79^{ns}	2.39^{ns}	0.20^{ns}	0.4508^{ns}	0.47^{ns}	0.82^{ns}	0.3296^{ns}	0.6739^{ns}	0.64^{ns}
Prob>F										
Water level	0.118	0.3771	0.0015	0.710	0.8739	0.0079	<0.0001	0.0601	0.6952	<0.0288
Block	0.292	0.0623	0.6987	0.637	0.6884	0.0506	0.2283	0.0535	0.6168	0.2857
Fertilizer Level	0.0002	0.0002	0.0001	0.024	0.0379	<0.0001	<0.0001	<0.0001	<0.0001	0.0361
Water*Fertilizer	0.4632	0.5879	0.0627	0.973	0.8366	0.8250	0.5642	0.9141	0.6719	0.6951
CV (%)	**21.09**	**18.91**	**54.97**	**12.10**	**14.52**	**13.84**	**10.40**	**17.88**	**54.50**	

NB: **,* and $^{\mathbf{ns}}$ indicate significant at the 0.01, 0.05 probability levels and not significant, respectively.

CV = Coefficient of variance, NT = number of tillers, LAI= Leaf area index at 73 days after sowing, PH = plant height, panicle length, AGB = aboveground biomass, GY = grain yield, NFUE = nitrogen fertilizer use efficiency, IWUE = Irrigation Water Use efficiency.

Table 4. 5: Main effect of treatments on selected crop parameters

Treatment	Crop parameters										
	LAI	***NT***	***Lodging (%)***	***CC (%) (60DAS)***	***PH (cm)***	***PL (cm)***	***AGB ($kg.ha^{-1}$)***	***GY ($kg.ha^{-1}$)***	***Straw ($kg.ha^{-1}$)***	***NFUE ($kg.kg^{-1}$)***	***IWUE ($kg.kg^{-1}$)***
1. Water levels											
• Full irrigation	3.89a	6.67a	38.33a	69.20a	96.30a	31.92a	8640.78a	1901.86a	6739a	11.21a	0.61a
• Four irrigation	3.48a	6.00a	27.22a	63.00ab	94.71a	31.32a	8387.00a	1758.93ab	6628a	9.73a	0.47ab
• Two irrigation	3.46a	5.89a	21.44ab	60.33bc	96.41a	32.82a	7593.11ab	1583.43bc	6010a	8.98a	0.43ab
• Rainfed	3.00a	5.78a	9.67b	53.67c	90.84a	31.21a	6833.33b	1445.08c	5388a	8.26a	-
2. Fertilizer level											
100	4.20a	7.00a	58.83a	77.57a	99.90a	34.77a	101741.00a	2041.01a	8133a	16.03a	28.08a
50	3.49a	6.50a	10.83b	62.58b	97.07ab	31.93ab	8061.08b	1744.51b	6317b	12.65a	25.69a
0	2.70b	4.75b	2.75b	44.50c	86.73b	29.16b	5355.58c	1231.46c	4124c		18.42b

Levels not connected by same letter are significantly different

LAI= Leaf area index at 73 days after sowing, NT= Number of tiller, PH = plant height, panicle length, PL= panicle length, AGB = aboveground biomass, GY = grain yield, NFUE = nitrogen fertilizer use efficiency, IWUE = Irrigation Water Use efficiency.

In addition there was significant difference among the treatments of fertilizers for LAI but not for treatments of water (Table 4.5).

4.1.4. Number of tillers per plant

The result showed that fertilizer and water interaction has no effect on number of tillers. Fertilizer application has significantly affected the tiller number because nitrogen fertilizer enhanced vegetative growth whereas irrigation application has no effect on tiller number because irrigation was applied after tillering stage (Table 4.4).

4.1.5. Lodging

Tef lodging was commonly observed in the treatments with relatively higher fertilizer levels. This was due to the high rate of vegetative growth in response to influenced by higher application of N. Similarly water application has significantly affected tef lodging (Fig 4.2).

Figure 4. 2: Lodging effect on *tef* morphology 2012

NB: left: two irrigation with 100% fertilizer and **right**: full irrigation with 100% fertilizer

There was a significant different in lodging among irrigation (that received two, four and nine irrigation after cessation of rain) and rainfed treatments. But there was no significant difference in lodging among the irrigation treatments of four and nine treatments. Similarly, fertilizer has significantly affected lodging. There was significant difference among the treatment that received high fertilizer NP_{100} (64 kg.ha^{-1} and 46 kg.ha^{-1} P) and the other two NP fertilizer (NP_0 and NP_{50}) treatments. However, there was no significant difference at $p<0.05$ in lodging between fertilizer treatments that received low fertilizer (NP_0) and moderate fertilizer of 32 kg.ha^{-1}N and 23 kg.ha^{-1} P (Table 4.5).

4.1.6. Canopy cover

The average highest (89.9%) and lowest (35%) CC was obtained from the optimal (T_{12}) and rainfed with zero fertilizer (T_1) treatments (Fig 4.3) respectively. The maximum canopy cover was recorded 60 DAS for all treatments and starts to decline after when the crop stars the senescence stage. The graph of canopy cover showed almost parabolic change over time for all treatments.

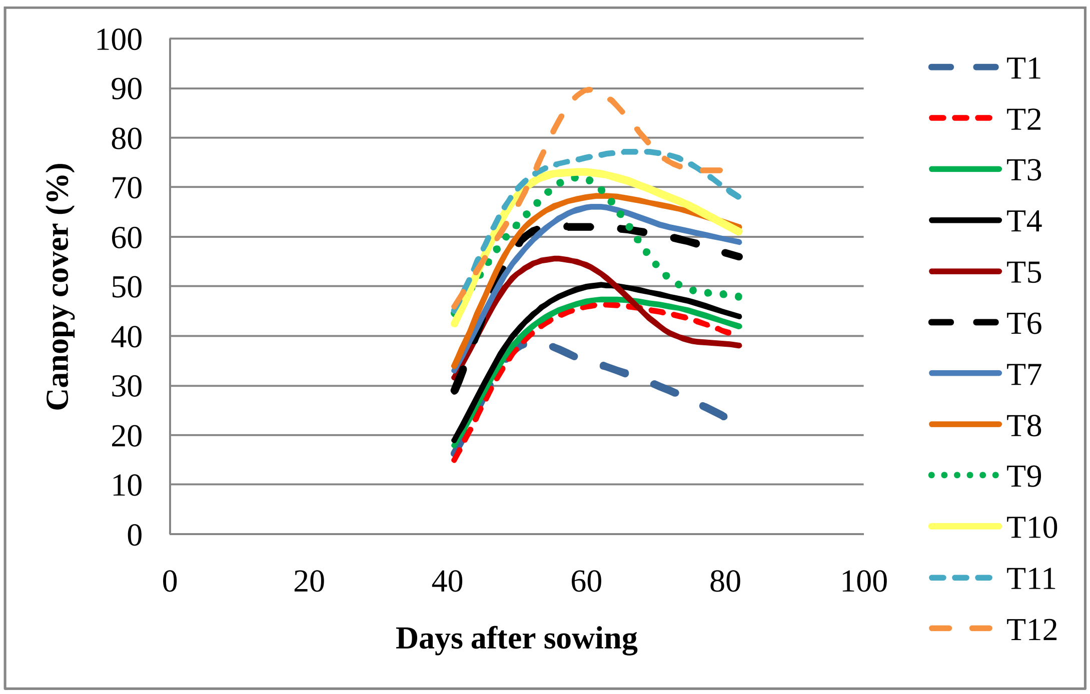


Figure 4. 3: Average observed green canopy cover of treatments

There was significant difference at $p<0.05$ in canopy cover among the three levels of NP treatments (Table 4.5). High, moderate and low canopy cover was observed for the treatments that received high (64 kg.ha^{-1}and 46 kg.ha^{-1} P), moderate (32 kg.ha^{-1}and 23 kg.ha^{-1}P) and low NP levels, respectively (Fig 4.3). This was due to N fertilizer enhances the vegetative growth of a crop.

4.1.7. Plant height and Panicle length

The maximum (103.23 cm) and minimum (84.53 cm) plant height at maturity were obtained from T_{12} and T_1, respectively (Table 4.6**).** Similarly the maximum and minimum panicle length values were measured to be 38.20 and 28.13 cm respectively for T_{12} and T_3 treatments. This was because the N fertilizer increases the vegetative growth and development of plant. Similar result was obtained from farmers' managed fields, where, the plant height of the same cultivar in La'elay Maichew was between 87.10 and 112.40 cm while the panicle length was between 29.1 and 44.30 cm. However, the plant height and panicle length for farmers' managed field in Enderta areas just close to the experimental site were between 59.00 and 66.80 cm and 12.00 and 20.40 cm, respectively. This variation was due to the agro-ecological difference, crop management, fertilizer application and soil type in the areas (Vertisol in La'elay Maichew and Cambisol in the study area). The result of the research agrees with the study carried at Debrezeit Research center by Kebebew, *et al. (*2011) found that *tef*'s (Quncho) plant height at experimental stations was about 102.20 cm.

Table 4. 6: Plant height and panicle length of *tef* at maturity stage

Treatment	Plant height	Panicle length
	cm	
T_1	83.53	30.13
T_2	87.80	28.53
T_3	84.53	28.13
T_4	88.97	29.40
T_5	93.77	30.87
T_6	96.67	31.73
T_7	98.53	32.03
T_8	96.70	32.50
T_9	95.23	32.63
T_{10}	104.77	38.20
T_{11}	96.40	32.77
T_{12}	103.23	33.87

There was no significant interaction among water and fertilizer treatments on plant height and panicle length (Table 4.4). The result of the research showed that application of supplementary irrigation didn't have any significant effect on panicle length and plant height this may be because irrigation was applied after the plant had reached maximum height (Table 4.5).

