Coping with drought for food security in Tigray, Ethiopia

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Coping with drought for food security in Tigray, Ethiopia

Araya Alemie Berhe

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Chapter 1

Introduction

Introduction

1.1 Problem definition

Droughts are a major obstacle to food security in Ethiopia. Development of strategies to effectively cope with drought and increase crop success is fundamental to ensure food security and improve the livelihood of the people of this country. The Ethiopian economy is highly dependent on agriculture. Agriculture is the largest sector of the economy accounting for 80 – 85 % of the income of its people; and about 46% of its GDP and 90% of its export earnings (FDRE, 1997; UNDP, 2002). Agriculture in Ethiopia consists primarily of small-holder farmers using low level technology in a mixed crop-livestock farming system, and is highly dependent on natural rainfall. The main natural hazard responsible for food shortages in Ethiopia is drought. Food shortages have been one of the most important problems in Ethiopia with, each year on average, 1 to 5 million Ethiopians facing the risk of food insecurity (USAID, 2002). Many people believe that the drought risk is principally associated to rainfall characteristics of the area. Rainfall variability and associated droughts have historically been identified as the major causes of food shortages and famine in the country (Pankhurst and Johnson, 1988).

A large part of Ethiopia has a semi-arid climate. The rainfall in semi-arid Ethiopia is characterized by its uncertainty in space and time. Reports show that rainfall variability has caused significant problems for the country's economy and food production in the last three decades (Tilahun, 1999; Bewket and Conway, 2007). Over the last decade the situation has worsened due to human induced climate change. This climate change seems to have increased the uncertainty and variability in the rainfall, making cropping more difficult. Projections of climate scenarios indicate that crop production may be limited by severe water and heat stress (Vorosmarty et al., 2000).

In northern Ethiopia severe droughts took the lives of millions, and destroyed crops and animals in 1971/1972, 1984/1985 and 2002/2003. Tigray is one of the northern regions of Ethiopia, and is the most severely affected by drought. Drought events occur every 2 to 4 years. These frequent droughts cause serious decreases in the income of the people who fully depend on agriculture. Many people live with chronic hunger (Devereux, 2000). On average, nearly 1 million people per year depended on food aid during the period 1995 to 2002 (TDPPC, 2002). People remain vulnerable and desperate as they do not have enough resources to cope with the vagaries of the weather. Crop failure due to occurrence of short and long dry spells is common, yet little is really known about how the seasonal rainfall variability and distribution influences the occurrence of seasonal soil water drought. Furthermore, there is limited understanding of the relation between past rainfall, soil water variability and the resulting crop failures in northern Ethiopia. While crop-climate suitability classifications exist, those currently in use are not very relevant to semi-arid northern Ethiopia. An improved agro-climatic classification will help policy makers, investors and agriculturists derive better crop suitability information and amend some existing cropping limitations, as well as plan for better short- and long-term development strategies under climate change scenarios.

In northern Ethiopia, the rainfall is torrential and falls in short intense events which often result in high runoff. Infiltration into the soil is negatively affected by the nature of the rainfall. The high runoff damages crops by taking away the fertile soil and exposing the crop roots to direct sunlight (Nyssen et al., 2005). This further aggravates the risk of drought due to the lack of available soil water resulting from deteriorated soil physical characteristics (Stroosnijder and Slegers, 2008; Stroosnijder, 2009). Better infiltration of rainfall and rainwater conservation could be established by suitable soil management practices. However, to what extent these measures are effective for reducing the negative effects of climate variability related water stress still needs investigation.

Soil and water conservation (SWC) has been practiced especially on steep slopes, wastelands, grazing land, forestlands and arable lands since the famine 1984/85. The major objectives of the structures were to reduce erosion and improve water availability in the root zone (Nyssen et al, 2000). However, improvements are hardly visible, especially in places where there is a lot of human and animal interference. Furthermore, it is not clear to what extent these practices could actually improve soil water availability in the root zone and/or boost crop yield under the smallholder farmer growing condition in the northern Ethiopia. In addition, adoption of these SWC structures by farmers is not universal and not consistent with time and place. Different NGOs recommend different types of SWC practices and people just carry out the practices as long as they get paid for their labours, regardless of the effect the structures have on crop production. It is therefore important to evaluate and find suitable and effective soil and water conservation techniques that can and will be applied by farmers at household level.

Tied ridging and mulching are some of the common SWC practices that may have potential for northern Ethiopia. In many semi-arid areas, tied ridging and mulching are well known as ways to improve soil water availability in the root zone and crop performance by minimizing runoff and maximizing infiltration (Papendick and Parr, 1987; Hulugalle, 1989; Hulugalle, 1990; Wiyo et al., 2000; Li et al., 2001; McHugh et al., 2007; Chakraborty et al., 2008; Nuti et al., 2009; Temesgen et al., 2009). However, before these practices are recommended to smallholders farmers in Tigray, the potentials of these practices have to be tested for the major crops grown in Tigray, northern Ethiopia. Recently, in an effort to alleviate food insecurity from an extended dry period various water harvesting programs such as small scale dams, ponds, river diversions, hand dug shallow wells have been introduced. So far 10s of thousands of household ponds, thousands of hand dug wells, hundreds of river diversions and about 60 small to medium scale dams have been built in the region. Household or farm ponds are the most common type of water storage structures in the northern Ethiopia but their use and effect are limited due to poor management of the pond water. If we can improve this water management system and verify the effect of other SWC practices, it may be possible to mitigate the impact of rainfall variability and improve food security in the region.

Drought is a reality that must be dealt with to secure food, livelihoods and the future for the people of northern Ethiopia. Improved understanding of this phenomenon and methods for dealing with it will greatly help to alleviate drought stress and reduce the risk of crop failure. This PhD-study aims to combine agro-climatic information with soil water technology and crop modelling to determine strategies that can be used by policy makers and farmers to improve soil and water management, reduce the risk of crop failure, and enhance food security in the northern Ethiopia. It is hoped that this will help farmers and policy makers move toward greater food security in the northern Ethiopia.

1.2 Research approach

We used a systems approach to reach our aim. Agro-climatic data and farmers' data was collected and analyzed to understand how these constraints are related to cropping risks. Data from field experiments were used to quantify crop-water relationships and validate FAO's AquaCrop model that is subsequently used to explore soil and water conservation interventions. Aim and research approach lead to a number of research questions.

1.3 The research questions

- How suitable is northern Ethiopia for barley and teff production and have changes in rainfall affected this suitability?
- How does seasonal rainfall variability and distribution influence the occurrence of soil water drought in semi-arid northern Ethiopia?

- How useful is FAO's AquaCrop model to explore soil and water conservation interventions?
- What is the effect of optimal timing of sowing/planting?
- Can soil and water conservation measures like tied ridges or mulching be used to mitigate the effects of dry spells?
- What is the potential for supplementary irrigation?

The ultimate objective is to devise an agro-meteorological and soil water conservation drought coping strategy to support greater food security in semi-arid northern Ethiopia.