4.1.8. Final aboveground biomass of *tef*

The analysis of variance (ANOVA) for final aboveground biomass shown (Table 4.4) indicated that tef biomass showed significant difference ($p < 0.05$ and 0.01) due to fertilizer treatments. Similarly, the ANOVA analysis (Table 4.5) also showed that water and fertilizer levels have no any significant effect ($p<0.05$ and 0.01) on final aboveground biomass. This means both explanatory variables (water and fertilizer) have an additive effect on biomass of *tef*. The highest biomass was for high NP_{100} whereas the lowest was observed for low NP_0) fertilizer treatments. In agreement with this finding of Habtegebrial *et al*. (2007; Teffera and Ketema (2001) reported that biomass increased linearly with increase in N up to 90 N per hectare, respectively. However, there was no significant difference among the biomass that received full and four irrigations (Table 4.5). But there was significant difference for biomass between the treatments that received irrigation and that did not received irrigation (rainfed).The lowest final aboveground biomass (4375 $kg.ha^{-1}$) was obtained from treatments grown under rainfed conditions (Fig.4.4). Application of supplementary irrigation increased average final aboveground biomass by 23, 27 and 40% for treatments with two, four and full (nine) irrigations compared to rainfed treatments under the application NP_0 fertilizer level. In line with this statement application of NP fertilizers increased final aboveground biomass of tef by 54 and 114% (for rainfed);41 and 83% (for two irrigation);54 and73% (for four irrigation) and 49 and 70% (for full irrigation) with application of moderate and high NP fertilizer levels, respectively compared to low NP fertilizer levels (Fig 4.4 and Table 4.5). Generally the finding of this research agreed with the study carried at Debrezeit Research center by Kebebew *et al. (*2011) in that the biomass of *tef (*Quncho) on experimental and farmers' station was found to be 10110 and 8110 $kg.ha^{-1}$, respectively. The highest and lowest biomass was found to be 11.08 $t.ha^{-1}$ and 4.3375 for four irrigation treated with NP_{100} fertilizer and rainfed with zero fertilizer at the experimental site, respectively. This result agreed with the study carried at Debrezeit Research center by Kebebew, *et al. (*2011) in that the biomass of *tef* (Quncho) on experimental station and farm station was found to be 10.11 and 8.11 t.ha^{-1} respectively.

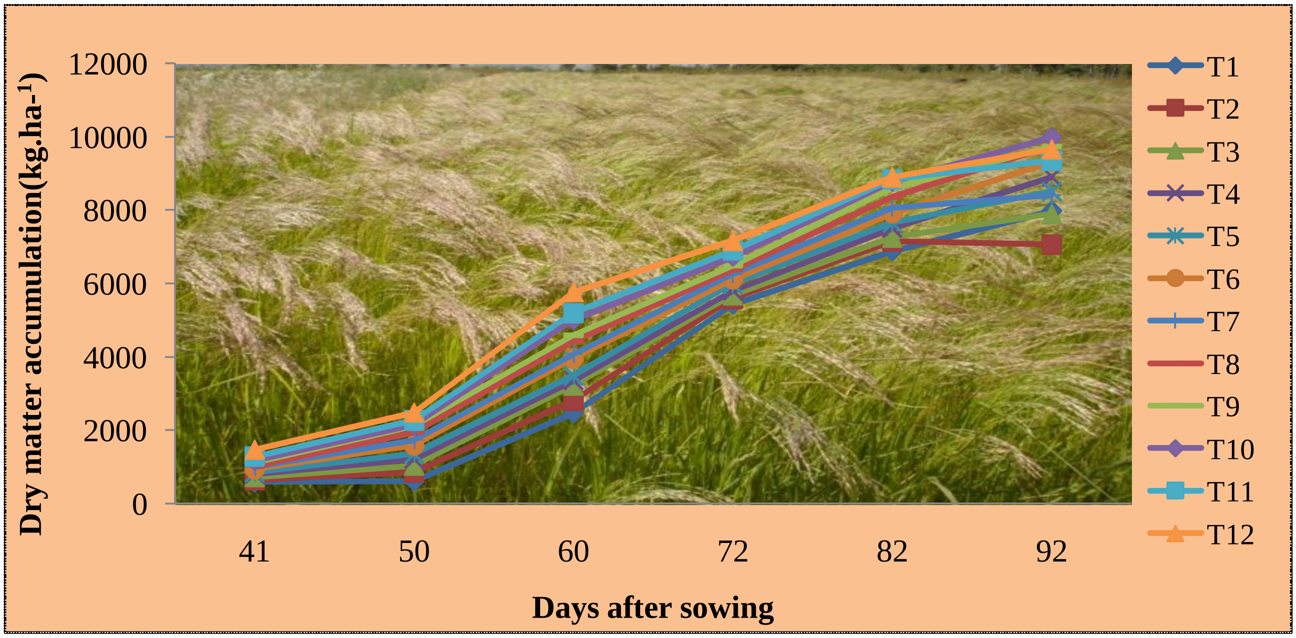


Figure 4. 4: Sequential aboveground biomass (kg.ha^{-1}) of *tef* during the growing period 2012.

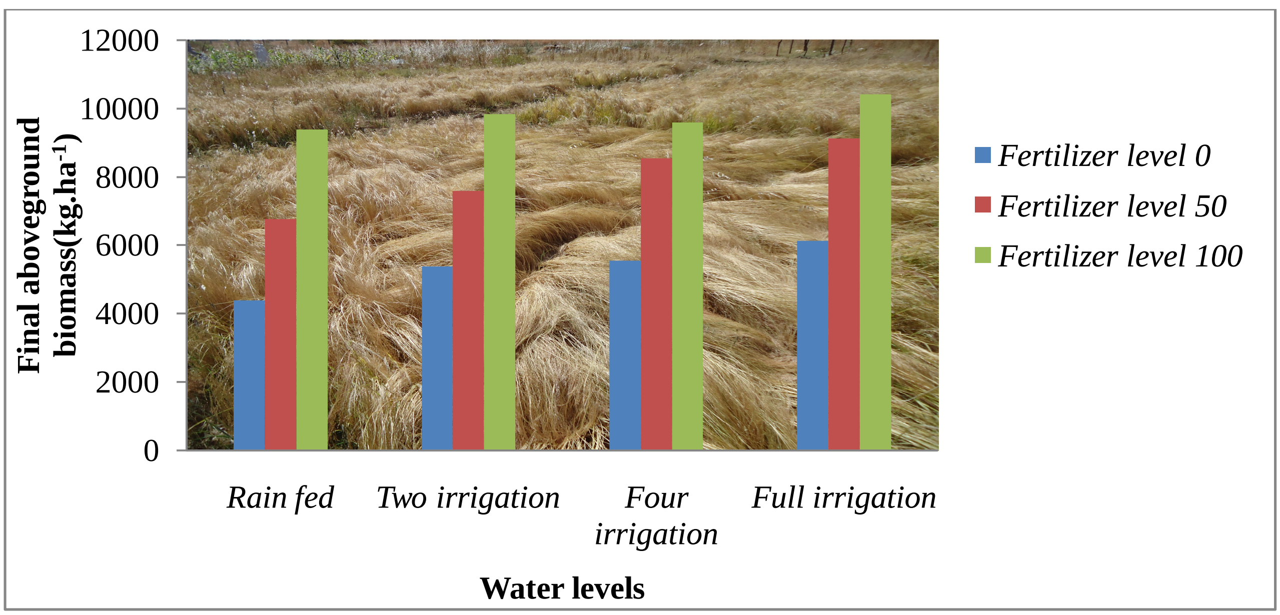


Figure 4. 5: Comparison treatments on final above ground biomass (kg.ha^{-1}) of tef

4.3.7. Final grain yield of *tef*

Normal probability plot of final grain yield showed that the probabilities of residuals (random errors) versus their values of the different treatments are normally distributed as shown in (Fig 4.6). The plot also gave straight line with no curvilinear or serious problems of variation among all values of the treatments. Hence as it is depicted from the graph (Fig. 4.6) no serious departure is observed from normality assumption is noticeable for the response (grain yield) data of the experiment and it is possible for analysis of the grain yield of the respective treatments.

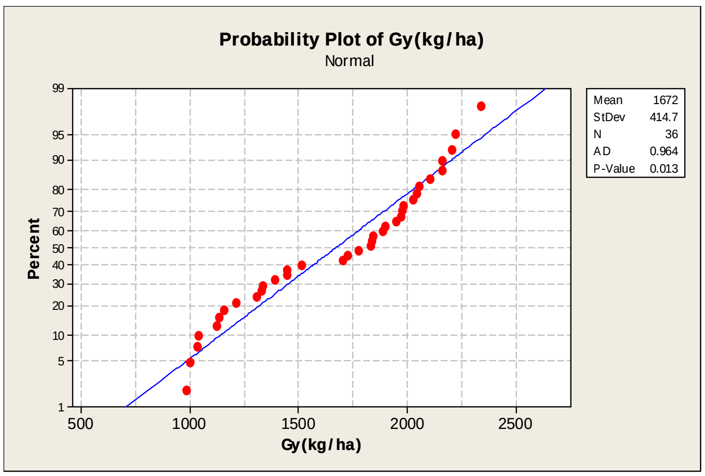


Figure 4. 6: Normal probability plot of all treatments for final grain yield (kg.ha^{-1}) of *tef*

Application of NP fertilizers and supplementary irrigation significantly ($p< 0.05$) influenced *tef* grain yield. The highest (2190.80 kg.ha^{-1}) and lowest (1008.13 kg.ha^{-1}) average grain yield were obtained from treatments that received high NP_{100} fertilizer with full (nine) irrigation and NP_0 kg.ha^{-1} with rainfed, respectively (Fig 4.7). These results are higher than the yield reported (1133 to1388 kg.ha^{-1}) by Haftamu *et al*, (2009) at Hatsebo, Aksum, Ethiopia. Application of full (optimal) irrigation increased the grain yield of *tef* by 15, 40 and 48 % compared to rainfed respectively for the high NP, low NP and moderate NP fertilizer levels, respectively whereas application of two irrigation after cessation of the rainfall increased the final grain yield of *tef* by 3, 18 and 30% compared to the rainfed respectively for the high NP, low NP and moderate NP fertilizer levels, respectively.

The results obtained by this study confirmed that *tef* is likely to give significantly higher grain yield when a nearly optimal water supply is provided (Araya, *et al.*, 2010a). In addition research results conducted by Araya *et al.* (2011) in Tigray also showed that more than 80% of yield reduction and more than 50% of crop failure in *tef* and barley can be avoided when supplementary irrigation is applied during the critical growth stages of the crops. Similarly, under high NP fertilizer condition the tef grain yield has increased by 3, 10 and 15% just by applying two, four and nine irrigation, respectively, compared to the rainfed (Table 4.7). Increase in application of nitrogen and phosphorus fertilizers caused significant increase ($p < 0.05$) and ($p<0.01$), (Tables 4.5) on grain yield in the study area. For example, application of moderate NP and high (64 and 46 kg.ha^{-1} NP) fertilizer levels significantly increased the final grain yield by 41 % and 117% compared to zero NP fertilizer levels (Table 4.7) and this research finding was in line with Habtegebrial *et al*. (2007) that grain yield increased linearly with increase in N up to 90 kg N per hectare, but grain yield showed a decreasing trend when the N fertilizer increased from 60 to 90 kg ha^{-1}. In line with this finding lower grain yield of *tef* 510 kg.ha^{-1} than the national average are reported by Rockstrom *et al*. (2009) from conventional tillage without fertilizer application. It is also common that many subsistent farmers in Ethiopia get such a low yield from tef when they grow it with low or without fertilizer application. Similarly, Habtegebrial *et al*. (2007) reported 370 kg.ha^{-1} yield of *tef* under zero nitrogen fertilizer application condition.

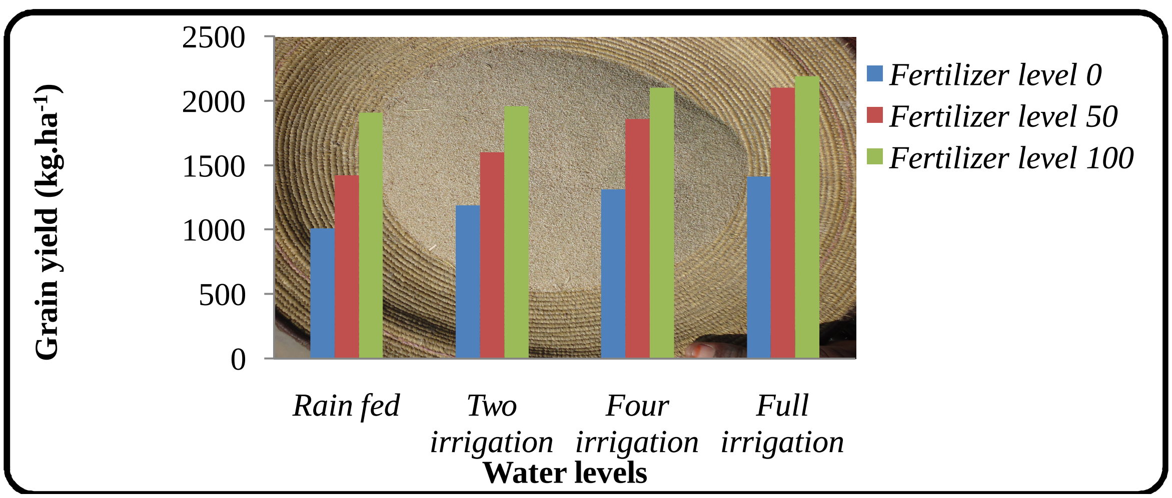


Figure 4. 7: Comparison of average grain yield (kg.ha^{-1}) of *tef* among treatments

Table 4. 7**:** Final grain **y**ield increment (%) for different treatment levels

Treatment code	Increased (%) Water level	Increased (%) Fertilizer level
T1		
T2	18.03	
T3	30.39	
T4	40.19	
T5		**40.94**
T6	30.87	
T7	30.87	
T8	47.89	
T9		
T10	3.05	
T11	10.31	
T12	14.93	**117.31**

4.3.8. Harvest index of *tef*

The average highest (0.25) and lowest (0.21) harvest index (HI) records were obtained for the four irrigation (T_3) and full irrigation (T_{12}) treatments, respectively (Fig.4.8).This was because harvest index was influenced by the accumulation of aboveground biomass. Similarly the harvest index (HI) of the famers' field at La'elay Maichew and Enderta woreda were 24 to 31; 19 to 31 and 21 to 24%, respectively. This was due to the final aboveground biomass obtained from farmers' field was low as compared to this experiment.

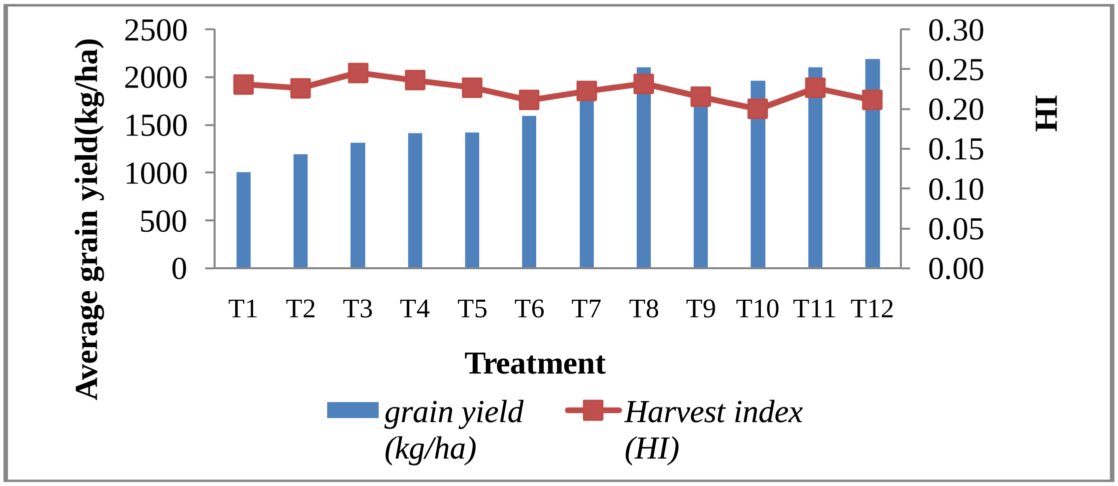


Figure 4. 8: Average final grain yield (kg.ha^{-1}) versus HI of *tef*

4.3.9. Straw Yield

Straw is the bi-product of tef which is very nutritious valuable for animal feed as shown in (Fig 4.9). Application of NP fertilizer levels significantly affect ($p<0.05$ and 0.01) the yield of straw (Table 4.4), whereas, application of supplementary did not show any significant difference (Table 4.5).The average highest (8226 kg.ha^{-1}) and lowest (3367 kg.ha^{-1}) straw yield of tef were obtained from high NP fertilizer combined with full irrigation and zero NP fertilizer combined with rainfed, respectively (Table 4.8).

Figure 4. 9: Cattle feeding *tef* by- product (*Photo at Aksum*, 2012)

Table 4. 8: Final average straw yield ($kg.ha^{-1}$) of tef

Treatment	Average yield ($kg.ha^{-1}$)
T1	3366.87
T2	4185.13
T3	4227.19
T4	4717.33
T5	5329.09
T6	5987.18
T7	6676.28
T8	7023.62
T9	7468.87
T10	7856.75
T11	7480.60
T12	8225.87

4.3.10. Nitrogen Fertilizer Use Efficiency (NFUE, $kg.kg^{-1}$)

The ANOVA analysis of yield component and main effect of treatments (Table 4.4 and Table 4.5), respectively, showed that the NFUE is significantly ($p<0.05$) affected by rate of NP fertilizers. Moderate NP fertilizer application has higher NUE than that of high NP fertilizer (Table 4.4 Appendix 22). However, nitrogen fertilizer use efficiency is not significantly affected by application of supplementary irrigation, though full (nine) irrigation with moderate fertilizer showed higher nitrogen fertilizer use efficiency (Table 4.5).This was due to the NFUE is highly correlated with application of nitrogen rather than supplementary irrigation.

4.3.11. Water Use efficiency (WUE)

Grain-WUE increased with an increase in water supply up to nine irrigations indicating that a nearly optimum water supply may improve the grain yield of *tef*. Biomass-WUE, however, attained a maximum and value in the two irrigation treatment (Table 4.9). The Green-WUE increased when water supply was improved. The values showed a minimum of 19% and a maximum of 35% for *tef* under two irrigation and full irrigation (well irrigated conditions), respectively (Table 4.9). These findings are much higher than those reported by Stroosnijder (2009) for sub-Sahara Africa (5–15%) and east Africa (20%) but lower than those reported by Araya *et al., (*2010a) for study area (25-50%) in 2008 and 2009. Similarly, Grain-WUE increased with increasing NP fertilizer level (Table 4.9). In line with this statement Raes *et al*. (2009a) out lined that lower N doses may lead to lower crop water productivity.