1.4 The study area

The Tigray region is located in northern Ethiopia (12° 15'N and 14° 57'N latitude and 36° 27'E and 39° 59'E longitude); it has six administrative zones with a total area of about 53,000 km^2. The total population of Tigray is 4.3 million with an average family size of five persons per household and a growth rate of 2.5 % per year (CSA, 2008). The land cover and use type in Tigray is 36.2 % bush and shrub lands, 28.2 % cultivated land, 22.8 % grassland and about 10.8 % other land uses (BFED, 2007). The region is comprised of diverse topographic features (about 39 % midland, 1800 – 2400 m a. s .l; 53 % lowland, 1400 – 1800 m. a. s. l.; and 8 % highland, 2400 – 3400 m. a. s. l.) (BFED, 2007). The region is classified into three agro-ecological zones: 67 % dry; 24 % moist and 9 % wet (BFED, 2007). The mean annual rainfall ranges from 500 to 1000 mm (ENMA, 2007). A subsistence mixed crop-livestock agriculture system is the main source of income and contributes to about 57 % of the GDP. Since agriculture is mainly dependent on the erratic rainfall with a low level of applied technology, food insecurity has been the major challenge in the region for several decades. About 75 % of the people are seriously affected by recurrent droughts (Rami, 2003).

The study area is located in northern Ethiopia, administered in the eastern, (Hawzen and Edagahamus); central, (Hagereselam); and southern, (Mekelle, Adigudom, Maychew and Alamata) zones of Tigray region (Figure 1.1). The majority of the northeastern part of the study area is located in the Giba catchment. The study area has similar land cover and use, agro-ecology and demographic features to that described for Tigray region as a whole. The grassland, rangeland and forest are communally owned; the topography is mountainous, with steep slopes, undulations and some flat lands and severe land degradation; the natural vegetation cover is sparse due to massive deforestation; the majority of the soils are shallow with low water holding capacity.

All agriculture is done on small family farms (Hendrie, 1999). An average family's landholding is between 0.5 and 1 ha. The most dominant cultivated crops are cereals such as barley (*Hordeum vulgare*) and teff (*Eragrostis tef*) as well as wheat (*Triticum* sp.). Other important crops grown in the lower parts of the study area are horse bean (*Vicia faba*) and sorghum (*Sorghum bicolor*) (Ruthenberg, 1980). Teff is adapted to a wide range of environmental conditions (1000 to 3000 m a. s. l.). Most teff cultivars are most suitably grown between 1500 to 2500 m. a. s. l. (Teffera et al., 2000), and the largest area under cereal cultivation in Ethiopia is used for teff production (Ketema, 1997; Habtegebrial et al., 2007). Barley is grown at elevations between 1800 to 3000 m. Both teff and barley crops are adapted well to the harsh environment of northern Ethiopia. These two crops are grown for various purposes: teff grain is used for the typical Ethiopian dish *Enjera*, while its straw is an excellent livestock fodder. Barley is a major food source for preparing various types of traditional foods such as *Kita, Kolo, Beso, Enjera, Giat*, and has many others uses as well (including beer). Its hay is also an important source of fodder. Barley accounts for over 60% of the food of the people in the highlands of Ethiopia and it is the cheapest food source in the local market.

Crop production from the small-size parcels and just one harvest per year is usually not enough for a family. Grain yield ranges from 0.3 to 1 t ha^{-1}. Many factors are responsible for this low yield but the most important factor is associated with low soil moisture resulting from the dependency of their agriculture on erratic rainfall.

The rainfall characteristic in the majority of the study area is bimodal. The short rainy season is locally known as *'Belg'*. The *Belg* season occurs between the months of February and May. It has little agricultural importance because of its low amount and high variability. The other rainy season (known as '*kiremt')* occurs during the crop growing period, which is between June and September, and constitutes about 70 to 80% of the annual rainfall. As in many other parts of the country, the *Kiremt* season rainfall in northern Ethiopia is characterized by temporal and spatial fluctuations (Araya, 2005; Tilahun, 2006a; Bewket and Conway, 2007).

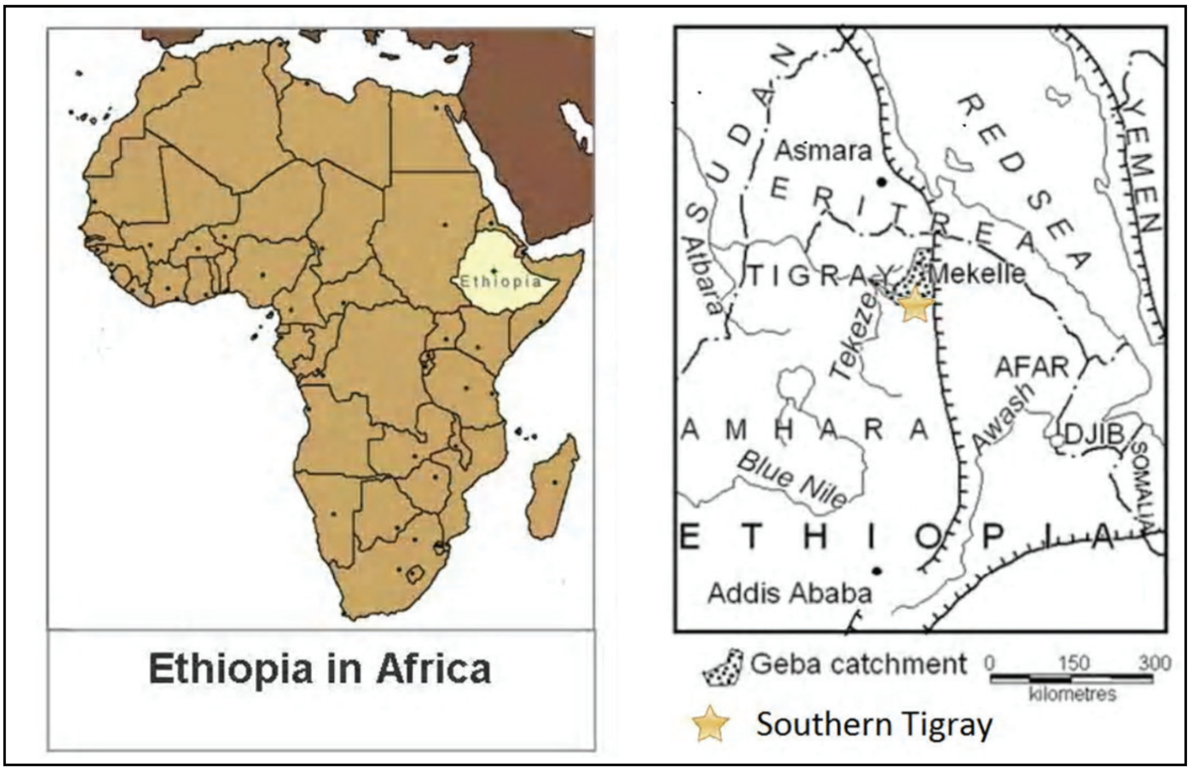

Figure 1.1. The study area (Giba catchment and the southern Tigray) located in Tigray, the northern state of Ethiopia.