Under normal weather conditions, water shortage occurs in this semi-arid region at about the time crops achieve full ground cover. If the water supply is well distributed and adequate (from irrigation or rainfall), it is likely that crop transpiration and Green-WUE of the *tef* crops could be higher compared with *tef* crops that have encountered a shortage of water in the mid stage of its growth(Fig 4.10 and Table 4.9).

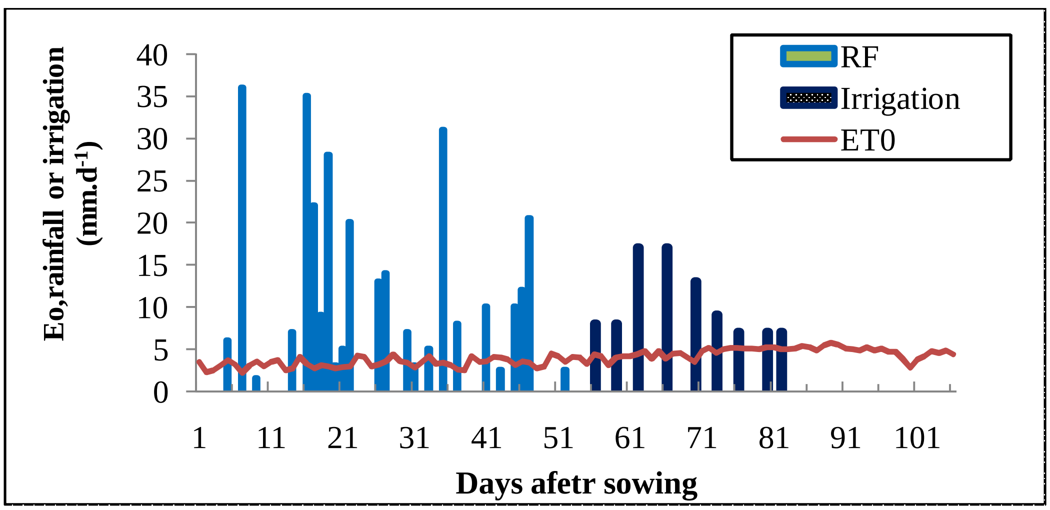


Fig. 4. 10: Daily ETo, RF and applied irrigation during the cropping season 2012.

Table 4. 9: HI, Grain-WUE, BM-WUE and Green-WUE under various irrigation treatments

Treatment code	T ($m^3.ha^{-1}$)	Rain +Irr. ($m^3.ha^{-1}$)	HI	Grain-WUE ($kg.m^{-3}$)	BM-WUE ($kg.m^{-3}$)	Green-WUE ($kg.m^{-3}$)
T2	664	3450	0.23	1.79	8.09	19
T3	736	3670	0.25	1.79	7.53	20
T4	979	4040	0.24	1.44	6.26	24
T6	861	3450	0.21	1.85	8.81	25
T7	1000	3670	0.22	1.86	8.54	27
T8	1208	4040	0.23	1.74	7.55	30
T10	972	3450	0.20	2.02	10.1	28
T11	1142	3670	0.23	1.84	8.39	31
T12	1405	4040	0.21	1.56	7.41	35

NB: transpiration (T) is determined by AquaCrop model. R, rainfall; Gy, grain yield (measured); HI, harvest index; BM, final aboveground biomass (measured); WUE, water use efficiency.

4.3.12. Irrigation Water Use Efficiency (IWUE)

From Table 4.4 and Table 4.5, it is clearly depicted that there is significant mean main effect of water level and on IWUE at ($p<0.05$). IWUE of tef decreased with increasing irrigation application (nine irrigation< 4 irrigation < 2 irrigation).This was due to the increase in yield compared to the increase in the amount of irrigation was not proportionally linear (Fig. 4.7**)**. Application of fertilizer showed significant difference in IWUE compared to non-fertilized treatments. But there was no significant difference between the treatments that received moderate and high NP fertilizer (Table 4.4).

4.3.13. Correlation of yield with yield related parameters

Yield is a complex component of a crop, which is governed by many yield parameters interacting with the environment and depends on a number of related crop parameters. Knowledge of interrelationship among various traits affecting yield directly as well as indirectly is essential for selecting best yielding genotypes. The results of the study indicated that there was significant correlation between biomass (r = 0.34) and grain yield (Table 4.10). Plant height showed high correlation coefficient with grain yield (r = 0.87). Plant height had significant but negative association with harvest index (r = -0.82).This could be due to increase in biomass. Plant height (r= 0.87) and number of tillers per plant (r= 0.84) exhibited positive correlation with grain yield (Table 4.10).

Nitrogen fertilizer use efficiency (r = 0.69) and canopy cover (r = 0.97) had positive and high correlation with grain yield. The significance correlation suggests that canopy cover could be used as indirect selection traits for grain yield. Biomass yield (r = 0.45) correlated with nitrogen use efficiency. The high positive correlation between different crop parameters showed the possibility of simultaneous improvement of this variety. Negative correlations between two parameters show that an increase or decrease in one parameter has a negative effect on another crop parameter. Accordingly, it was observed that the grain yield and harvest index was correlated with r =-0.52, this was because the harvest index of the different treatments was different due to the different in biomass difference.

The result from field assessment from farmers' field showed that grain yield and final aboveground biomass had high correlation (r = 0.88) for La'elay Maichew and (r = 0.81) for Enderta woreda (Appendix 29 and 30).

Table 4. 10: Correlation of yield and yield components of *tef* in experimental site

	LAI	PH	PL	AGB	GY	NUE	IWUE	Straw	NT	60%CC	HI
Lodging	0.74**	0.76**	0.76**	-0.03	0.82**	0.27	0.28	0.84**	0.69*	0.82**	-0.55
LAI		0.78**	0.80**	0.59*	0.85**	0.54	0.51	0.85**	0.72**	0.86**	-0.46
PH			0.89**	0.28	0.87**	0.73**	0.46	0.93**	0.89**	0.91**	-0.82**
PL				0.38	0.74**	0.54	0.44	0.83**	0.81**	0.77**	-0.84**
AGB					0.34	0.45	0.37	0.34	0.38	0.34	-0.15
GY						0.69*	0.30	0.97**	0.84**	0.97**	-0.52
NUE							0.22	0.68*	0.69*	0.67*	-0.52
IWUE								0.32	0.15	0.35	-0.45
Straw									0.90**	0.99**	-0.67*
NT										0.86**	-0.70*
60 CC (%)											-0.62*
HI											

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

LAI= Leaf area index (73DAS), PH = plant height, PL=Panicle length, AGB=above ground biomass=GY= Grain yield, NUE= Nitrogen use efficiency, IWUE= Irrigation water use efficiency, NT= number of tillers and CC= canopy cover (%) 60DAS.

4.4. Fertilizer Application rate used by farmers at field level

As it is clearly depicted in Table 4.11 in all the studied area it was investigated that in appropriate and lower than the regional recommendation were applied. Hence 57% and 60% of the respondents in La'elay Maichew used 100 kg.ha^{-1} urea and DAP, respectively, whereas only 26.7 and 20% of the respondents in Enderta woreda applied for the respective fertilizers. The lower application of fertilizer at farmers' managed field (Enderta woreda) affected the biomass and grain yield and it was lower than the experimental site and the national level. This could be due to the reason that under rainfed condition the fertilizer rate has to be lower than under full irrigation. The recommended fertilizer rate can be applied when sufficient water is available. However in La'elay Maichew farmers, in 2012, fortunately obtained boost harvest because they have received ample rainfall which could be equivalent to full irrigation.

Table 4. 11**:** Rate of fertilizer used by the respondents during the growing season 2012.

La'elay Maichew woreda						**Enderta woreda**					
Urea			DAP			Urea			DAP		
Rate (kg.ha)	Fr	%	Rate (kg/ha)	Fr	%	Rate (kg.ha)	Fr	%	Rate (kg.ha)	Fr	%
0	1	3.3	0	1	3.3	0	5	33.3	0	3	20
50	3	10	50	4	13.3	50	6	40	32	1	6.7
67	1	3.3	67	1	3.3	100	4	26.7	50	8	53.3
80	1	3.3	70	1	3.3	**Total**	**15**	**100**	100	3	20
100	17	57	80	1	3.3				**Total**	**15**	**100**
125	1	3.3	100	18	60						
150	2	6.7	150	1	3.3						
200	3	10	200	3	10						
300	1	3.3	**Total**	**30**	**100**						
Total	**30**	**100**									

NB: *Fr, frequency (number of respondents) and (%), percentage of the respondents*

4.5. Model Calibration and validation

The measured model data inputs were entered into the model and reasonably accurate simulation (outputs) were obtained. The normalized crop water productivity (WP*) was calculated based on the available measured data and was found to be 30g.m^{-2}. Tef is C_4 plant hence the obtained WP value is in agreement with Raes *et al.* (2009b). The simulated canopy cover (Fig. 4.11) grain yield, and sequential aboveground biomass, for the optimal data set agreed well with the observed.

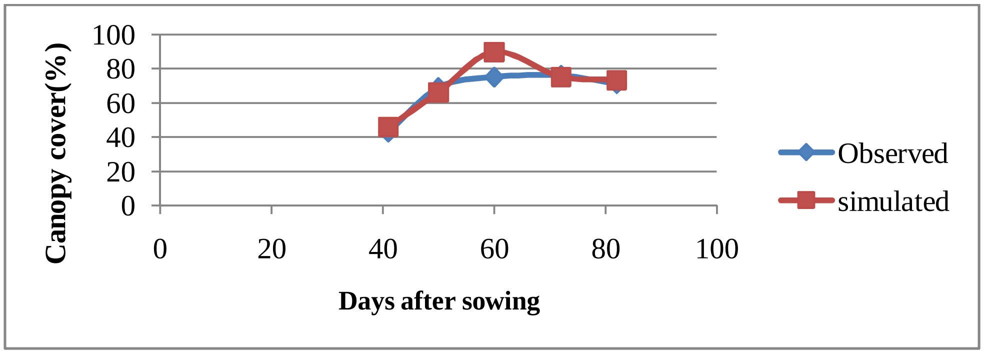
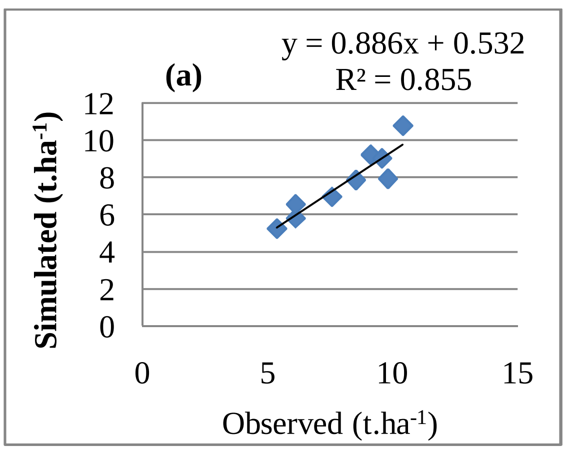


Fig. 4. 11**:** Simulated and observed canopy cover for the optimal data set

Similarly, Figure 4.12 shows the observed and simulated final aboveground biomass and grain yield simulated by the model under different irrigation applications at experimental site. There was a good match between the simulated and observed values.



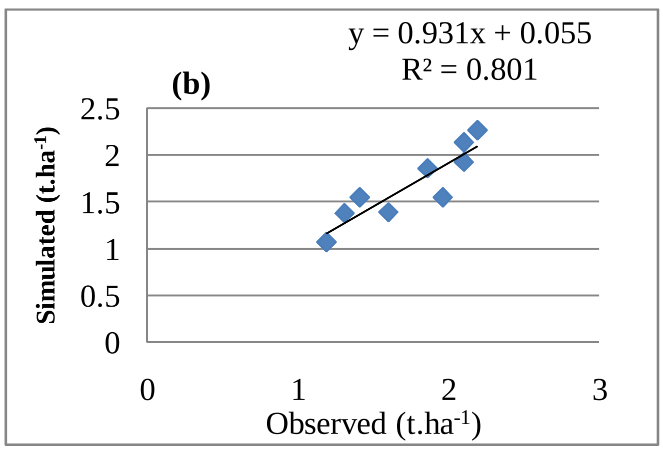


Figure 4. 12**:** Simulated Vs observed values

(a) Final aboveground biomass and (b) final grain yield.

4.6. Simulation with FAO AquaCrop model for predicting tef yield

4.6.1. Biomass and grain yield

The simulated and observed value of biomass and grain yield of *tef* is depicted in Table 4.12.

Table 4. 12**:** Simulated and observed value of biomass and grain yield of *tef*

Treatment code	Biomass (t.ha-1)		D (%)	Grain yield(t.ha^{-1})		D %)	Remark
	Observed	Simulated		Observed	Simulated		
T2	5.38	5.24	-2.68	1.19	1.07	-10.50	
T3	6.13	5.80	-5.42	1.31	1.38	5.65	
T4	6.13	6.54	6.64	1.41	1.55	10.21	
T6	7.58	6.94	-8.40	1.6	1.39	-13.44	
T7	8.54	7.84	-7.38	1.860	1.86	0.00	
T8	9.13	9.20	0.77	2.1	2.14	2.10	
T10	9.82	7.91	-19.45	1.96	1.55	-20.92	
T11	9.58	9.01	-5.95	2.10	1.93	-8.33	
T12	10.42	10.76	3.26	2.19	2.27	3.65	**Calibration data set**
ME			**0.81**		**0.74**		
RMSE(t.ha^{-1})			**0.77**		**0.18**		

NB: *D (%) =Deviation* (%)

From Table 4.12, the output of the simulation model showed deviation ranges from -19.45 to 6.64% and -20.92 to 10.21% for biomass and grain yield respectively. In Araya *et al.* (2010c) to simulate the growth of barley, the simulated grain yield deviated from the observed data with a range of -13% to 15.1% and the range for biomass was -4.3% to14.6%. Also in another investigation of Araya *et al*. (2010a) simulated the *tef* yield response to water with FAO's AquaCrop model in the Mekelle and Ilala areas in northern Ethiopia. They showed an agreement between the simulated and observed aboveground biomass and grain yield. The same finding was of Saadati *et al*.(2011) in calibration and evaluation of AquaCrop model in rice growth simulation under different irrigation managements confirmed that deviation (%) of simulated biomass were gained between -26% and 9.4%.,whereas the deviation of the simulated yield from the observed was between -19% and 7.8%. The results of this research showed that AquaCrop model has abled to simulate the growth of *tef* .These results also confirmed that the model has simulated better for the grain than biomass. The values of RMSE, ME ranged from 0.77 to 0.18 for yield and 0.81 to 0.74 for biomass (Table 4.12).These findings agreed with the research conducted by Araya *et al*. (2010a) on simulating biomass and yield of *tef*. Araya *et al*. (2010a) obtained ME values for tef biomass and yield in the range of 0.82 to 1 and 0.64 to 1, respectively. Whereas the RMSE values for biomass and grain yield were between 0.2 and 0.92 t ha^{-1} and 0.05 and 0.21 t .ha^{-1}, respectively. Similar research was investigated by Araya *et al*. (2010c) study on simulating biomass and yield of barley, the ME values for biomass and yield simulations were obtained between 0.53 and 1 and 0.5 and 0.95 and the RMSE values were obtained between 0.36 to 0.9 t. ha^{-1} and 0.07 to 0.27 t.ha^{-1}, respectively on the same area. In line with this statement Saadati *et al*., 2011 found that ME and RMSE of 0.94 to 0.27; 1.50 to 1 and 0.98 to 0.5; 0.09 to 0.7 for biomass and yield of rice in 2000 and 2001 respectively. Similar results of were obtained in Hsiao *et al.* (2009) to simulate biomass and yield of corn using AquaCrop model, the RMSE values for yield simulation was obtained between 0.65 to 1.33 t. ha^{-1} and in Garcia *et al.*, 2009 in Deficit Irrigation Optimization of Cotton with AquaCrop were obtained with 1.11 to 1.98 t.ha^{-1} for yield and biomass and RMSE of 0.72 to 1.01t.ha^{-1} respectively. The results showed a slight deviation in ME and RMSE from that of the study carried by Araya *et al.*, 2010a because there was difference in tef cultivar characteristics.

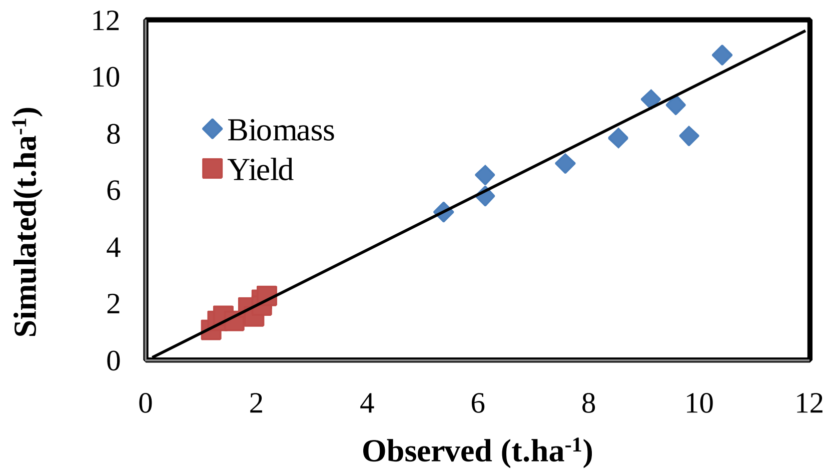


Figure 4. 13: Simulated and observed value of biomass and grain yield of *tef*

Figure 4.13.showed the simulated and observed of biomass (diamond filled) and grain yield (filled squared) which shows (1:1 line) and R^2 = 0.86 and 0.80 for biomass and yield respectively, during growing season for the different treatments. As shown, the variation of values during growing season could be simulated by AquaCrop. Therefore; the AquaCrop model has a good simulation for *tef* biomass and grain yield.