1.5 Outline of the thesis

After the general introduction (Chapter 1), Chapter 2 addresses the suitability of the climate in north Ethiopia for barley and teff. In this chapter a new comprehensive agro-climatic classification system is developed by merging the traditional zoning with growing period zones. Chapter 3 investigates how the occurrence of drought is related to crop failure and how past crop failure seasons can be captured using a simple model. Chapters 4 and 6 determine the crop coefficient, yield response factor and water productivity of teff and barley, respectively. These chapters also suggest the best use of farm ponds for supplementary irrigation. Chapters 5 and 7 deal with simulations of yield response to water of teff and barley using the FAO AquaCrop model, respectively. This includes the calibration and validation of the model for subsequent evaluation of the performance of teff and barley under various water availability conditions in northern Ethiopia. Chapter 8 analyses the cropping risk based on sowing time criteria, and Chapter 9 evaluates how in-situ water conservation measures such as tied ridging improve the performance of barley under the erratic rainfall conditions. The findings are compared with the use of straw mulch. Chapter 10 summarizes the major conclusions and provides a synthesis and implications of this study.

Chapter 2

A new agro-climatic classification for crop suitability zoning in northern semi-arid Ethiopia

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A new agro-climatic classification for crop suitability zoning in northern semi-arid Ethiopia

Abstract

The agro-climatic resources of Giba catchment in northern Ethiopia were assessed and characterized. The objectives were (i) to ascertain the suitability of the climate for growing teff (*Eragrostis tef)* and barley (*Hordeum vulgare*); (ii) to determine the onset and length of the growing period (LGP), (iii) to evaluate the traditional method of climate classification, and (iv) to produce comprehensive agro-climatic zones of the Giba catchment. The Ethiopian traditional method of climate classification based on temperature and altitude was found to be less relevant to crop suitability zoning in semi-arid regions of Northern Ethiopia because within this semi-arid drought-prone environment the rainfall is more important for crop growth than temperature. The LGP ranges from 60 to 100 days over the catchment, increasing from north-east to south-west. For the crop suitability zoning, the concept of growing period was introduced into the traditional approach, to produce agro-climatic zones. This method could be used to develop agronomic strategies to cope with the anticipated increase in drought in the semi-arid tropics under climate change. Accordingly, quick maturing and drought-resistant varieties of teff and barley can be grown in the centre and in the east, while medium maturing cultivars should do well in the south-west. The method requires limited input data and is simple in its use.

2.1 Introduction

Agriculture in Ethiopia is generally dependent on rainfall. About 85% of the population is directly dependent on livestock farming and crop production, and of these, over 90% depend on rain-fed agriculture for their livelihood.

Giba catchment is located in northern Ethiopia (Figure 2.1). Here all the agriculture is done on small family farms (Hendrie, 1999). An average family's landholding is between 0.5 and 1 ha. Grassland, rangeland and forest are communally owned. The most dominantly cultivated crops are cereals such as barley and wheat (*Triticum* sp.), and also teff, a cereal endemic to Ethiopia, with very fine grains. Other important crops in the lower parts of the catchment are horse bean (*Vicia faba*) and sorghum (*Sorghum bicolor*) (Ruthenberg, 1980).

Barley and teff are the two major food crops grown under rainfed condition in the Giba catchment. Teff is adapted to a wide range of environmental conditions (1000 to 3000 m above sea level (a. s. l.)) although most teff cultivars are more suitably grown between 1500 to 2500 m. a. s. l. (Teffera et al., 2000). Barley is grown at elevations between 1800 to 3000 m. Both crops are adapted well to the harsh environments in northern Ethiopia. These two crops are grown for various purposes: teff grain is for food while its straw is an excellent livestock fodder. Barley is major food source in various forms (including beer) and its hay is also an important source of fodder.

The climate of northern Ethiopia where the study area lies is semi-arid (UNESCO, 1979). The mean summer rainfall ranges from 300 to 700 mm and the inter-annual variability ranges from 25% to 50%. The rainfall is characterized by temporal and spatial fluctuation (Araya, 2005; Tilahun, 2006a; Bewket and Conway, 2007). Unfortunately, little relevant information is available on the climate in the region. Information on evapotranspiration, temperature and rainfall and on derivatives such as onset of growing season, length of growing period and agro-climatic zones is vital in weather-sensitive sectors such as agriculture (Stern, et al., 1982; Kowal, 1987; De Pauw, and Bruggeman, 1988; Mersha, 2001; Kipkorir et al., 2002; Raes, et al., 2004; Tilahun, 2006a; Geerts et al., 2006; Kipkorir et al., 2007; Garcia, et al., 2007). Documentation of these climatic details will contribute to better planning of resources, productivity and environmental sustainability (Simane and Struik, 1993; De Pauw et al., 2000). For example, the development of agro-climatic zones is valuable as it provides a concise inventory of the agro-climatic potential and constraints.

Previous agro-climatic studies in the region were more general, less detailed and less relevant to Ethiopian rain-fed agriculture. For instance, both the classic Köppen climate classification and the Ethiopian traditional climate classification rely heavily on temperature as a basis for demarcating climate boundaries. But temperature is not an important limitation to crop-growing conditions in the semi-arid tropics (Tilahun, 2006a). The UNESCO aridity index approach of agro-climatic classification system uses the most important climatic variables in the semi-arid region: rainfall and evapotranspiration (De Pauw et al., 2000; Tilahun, 2006b). However, it does not consider variation in the length of growing period and it looks at the large-scale picture, ignoring details of landscape–climate interaction (De Pauw et al., 2000): it classifies the entire Giba catchment as semi-arid.

For agriculture in the dry semi-arid tropics, appropriate characterization of agro-climatic classification should link the rainfall with evapotranspiration. This relationship would enable evaluation of growing period. Combining the traditional zones with growing-period zones will improve the agro-climatic classification system because this approach takes more account of crop growth, hence, will influence the crop suitability classification. For example, crop performance depends on the onset, cessation and distribution of rain, and the evaporative power of the atmosphere.

One of the main challenges to agriculturists in semi-arid Ethiopia has been to determine the onset of the growing season. Our aim was to determine the onset and cessation of the growing season in order to be able to derive LGP zones. By combining the LGP with other climatic elements it is possible to appropriately classify the climate of an area. Proper agro-climatic classification will help policy makers, investors and agriculturists to derive the crop suitability and to amend the existing limitations to cropping, as well as to plan for better short- and long-term development strategies under climate change scenarios.

This paper has four objectives: to characterize the temperature, evapotranspiration and rainfall; to determine the length of growing period on the basis of pre-existing onset and cessation criteria; to classify the Giba catchment into agro-climatic zones; and to evaluate the catchment's suitability for teff and barley crops.

2.2 Materials and methods

2.2.1 Study Site

The Giba catchment, located in the Tigray highlands in northern Ethiopia (lat. 13^{o} 15'N to 14^{o} 16'N and long. 39^{o} 0'E to 39^{o} 44'E) (Figure 2.1) was selected for this study because it is representative of northern Ethiopia in terms of variability in elevation, agro-climatology, crops, soils and geology. The catchment area is approximately 6500 km^2.

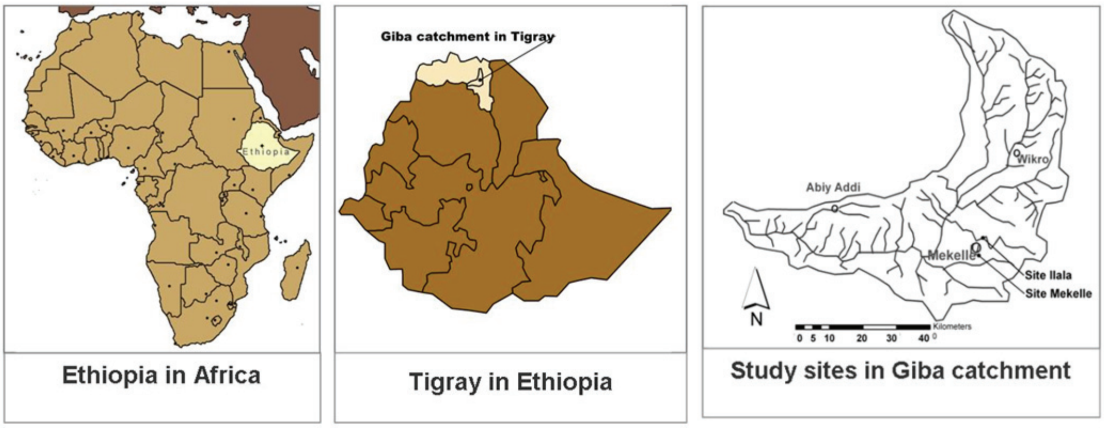

Figure 2.1. The Giba catchment in relation to Ethiopia and the Tigray region.

2.2.2 Data and method of data analysis

Climate data

Temperature and rainfall data were available from the meteorological stations in the Giba catchment (Table 2.1). Temperature observations from 1994 to 2008 were used to calculate the mean temperatures and estimate the reference evapotranspiration (ET_o). This data range was universally available across the stations in the study area. The mean temperatures were calculated from daily mean minimum and maximum temperature data.

Table 2.1 Altitude and the types of climate data available in the meteorological stations in the study area. All stations recorded temperature from 1994-2008; precipitation data was universally available in all stations for the years 1974-1980 and 1994-2008. ET_o data was computed for the period 1994-2008.

Stations	Altitude (m a. s. l)	Mean annual rainfall (mm)	Mean annual ET_o (mm)
Adigudom	2000	499	1748
Adigrat	2480	576	1713
Qwiha	2130	583	1700
Abyiadi	1970	935	1950
Hawzen	2280	561	1840
E/hamus	2650	524	1495
Dongolat	2350	673	1589
H/selam	2600	718	1529

The ET_o of the stations in the study area was calculated using Hargreaves's equation and the ET_o program (FAO, 2009). Since the ET_o values calculated from limited data sets are less accurate, certain calibration procedures were followed as described in Allen et al., (1998). In the calibration, the estimates of Hargreaves's equation were compared with the estimates of FAO Penman-Monteith at one of the stations in the Giba catchment (Qwiha) where wind speed, humidity, temperature and sunshine hours are measured. The ratio method was then used to calibrate the estimates of the Hargreaves equation for all stations in the Giba catchment. In the validation, however, ET_o values estimated with FAO Penman-Monteith at another station in the Giba catchment (Ilala) where wind speed, humidity, temperature and sunshine hours are measured were compared with the corresponding corrected values (calibrated) of the same (Ilala) station.

Data on daily rainfall from 1974-1980 and 1994-2008 was used in the rainfall analysis because these ranges were universally available across the stations in the study area. We tested the homogeneity of the data according to Buishand (1982). After confirmation of the consistency of the data, the rainfall means and coefficient of variations were calculated.

The main growing season (*kiremt*) was classified on the basis of the rainfall distribution. To study the rainfall distribution, pentad dry spell and pentad rainfall probability analysis were used. Based on this analysis three different periods were identified in the growing season. The three periods are: pentads 33 to 38 (1st period), pentad 39/40 to 49/50 (2nd period) and pentad 50/51 to 53/54 (3rd period) respectively.

Estimation of onset and cessation of rain

Onset is the start of the growing season during which sufficient rain is received for the seedling survival (Ati et al., 2002). To estimate the onset we used three criteria, in order to ascertain if they would generate similar values for the onset over the seasons in the study area.

Criterion 'A': Onset generated from cumulative rainfall–evapotranspiration relationships. Onset is assumed to occur after June 15 when the long-term cumulative five-day rainfall is greater than or equal to the cumulative half of the five days' reference evapotranspiration. The prerequisites are that this trend should continue for at least two consecutive pentads and during this period the rainfall sum should be greater than 20 mm, and that no dry spell longer than 7 consecutive days should occur within 30 days of the onset. This criterion was adopted from Ati, et al., (2002), but with minor changes to take account of the different climate and crop characteristics in our study area (for example, the period we considered was June to September and our analysis was based on pentads).

Criterion 'B': conditional probability approach: average runoff coefficient and daily evapotranspiration values were considered in the estimation of the threshold limit for sowing (Equation 2.1) (Araya, 2005). This is approximately equivalent to 30 mm per 10-day period (decade) or 20 mm per week as described in Simane and Struik, (1996) and Reddy (1993) respectively.

$$R_{\min} = \left[\; [\; {ET_o}/{2} \;] * 5days \; \right] + C * \left[{ET_o}/{2} \right] * 5days \qquad [2.1]$$

Where:

C is the mean seasonal runoff coefficient, which is approximately 20% or (0.2). The runoff coefficient was derived from a separate experiment in the study area (Araya and Stroosnijder, 2010). R_{min}, is the amount of rainfall needed to wet the topsoil sufficiently for crop seed to germinate successfully. Mean daily ET_o (mm) over the growing period was considered.

For the study area, Equation 2.1 yields approximately 14 mm per pentad. Hence, the number of occasions that the pentad rainfall is greater than or equal to 14 mm was analysed and a probability curve was plotted. In the Giba catchment, the first pentad with a probability of 40% of receiving 14 mm followed with a consecutive greater chance of occurrence was considered as the start of the growing period (Araya, 2005), because the farmers in the study area plan to plant earlier as the rainy season is so short. According to Kipkorir et al. (2007), farmers in Kenya also sow early.

Criterion 'C': mean long-term daily rainfall versus mean daily ET_o relationships: mean long-term daily rainfall and ET_o values for the observation period were analysed. The onset was estimated from the chart by looking at the first day on which daily rainfall is greater than half of the mean daily ET_o and which is followed by consecutively greater rainfall values and with no dry spell of more than 5 days within 15 days of the onset. Contrary to Benoit's (1977) approach, we used the daily values instead of cumulative values.

The end of rain in the growing season is termed cessation. Since the rainy period varies slightly from season to season, it was important to set a criterion for cessation. Accordingly, cessation was assumed to occur at the end of the growing period, a week after half of the five days' cumulative ET_o exceeds the cumulative five days' rainfall.