4.6.2. Simulation of Canopy cover (%)

The canopy cover is a crucial feature of AquaCrop. Through its expansion, aging, conductance, and senescence, determines the amount of water transpired, which in turn determines the amount of biomass produced. AquaCrop introduces significant simplification in the simulation, consolidating leaf expansive growth, angle, and distribution to an overall growth function and allowing the user to enter actual values of CC, even that estimated by eye Steduto *et al.* (2009). In addition, there is an advantage that CC may be easily obtained from remote sensing sources either to check the simulated CC or as input for AquaCrop. As shown in Figure 4.11, the variation of canopy cover development during growing season could be estimated from a photograph taken at different growth stage of the crop using software (SamplePoint1.55). The observed canopy cover was compared with simulated canopy cover. The values of RMSE, ME, for canopy cover are presented in Table 4.13. The result showed ME for canopy cover was between 0.94 and 0. 98 while the RMSE values were between 1.72 and 2.67%. Hence, the model has simulated the canopy cover quite accurately during the growing period (Table 4.13 and Fig 4.14). Studies carried out by Hsiao *et al.* (2009) on simulating growth of maize with AquaCrop model, the RMSE for canopy cover simulations was between 5.06 and 34.53%, which is lower than this study. Similarly, Araya *et al.,* 2010a found no significant difference between the simulated and observed canopy cover for the irrigated and rainfed treatments in the 2008.

Table 4. 13**:** Observed and simulated value of *tef* canopy cover (%)

Treatment code	**DAS**									
	41		**50**		**60**		**72**		**82**	
	Ob	Si	Ob	Si	Ob	Si	Ob	Si	Ob	Si
T2	15.00	17	37.50	38	46.00	45	44.50	45	40.00	42
T3	18.00	17	39.00	38	47.00	45	46.00	45	42.00	43
T4	19.00	17	41.00	38	50.00	46	48.50	47	44.00	43
T6	29.00	31	58.33	57	62.00	63	60.00	63	56.00	53
T7	33.00	31	55.70	57	66.00	63	62.00	63	59.00	60
T8	34.00	31	60.00	57	69.00	64	66.00	65	62.00	60
T10	42.50	43	68.23	69	75.03	74	68.00	74	61.00	58
T11	45.00	43	69.50	69	79.00	74	76.57	74	68.00	71
ME		**0.97**		**0.98**		**0.95**		**0.94**		**0.95**
RMSE (%)		**1.94**		**1.72**		**2.55**		**2.67**		**2.18**

NB: Ob= observed, and Si=simulated value, ME = model efficiency, RMSE=Root means square error.

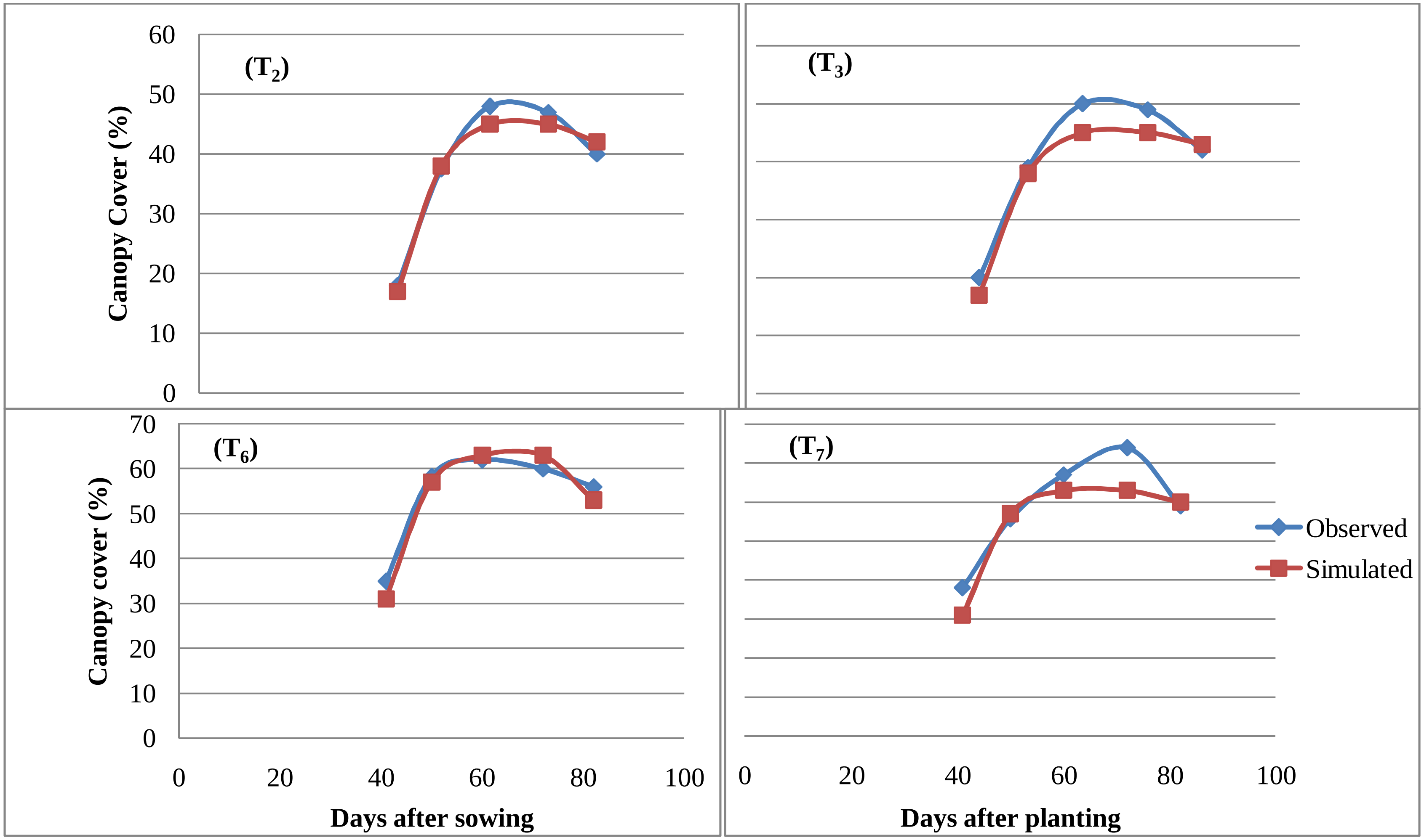


Figure 4. 14: The simulated and observed CC values of *tef* for selected treatments

CHAPTER V: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Based on the research result the following can be concluded

- Increasing level of NP fertilizer has increased the grain yield for both rainfed and irrigated treatments compared to non fertilized treatments. Similarly, applying fertilizers to low organic content of poor soils can increase the yield of *tef* by double compared to the control.
- For areas where rainfall is the only means of mitigating drought stress, moderate NP levels of fertilizer (32 N $kg.ha^{-1}$ and 23 P $kg.ha^{-1}$) could improve the grain yield significantly.
- The study revealed that applying supplementary irrigation after cessation of rain could mitigate drought stress and stabilize yield.
- The Grain-WUE of *tef* was improved when supplied with 2 irrigation compared to 4 and full irrigations after start of flowering. Similarly two irrigation has resulted in better Biomass-WUE as compared to other treatments. Assuming that water is scarce, both grain and biomass gave higher yield with two irrigations after start of flowering, though more biomass would have been gained if more irrigation had been applied to a larger area.
- There was close agreement between the simulated and observed canopy cover under different irrigation conditions. Similarly, the simulated aboveground biomass and grain yield was also in close agreement with the observed. The statistical evaluations for biomass and grain yield also confirm the model's validity. These findings confirm that the AquaCrop model can be considered as a valid model to simulate the yield and biomass of tef. From the result, we conclude that AquaCrop can be used to evaluate water use efficiency, as well as to assess yield from scenarios for alternative water management strategies in tef.
- AquaCrop model represents an effort to incorporate current knowledge of crop physiological responses into a tool that can predict the attainable yield of a crop based on the water supply available. Therefore, this model can be used as a decision support tool in increasing water productivity for tef by various users and it can be used to evaluate water use efficiency, as

well as to assess yield from different fertilizer scenarios for alternative water management strategies in tef. Overall, it is particularly suited to develop agricultural water management strategies for a variety of objectives and applications.

5.2. Recommendations

- For farmers which are growing tef under rainfed condition, extension agents shall advice farmers to apply fertilizer (32 $kg.ha^{-1}$ N and 23 $kg.ha^{-1}$) half of the currently recommended amount. In other words, for area having a rainfall amount 311 to 404 mm (for those without irrigation) moderate fertilizer level (32 N and 23 P kg.ha $^{-}$1 is recommend while for those area that have irrigation possibilities 64 k ha^{-1} N and 46 kg ha^{-1} P is recommended.
- AquaCrop model can be recommended to simulate and predict tef (Quncho) variety under different water levels and it can be used for irrigation practitioners. But the applicability of key calibration parameters must be retested and refined under different agronomic management, climate and soil conditions.