Estimation and classification of length growing period (LGP)

We defined LGP as the period between the onset and cessation of rain during which a dryland crop such as barley grows under rain-fed condition. Onsets determined using the relationship between rainfall and reference evapotranspiration have been proven to be reliable (Ati et al., 2002). Hence, the LGP was derived from onsets with valid onset, criterion 'A'. The LGP isohyets were drawn and compared across the stations in the study area. As there was a large range in the LGP (60-100 days) we subdivided the study area into two LGP zones which we then validated using separate field experimental data from the study area (Araya and Stroosnijder, in preparation). This resulted in the boundary of 80 days being chosen as a threshold limit for growing crops with a short or medium time to maturity.

Classification of traditional zones and Agro-climatic zoning

The traditional climate classification was compiled by Negash and Ermias, (1995) and NEDECO, (1997). We compared the compiled information with the classification used by local people, which is presented in Table 2.2.

Table 2.2 Traditional climate zones and their characteristics as adopted partially from Nagash and Ermias, 1995 and NEDECO, (1997).

Altitude (m. a. s. l.)	Mean temperature (^oC)	Traditional climate zone	Interpretation for the traditional climate zones
1000-1500	24-27	Kolla	hot
1500-2000	21.5-24	Weina-Kolla	warm
2000-2500	15-21.5	Weina dega	Tepid
2500-3000	11.5-15	Dega	cool
>3000	<11.5	Wurch	Very cool

The LGP zones were overlaid on top of the traditional zones to produce agro-climatic zones. The characteristics for semi-arid zone as described in UNESCO (1979) were adopted. Accordingly all of the Giba catchment was broadly categorized as semi-arid region. However, in our study, we further subdivided the semi-arid zone on the basis of LGP and the traditional climate zones in the study area to produce the new agro-climatic zones. Finally codes were assigned and descriptions were given to each agro-climatic zone.

GIS mapping

With the help of an available digitized map of the Giba catchment we made maps using the indices for LGP zones and traditional climate zones. Based on these two zones, new agro-climatic zones were produced using Arcview 3.3. The kriging and cross-validation techniques were applied as described in Geerts et al., (2006).

2.3 Results

2.3.1 Temperature

In the Giba catchment the mean annual maximum temperature ranges from 21^{o}C to 31^{o}C and the mean annual minimum temperature ranges from 3 ^{o}C to 16^{o}C. The lowest mean minimum temperature occurs during the months of November, December or January. For most stations in the study area, the mean minimum temperatures during the months of November, December and January were generally between 7 °C and 14 °C. The exception was Adigrat: 3.3 °C to 4.9 °C.

The highest mean maximum temperatures occurred during the months of April, May and June in the lowlands of the study area. The highest mean maximum temperatures were recorded at Abyiadi (April 31°C); at the other stations the mean maximum values recorded ranged from 23 °C to 28°C.

During the growing period (July, August and September), the mean maximum temperature ranged from 22.4 °C and 27 °C and the mean minimum temperature ranged from 6.4 °C to 14 °C. The lowest value (6.4 °C) was recorded at Adigrat.

2.3.2 Evapotranspiration

There was a perfect match between the calibrated ET_o and the ET_o derived from the standard FAO Penman–Monteith equation (data not shown). The mean annual daily ET_o over the study area ranged from 4.1 mm d^{-1} in the highland to 5.3 mm d^{-1} in the lowland. The mean annual daily ET_o values in eight years out of ten years in the Giba catchment stations were between 4.4 and 5.7 mm d^{-1}. E/hamus had the lowest value, and Abyiadi the highest (Figure 2.2). Generally, there was little variation in ET_o (CV < 25%) in ten years period in the Giba catchment.

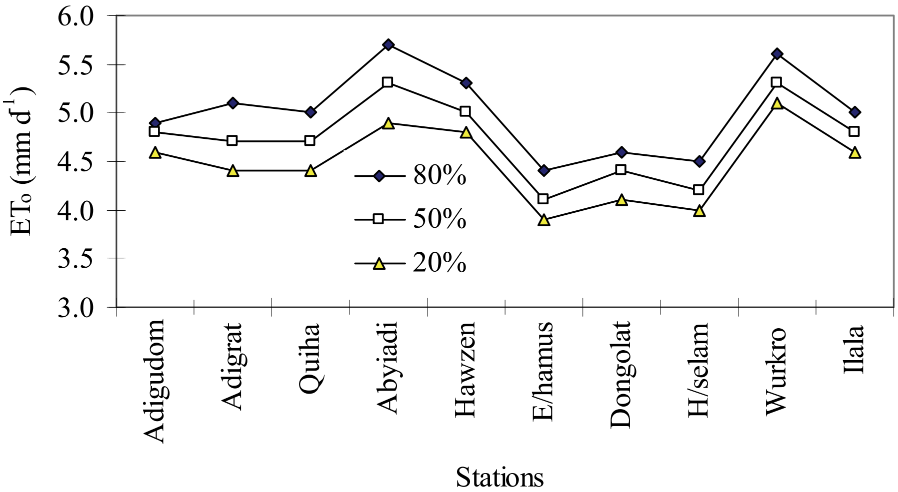

Figure 2.2. Long-term (20%), (50%) and (80%) probability of exceedance levels of ET_o during the main season (June-Sep) in the Giba catchment.

2.3.3 Rainfall

The main growing season

The '*Kiremt*' season, (the main rain), which occurs between June to September, constitutes about 60 to 80% of the annual rainfall (Figure 2.3). Rainfall is lowest in the east of the study area and highest in the west. *Kiremt* rainfall generally increases from north-east to south-west, regardless of the altitude.

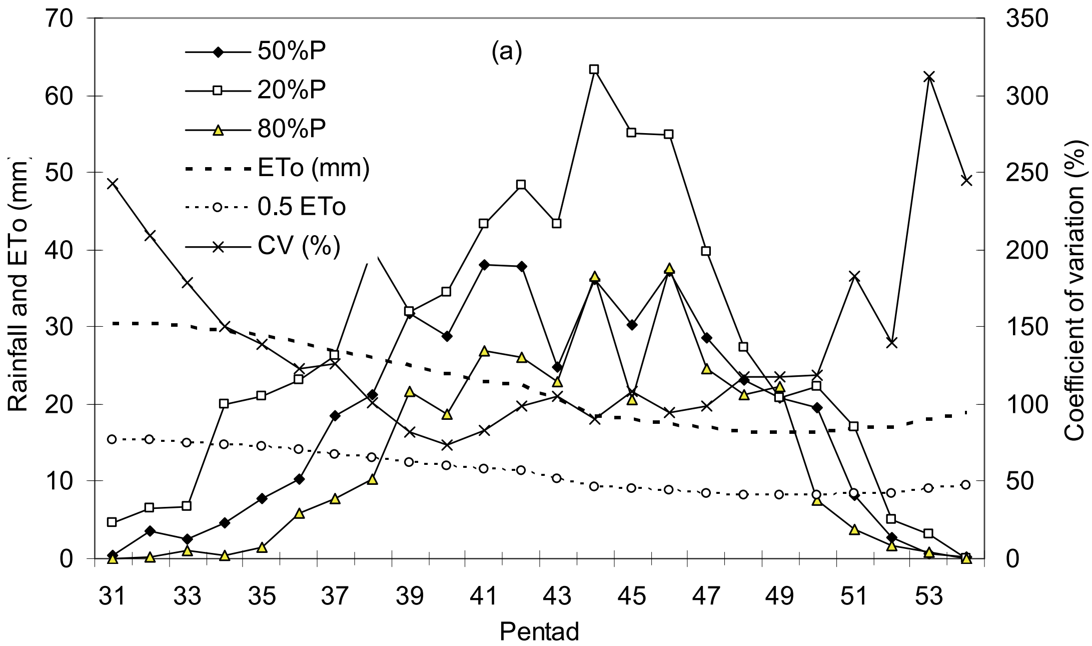

Figure 2.3. The average values of the 20, 50 and 80% probability of exceedance rainfall versus the reference evapotranspiration (ET_o) and coefficient of variation (CV) for stations in the Giba catchment during the growing period. CV is an average value for the 50% probability of exceedance pentad rainfall over the stations in the Giba catchment. ET_o is the average value of reference evapotranspiration over the stations during the growing period.

The periods in the main growing season

The main growing season was classified into three periods on the basis of the rainfall distribution. Figure 2.3 shows the pentad rainfall for three probabilities of occurrence, and the corresponding coefficient of variation and potential evapotranspiration during the growing season. In the growing season from pentads 33 to 38 (1st period), the 80% probability pentad rainfall was far below the 0.5 ET_o (Figure 2.3). Figure 2.4 (a) shows the probability of a pentad receiving 14 mm or more rainfall in the main growing periods and Figure 2.4 (b) shows the probability of occurrence of dry spells over the pentads in the main growing season. Although there were more rainfall variability in the 1st period (CV = 100-150%), the probability of receiving 14 mm rainfall per pentad increased linearly from about 7% in pentad 33 to 70 % in pentad 37/38 (Figure 2.4a) while the probability of occurrence of dry spells decreased over time. In most cases, the probability of occurrence of dry spells decreased from about 90% in pentad 33 to around 35% in pentad 37 (Figure 2.4 (b)). The occurrence of dry spells in the 1st period also slightly decreased south westwards in the catchment. For example, for three stations from different areas in the catchment the ranges in the probability of a dry spell per pentad over the 1st period are: Qwiha (south):35-90%; E/hamus (north-east) 50-90%; and Abyiadi (south-west) 40-80%.

The 2nd period (pentads 39/40 to 49/50) is more reliable in terms of rainfall than the 1st period. We found that in eight years out of ten, in most cases the rainfall received per pentad in the 2nd period was very close to or slightly above the reference evapotranspiration (Figure 2.3) and that in over 60% of the years the rainfall in this period was reaches at least 14 mm per pentad (Figure 2.4 (a)). In addition, at most stations the chance of a dry spell occurring was less than in the 1st period. The probability of a dry spell occurring per pentad in the 2nd period ranged from 20% to 60% (Figure 2.4 (b)). The fewest dry spells occurred between pentads 39 and 46. The probability of a dry spell occurring increased after pentad 46 (Figure 2.4 (b)).

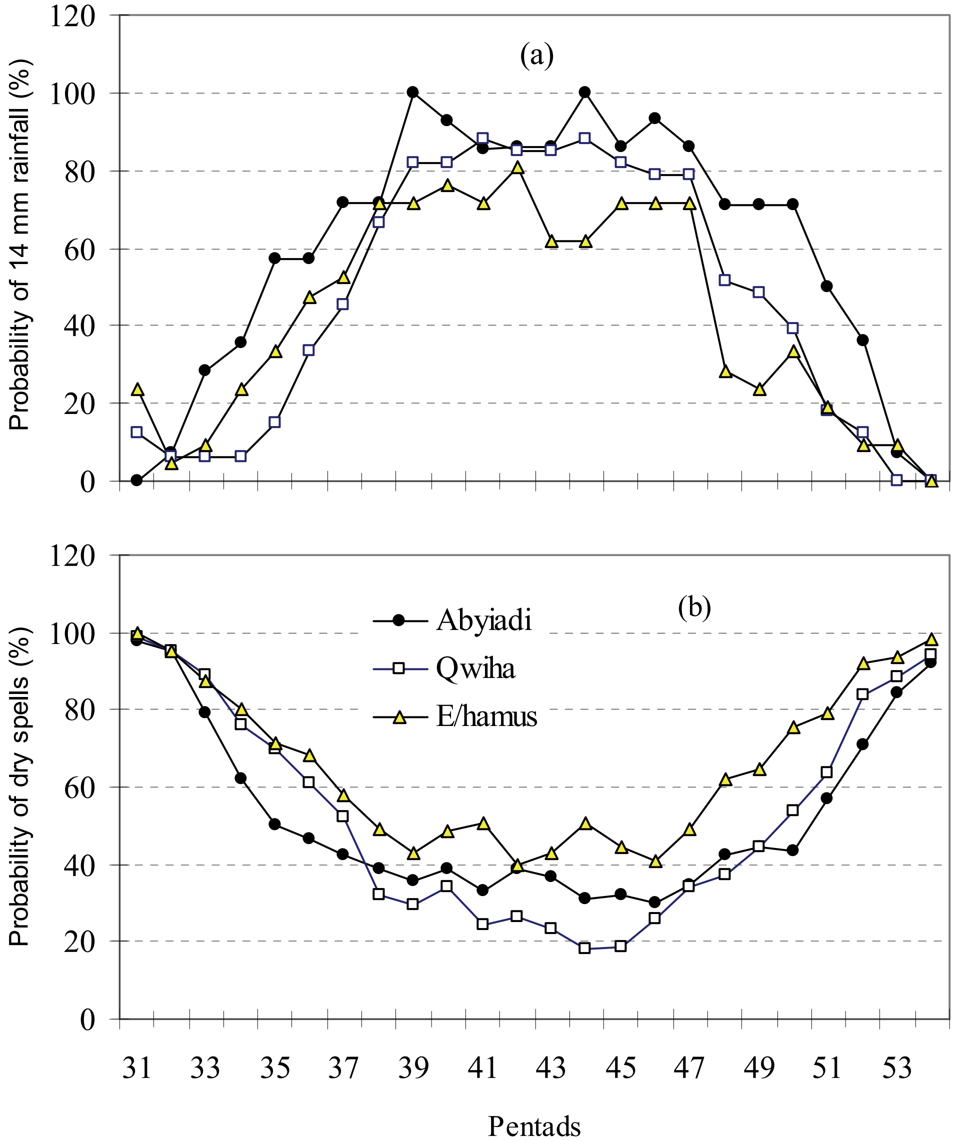

Figure 2.4a & b. The probability of 14 mm rainfall (a) and probability of occurrence of dry spells over the pentads in the main growing season for three stations in the Giba catchment.

The period from pentads 50/51 to 53/54 (3rd period) is characterized by great variability in rainfall and long and frequent dry spells. In most cases, the occurrence of a dry spell increased over time: from 40% in pentad 50/51 to 100% in pentad 53/54.