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APPENDICES

Appendix 1**:** Mean monthly climatic data of the study area (1992-2012)

Month	Tmax (°C)	Tmin (°C)	RF (mm)	Pe (mm)	ETO (mm/day)	RF (mm) in 2012
January	26.50	8.50	2.37	0.00	3.06	0
February	27.70	10.40	3.57	0.00	3.58	0
March	28.20	12.60	17.53	4.50	3.82	6.2
April	28.80	14.70	43.24	0.00	4.23	35.7
May	30.00	14.70	17.81	2.10	4.23	29.2
June	29.50	14.70	30.21	43.20	3.66	45.9
July	25.30	14.00	171.17	43.20	3.37	177.7
August	25.30	13.40	223.60	144.00	3.21	210
September	27.60	11.70	41.45	24.50	3.57	57.5
October	26.30	10.50	3.51	0.00	3.53	0
November	25.40	9.70	4.56	0.00	3.14	0
December	25.40	8.40	0.31	0.00	2.89	0
Total						**562.2**

ANOVA and other results for the experimental site

Appendix 2**:** Irrigation amount and scheduling for *tef* in the 2012**.**

S/n	Date	mm	treatment	Remark
1	16/09/12	8	For full only (before scheduling)	*Started at 56 DAS*
2	19/09/12	8	For full only (before scheduling)	
3	22/09/12	17	for full, 2 and four irrigations	*Started at 62 DAS*
4	26/09/12	17	for full, 2 and four irrigations	
5	30/09/12	13	for full and four irrigations	
6	03/10/12	9	for full and four times irrigation	
7	06/10/12	7	for full only	
8	10/10/12	7	For full only	
9	12/10/12	7	For full only	
	Total	**93**		

Appendix 3: ANOVA of treatments for the LAI ($m^2 . m^{-2}$) of tef 73 DAS

Source of variation	DF	SS	MS	F Ratio	Prob > F
Water level	3	3.52	1.17	2.19	0.118
Block	2	1.40	0.70	1.3	0.292
Fertilizer Level	2	13.63	6.82	12.72	0.0002
Water level*Fertilizer Level	6	3.14	0.52	0.98	0.4632
Error	22	11.78	0.54		
Total	**35**	**33.47**			

CV=21.09%, R^2 =64.79 %, R^2adj=43.99 %, RMSE=0.73, Mean of Response=3.46

Appendix 4: Interaction effect of treatments on LAI of *tef*

Level			Mean
Two irrigation,100	A		4.77
Four Irrigation,100	A		4.77
Full irrigation,50	A	B	3.81
Four Irrigation,50	A	B	3.76
Full irrigation,100	A	B	3.65
Rainfed,100	A	B	3.63
Two irrigation,50	A	B	3.23
Four Irrigation,0	A	B	3.15
Rainfed,50	A	B	3.13
Full irrigation,0	A	B	2.98
Two irrigation,0		B	2.39
Rainfed,0		B	2.27

Levels not connected by same letter are significantly different

Appendix 5: ANOVA of the number of tillers per plant.

Source of variation	DF	SS	MS	F Ratio	Prob > F
Water level	3	4.31	1.44	1.08	0.3771
Block	2	21.50	10.75	8.08	0.0023
Fertilizer Level	2	33.50	16.75	12.59	0.0002
Water level*Fertilizer Level	6	6.28	1.05	0.79	0.5879
Error	22	29.17	1.33		
Total	**35**	**94.76**			

CV=18.91%, R^2 =69.21 %, R^2adj=51.03 %, RMSE=1.15, Mean of Response=6.08

Appendix 6: Mean interaction effect of treatments on number of tillers (NT) per plant

Treatment			Mean
Full irrigation,100	A		7.33
Four Irrigation,50	A	B	7.00
Full irrigation,50	A	B	7.00
Rainfed,100	A	B	7.00
Two irrigation,100	A	B	7.00
Four Irrigation,100	A	B	6.67
Rainfed,50	A	B	6.33
Full irrigation,0	A	B	5.67
Two irrigation,50	A	B	5.67
Two irrigation,0	A	B	5.00
Rainfed,0	A	B	4.67
Four Irrigation,0		B	3.67

Levels not connected by same letter are significantly different

Appendix 7: ANOVA of lodging (%) of *tef* during maturity

Source of variation	DF	SS	MS	F ratio	Prob > F
Water level	3	3820.97	1273.66	7.23	0.0015
Block	2	128.39	64.20	0.36	0.6987
Fertilizer Level	2	22058.72	11029.36	62.61	<.0001
Water level*Fertilizer Level	6	2524.61	420.77	2.39	0.0627
Error	22	3875.61	176.16		
Total	**35**	**32408.3**			

R^2 =88.04 %, R^2adj=80.97 %, RMSE=13.27, Mean of Response=24.14

Appendix 8**:** Mean interaction effect of treatments on lodging of *tef*

Water, fertilizer(%) level				Mean
Full irrigation,100	A			85.33
Two irrigation,100	A	B		62.67
Four Irrigation,100	A	B		58.33
Rainfed,100		B	C	29.00
Full irrigation,50		B	C	25.00
Four irrigation,50			C	18.33
Four irrigation,0			C	5.00
Full irrigation,0			C	4.33
Two irrigation,0			C	1.67
Rainfed,0			C	0.00
Rainfed,50			C	0.00
Two irrigation,50			C	-0.00

Levels not connected by same letter are significantly different

Appendix 9: ANOVA for canopy cover (%) of *tef* 60 DAS

Source	**DF**	**SS**	**MS**	**F Ratio**	**Prob > F**
Water level	3	118.27	39.42	11.40	0.0001
Block	2	55.17	27.59	0.365	0.6983
Fertilizer Level	2	6579.65	3289.83	100.62	<0.0001
Water level*Fertilizer Level	6	205.74	34.29	1.05	0.4218
Error	22	652.17	29.64		
Total	**35**	**7611.00**			

CV=9.29%, R^2 =91.68 %, R^2adj=86.76 %, RMSE=5.72 Mean of Response=61.55

Appendix 10**:** Interaction effect of treatments on measured canopy cover (%) of *tef 60 DAS*

Level							Mean
Full irrigation,100	A						89.60
Four Irrigation,100	A	B					76.00
Two irrigation,100	A	B					73.00
Rainfed,100	A	B					71.67
Full irrigation,50	A	B	C				68.00
Four Irrigation,50	A	B	C	D			66.00
Two irrigation,50		B	C	D	E		62.00
Rainfed,50			C	D	E		54.33
Full irrigation,0				D	E	F	50.00
Four Irrigation,0					E	F	47.00
Two irrigation,0					E	F	46.00
Rainfed,0						F	35.00

Levels not connected by same letter are significantly different

Appendix 11: ANOVA for canopy cover (%) of *tef* 72 DAS

Source	DF	SS	MS	F Ratio	Prob > F
Water level	3	3040.77	1013.59	72.068	<.0001
Block	2	20.48	10.24	0.728	0.4941
Fertilizer Level	2	4253.33	2126.67	151.198	<.0001
Water level*Fertilizer Level	6	94.97	15.83	1.125	0.3802
Error	22	309.44	14.06		
Total	**35**	**7718.99**			

CV=6.70%, R^2 =95.99 %, R^2adj=93.62 %, RMSE=3.75, Mean of Response=56

Appendix 12: Interaction effect of treatments on canopy cover (%) of *tef 72 DAS*

Level						**Mean**
Four Irrigation,100	A					77.00
Full irrigation,100	A					75.13
Two irrigation,100	A	B				70.00
Full irrigation,50	A	B				67.67
Four Irrigation,50		B	C			62.00
Two irrigation,50		B	C			60.00
Rainfed,100			C	D		51.67
Full irrigation,0				D		48.00
Four Irrigation,0				D		46.33
Two irrigation,0				D		44.53
Rainfed,50				D		40.67
Rainfed,0					E	29.00

Levels not connected by same letter are significantly different

Appendix 13: ANOVA of plant height (cm) at maturity stage

Source of variation	DF	SS	MS	F Ratio	Prob > F
Water level	3	182.54	60.85	0.46	0.710
Block	2	120.42	60.21	0.46	0.637
Fertilizer Level	2	1155.30	577.65	4.41	0.024
Water level*Fertilizer Level	6	156.25	26.04	0.20	0.973
Error(Residual)	22	2880.73	130.942		
Total	**35**	**4495.24**			

R^2 =35.92%, R^2adj=-1.95%, RMSE=11.44, Mean of Response=94.57, CV=12.09%[♣6],*,SS=Sum of Squares, MS= Mean of Squares.*

Appendix 14: Interaction effect of treatments on plant height (cm) of *tef*

Treatment		Mean
Two irrigation,100	A	104.77
Full irrigation,100	A	103.23
Four Irrigation,50	A	101.13
Full irrigation,50	A	96.70
Two irrigation,50	A	96.67
Four irrigation,100	A	96.40
Rainfed,100	A	95.23
Rainfed,50	A	93.77
Full irrigation,0	A	88.97
Two irrigation,0	A	87.80
Four Irrigation,0	A	86.60
Rainfed,0	A	83.53

[♣]*CV= quotient of RMSE to Mean of response*

Appendix 15**:** ANOVA of panicle length (cm) of *tef* at maturity

Source of variation	DF	SS	MS	F Ratio	Prob > F
Water level	3	14.801	4.93	0.2309	0.8739
Block	2	16.231	8.12	0.3797	0.6884
Fertilizer Level	2	162.971	81.49	3.8128	0.0379
Interaction effect	6	57.804	9.63	0.4508	0.8366
Error	22	470.808	21.40		
Total	**35**	**722.615**			

R^2 =34.88%, R^2adj=-3.61%, RMSE=4.62, Mean of Response=31.82, CV=14.51%

Appendix 16**:** Interaction effect of treatments on panicle length (cm) of *tef*

Level		Mean
Two irrigation,100%	A	38.20
Full irrigation,100%	A	33.87
Four Irrigation,100%	A	32.77
Rainfed, 100%	A	32.63
Four Irrigation,50%	A	32.60
Full irrigation, 50%	A	32.50
Two irrigation, 50%	A	31.73
Rainfed, 50%	A	30.87
Rainfed, 0	A	30.13
Full irrigation, 0	A	29.40
Four Irrigation, 0	A	28.57
Two irrigation, 0	A	28.53

Levels not connected by same letter are significantly different

Appendix 17: ANOVA for final aboveground biomass (kg.ha^{-1}) of *tef*

Source of variation	DF	SS	MS	F Ratio	Prob > F
Water level	3	18113098	6037699	5.10	0.0079
Block	2	11031374	5515687	4.65	0.0206
Fertilizer Level	2	140005145	70002573	59.07	<.0001
Water*Fertilizer Level	6	3322482	553747	0.47	0.8250
Error	22	26071258	1185057		
Total	**35**	**198543357**			