2.3.4 Agro-climatic classification

The LGP zones and onset

The onsets estimated using the three criteria are shown in Figure 2.5. The onsets yielded by the different criteria are very similar: they differ by less than five days. Early onsets were observed for Abyiadi and H/selam (in the south-west of the study area) and late onsets were observed for Qwiha (in the south of the study area) (Figure 2.5). Generally, onset generated by criterion 'A' was earlier than onset generated by 'B' or 'C'. However, the differences between the onsets per station and per criterion were not uniform and were not significantly different.

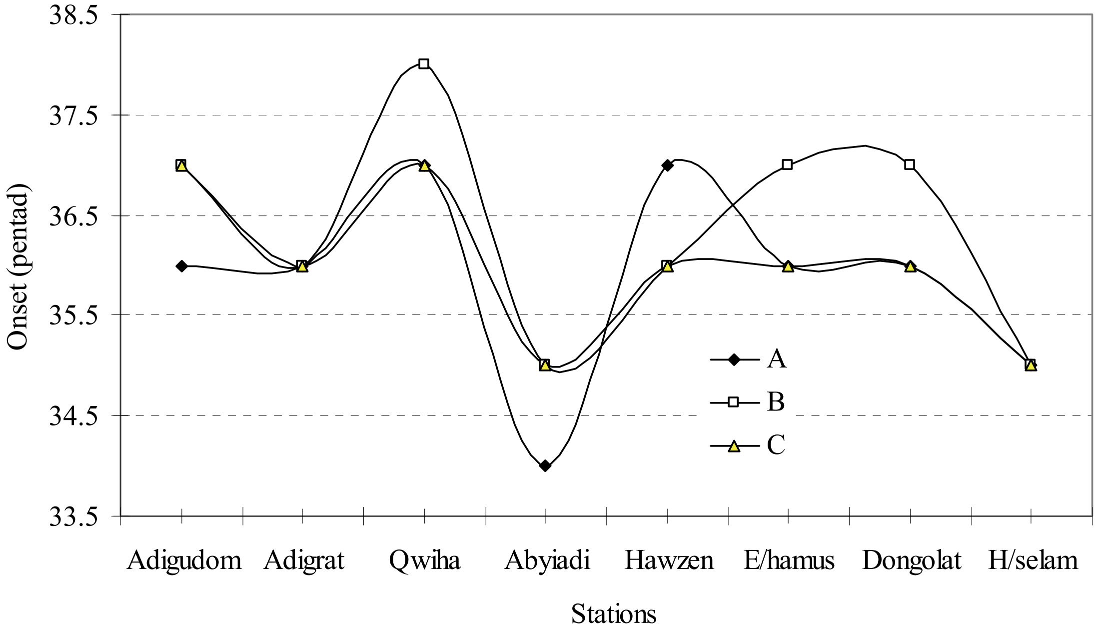

Figure 2.5. Comparisons of the onset (in Julian pentads) determined by criteria A, B & C for stations in the Giba catchment. Criterion 'A' was used for LGP analysis.

Although the LGP generated using the three onset criteria were similar, for our analysis we used the LGP determined on the basis of Ati, et al., (2002) (Figure 2.6). Accordingly, Abyiadi and H/selam stations have the longest LGP (90 days) while most of the other stations, such as Qwiha, Adigrat, Hawzen and E/hamus, have the shortest LGP (70 days) (Figure 2.6). Although the LGP at the stations (points) fall within a range of 70 to 90 days, the vast majority of the catchment isohyets were also between 60-70 and 90-100 days. The LGP zoning analysis showed that in the study area the growing period increases from north-east to south-west. Figure 2.7 shows the division of the study area into two LGP zones: north-eastern (LGP of 60 to 79 days) and south-west (LGP 80 to 100 days) respectively.

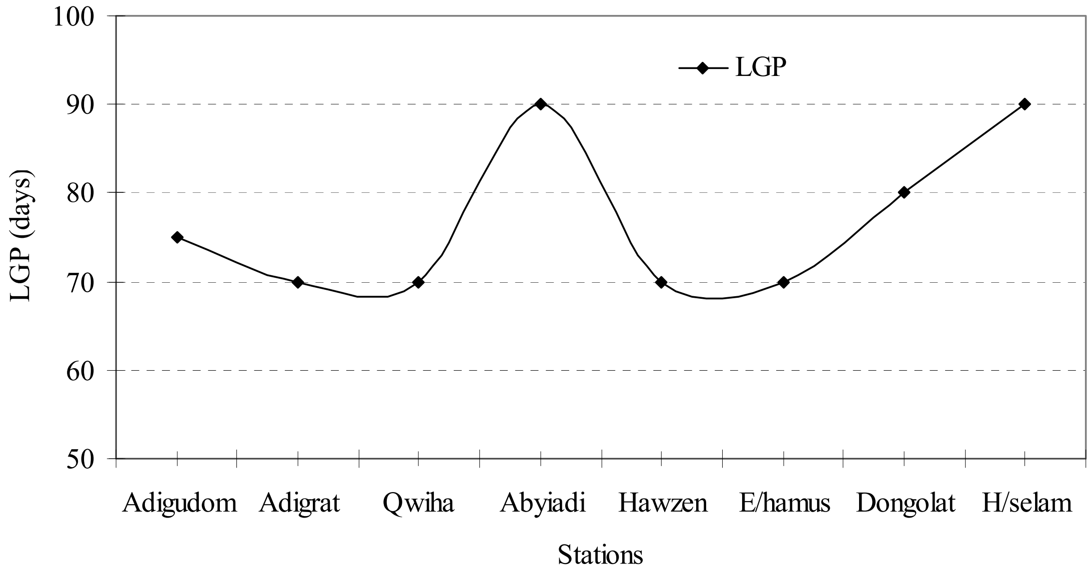

Figure 2.6. LGP as determined by criterion 'A' for the stations in the Giba catchment.

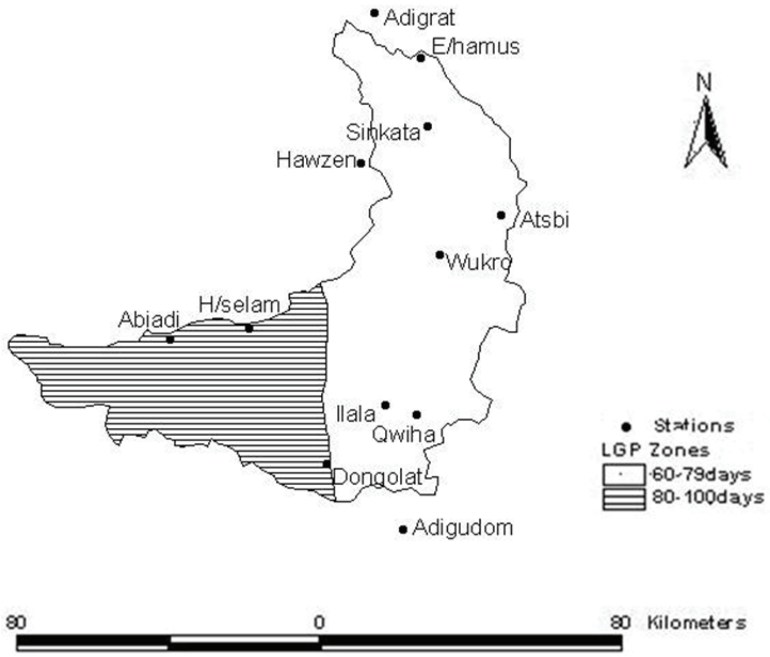

Figure 2.7. Growing period zones of the Giba catchment.