R^2=86.87% R2adj=79.11%, RMSE=1088.60 Mean of Response=7863.56 CV=13.85%

Appendix 18: ANOVA for final grain yield (kg.ha^{-1}) of *tef*

Source of variation	DF	SS	MS	F Ratio	Prob > F
Water level	3	1077554.80	359184.93	11.82	<.0001
Block	2	96098.80	48048.40	1.58	0.2283
Fertilizer Level	2	4026015.00	2013007.5	66.22	<.0001
Water *Fertilizer interaction	6	150131.60	25021.93	0.82	0.5642
Error	22	668768.90	30398.59		
Total	**35**	**6018569.0**			

R^2 =88.88%, R^2adj=82.32%, RMSE=174, Mean of Response=1672.33 CV=10.41%

Appendix 19: ANOVA of straw yield (kg.ha^{-1})

Source of variation	DF	SS	MS	F Ratio	Prob > F
Water level	3	105167	35055.67	2.8612	0.0601
Block	2	12899645	6449823.	5.2642	0.0135
Fertilizer Level	2	96708874	48354437	39.4660	<.0001
Water level*Fertilizer Level	6	2422818	403803	0.3296	0.9141
Error	22	26954766	1225217		
Total	**35**	**139091270**			

CV= *17.88%, R^2= 81.97%, R^2adj. =71.32%, RMSE=1106.895, Mean of response= 6191.23*

Appendix 20: Mean interaction effect of treatments on straw yield (kg.ha^{-1}) of *tef*

Level						Mean
Four Irrigation,100	A					8980.57
Full irrigation,100	A	B				8225.83
Two irrigation,100	A	B	C			7856.73
Rainfed,100	A	B	C	D		7468.83
Full irrigation,50	A	B	C	D		7273.60
Four Irrigation,50	A	B	C	D		6676.43
Two irrigation,50	A	B	C	D	E	5987.17
Rainfed,50		B	C	D	E	5329.10
Full irrigation,0			C	D	E	4717.33
Four Irrigation,0				D	E	4227.20
Two irrigation,0				D	E	4185.13
Rainfed,0					E	3366.83

Levels not connected by same letter are significantly different

Appendix 21: ANOVA for NFUE (kg.kg^{-1})

Source of variation	DF	SS	MS	F Ratio	Prob > F
Water level	3	43.29	14.43	0.4864	0.6952
Block	2	29.31	14.65	0.4940	0.6168
Fertilizer Level	2	1713.83	856.92	28.89	<.0001
Water*Fertilizer Level	6	119.95	19.99	0.6739	0.6719
Error	22	652.61	29.66		
Total	**35**	**2558.98**			

R^2=74.50%, R^2 adj =59.43%, RMSE=5.45, Mean of response=10.00, CV=54.50%

Appendix 22: Mean interaction effect of treatment means on NFUE(kg.kg^{-1})

Level			Mean
Full irrigation,50	A		21.5
Four Irrigation,50	A		17.03
Rainfed,100	A	B	14.03
Rainfed,50	A	B	12.9
Two irrigation,50	A	B	12.7
Four Irrigation,100	A	B	12.32
Full irrigation,100	A	B	12.15
Two irrigation,100	A	B	12.1
Rainfed,0		B	0
Two irrigation,0		B	0
Full irrigation,0		B	0
Four Irrigation,0		B	0

Levels not connected by same letter are significantly different

Appendix 23: ANOVA of IWUE (g.m^{-2}.mm^{-1})

Source of variation	DF	SS	MS	F Ratio	Prob > F
Water level	3	1.85	0.62	3.63	0.0288
Block	2	0.45	0.23	1.33	0.2857
Fertilizer Level	2	1.32	0.66	3.88	0.0361
Water level*Fertilizer Level	6	0.66	0.11	0.64	0.6951
Error	22	3.74	0.17		
Total	**35**	**8.01**			

R^2=53.35%, R^2adj=25.79%, RMSE=0.37, Mean of response=0.41

Appendix 24: Mean interaction effects of treatments on IWUE($g.m^{-2}.mm^{-1}$)

Level		Mean
Two irrigation,50	A	1.07
Four Irrigation,50	A	0.78
Full irrigation,50	A	0.73
Two irrigation,0	A	0.53
Four Irrigation,100	A	0.35
Full irrigation,100	A	0.31
Four Irrigation,0	A	0.27
Full irrigation,0	A	0.25
Two irrigation,100	A	0.22
Rainfed,100	A	0
Rainfed,50	A	0
Rainfed,0	A	0

Levels not connected by same letter are significantly different

Appendix 25: Average observed sequential green canopy cover (%) of the treatments

Treatment	**DAS**				
	41	**50**	**60**	**72**	**82**
T1	16.33	37.57	35.00	29.00	22.27
T2	15.00	37.50	46.00	44.53	40.00
T3	18.00	39.00	47.00	46.00	42.00
T4	19.00	41.00	50.00	48.00	44.00
T5	31.67	52.47	54.33	40.67	38.13
T6	29.00	58.33	62.00	60.00	56.00
T7	33.00	55.70	66.00	62.00	59.00
T8	34.00	60.00	68.00	66.00	62.00
T9	44.67	62.47	71.67	51.67	48.00
T10	42.50	68.23	73.00	68.00	61.00
T11	45.00	69.50	76.00	76.50	68.00
T12	46.00	66.10	89.60	75.13	73.33

Appendix 26: Average leaf area index of *tef* ($m^2.m^{-2}$)

Treatment	Days after sowing						
	30	**40**	**53**	**63**	**73**	**83**	**93**
T1	0.838	1.004	1.229	1.852	2.270	0.390	0.106
T2	0.666	0.762	1.326	2.122	2.392	0.381	0.147
T3	0.776	0.897	1.358	2.190	3.151	0.535	0.079
T4	0.618	1.326	1.117	2.562	2.976	0.606	0.255
T5	1.073	1.708	2.060	3.098	3.135	0.291	0.274
T6	1.078	1.363	1.721	2.846	3.232	0.764	0.237
T7	1.139	1.709	2.293	3.395	3.761	1.434	0.283
T8	1.108	1.063	2.001	3.192	3.814	0.553	0.131
T9	1.216	1.795	1.707	3.524	3.629	1.279	0.103
T10	1.395	1.758	2.258	3.334	4.775	0.736	0.253
T11	0.902	1.602	2.411	3.128	4.767	1.111	0.132
T12	1.066	1.618	2.240	3.782	3.645	1.112	0.170

Appendix 27: Treatments and crop phonology during the growing season of 2012 for *tef*

Treatments	Sowing date	Physiological stage					Rainfall (mm)	Amount of irrigation (mm)	Date of irrigation
		Emergence	Flowering	Senescence	Maturity	Harvest			
		DAS							
Full irrigation	23/07/12	6	62	86	92	105	311	8,8,17,17,13,9,7, 7, and 7 respectively, Total = 93 mm	16,19,22,26,30/09 -12 and 03,06,10 and 12/10-2012
Four irrigation	23/07/12	6	62	86	92	105	311	17,17,13,and 9 respectively, Total =56 mm	22,26,30/09-12 and 03 and 06/10-12
Two irrigation	23/07/12	6	62	86	92	105	311	17 and 17 respectively, Total=34 mm	22 and 26/09-12
Rainfed	23/07/12	6	62	86	92	105	311		

NB: DAS= Days after sowing.

Crop yield assessment at farmers' field level

Appendix 28: Sex composition of respondents in the respective woredas

Woreda	Sex	Frequency	Percent
Aksum	F	3	8.6
	M	27	77.1
	Total	**30**	**100**
Enderta	F	4	26.7
	M	11	73.3
	Total	**15**	**100**

Appendix 29: Correlation coefficient of crop parameters for Aksum area

crop response	DAP ($kg.ha^{-1}$)	Urea ($kg.ha^{-1}$)	AGB ($kg.ha^{-1}$)	GY ($kg.ha^{-1}$)	HI	PH (cm)	PL (cm)
DAP	1	.705**	.193	.127	-.179	.205	.195
Urea		1	.064	.055	-.032	.192	.249
AGB			1	.879**	-.516**	.104	-.096
GY				1	-.072	-.094	-.015
HI					1	-.445*	.029
PH						1	.113
PL							1

NB: and ** indicate correlation is significant at the 0.05 and 0.01 level, respectively. AGB= above ground biomass, GY= grain yield, HI= harvest index, PH=plant height and Panicle length*

Appendix 30**:** Correlation coefficient of crop parameters for *Enderta* woreda

Crop response	DAP ($kg.ha^{-1}$)	Urea ($kg.ha^{-1}$)	AGB ($kg.ha^{-1}$)	GY ($kg.ha^{-1}$)	PH (cm)	PL (cm)	HI
DAP ($kg.ha^{-1}$)	1	$.59^{*}$	.38	.48	.35	.38	0.09
Urea ($kg.ha^{-1}$)		1	$.58^{*}$	$.74^{**}$	.38	.50	0.124
AGB ($kg.ha^{-1}$)			1	0.81^{**}	$.54^{*}$	.23	-0.43
GY ($kg.ha^{-1}$)				1	.29	.12	0.175
PH (cm)					1	$.53^{*}$	-0.48
PL (cm)						1	-0.21
HI							1

*NB: *and** indicate correlation is significant at 0.05 and 0.01 levels, respectively*