The traditional climate zones

Giba catchment has five traditional climate zones: '*Kolla*', '*Weina Kolla'*, '*Weina Dega'*, '*Dega*' and '*Wurch*' (see Figure 2.9 and Table 2.3). Temperature and altitude has strong inverse (R^2 = 0.8 to 0.9) relationships (data not shown). The traditional climate zones of the Giba catchment are shown in Figure 2.8. The indices are presented in Table 2.2.

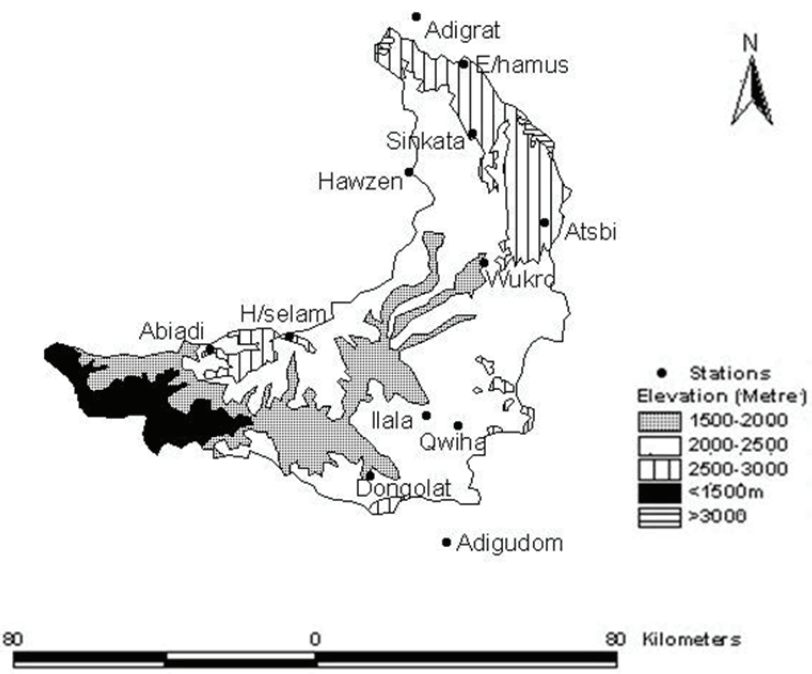

Figure 2.8. Traditional climate zones of the Giba catchment.

Agro-climatic zones

By combining the traditional climate zones (Figure 2.8) with the LPG zones (Figure 2.7), eight agro-climatic zones were generated (Figure 2.9 and Table 2.3) which are in effect subzones of the broad 'semi-arid' zone. The main elements in the resulting more detailed agro-climatic classification are LGP, temperature and altitude.

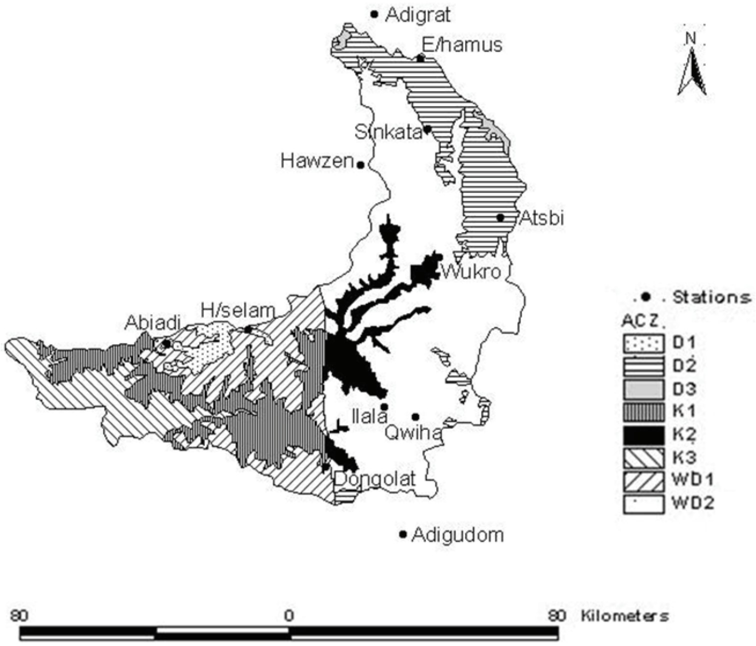

Figure 2.9. Agro-climatic zones of Giba catchment (ACZ, agro-climatic zone). Here, D1, cool semi-arid; D2, cool and dry semi-arid; D3, very cool and dry semi-arid; K1, warm semi-arid; K2, warm and dry semi-arid, K3, hot semi-arid; WD1, tepid semi-arid; WD2, tepid and dry semi-arid. See Table 3 for more details on these codes and zones.

Table 2.3. Descriptions of the new ago-climatic zones and cropping possibilities.

Altitude (m a. s. l)	Temperature (^{o}C)	LGP (Days)	Agro-climatic classification	Code	Description of the area grouped under the given agro-climatic zone	Cropping possibility
1000-1500	24-27.5	80-100	Hot semi-arid	*K3*	Lowlands of Abyiadi	Medium maturing teff and maize.
1500-2000	21.5-24	60-79	Warm and dry semi-arid	*K2*	Wukro & Ilala	Quick maturing teff
1500-2000	21.5-24	80-100	Warm semi-arid	*K1*	Lowlands to midlands between Abyiadi and Dongolat	Medium maturing teff and maize
2000-2500	15-21.5	60-79	Tepid and dry semi-arid	*WD2*	Hawzen, majority of Sinkata, Qwiha, mid to highlands of Wukro	Quick maturing teff and barley
2000-2500	15-21.5	80-100	Tepid semi-arid	*WD1*	Midland to highlands of Dongolat, H/selam and Abyadi	Medium maturing teff, barley, wheat and maize
2500-3000	11.5-15	60-79	Cool and dry semi-arid	*D2*	Atsbi, Sinkata and E/hamus	Quick maturing teff, wheat and barley
2500-3000	11.5-15	80-100	Cool semi-arid	*D1*	H/selam	Medium maturing wheat , barley, lentil and horse bean
> 3000	< 11.5	60-79	Very cool and dry semi-arid	*D3*	Small parts of Sinkata and Adigrat	Not suitable for most crops except some wild fruits such as Opuntia (*Ficus indica*)

These areas classified as having these codes are presented in Figure 2.9. In this case lowland, midland and highland refers to areas between the elevations of < 1800, 1800 to 2200 and 2200 to 3000 m. a. s. l respectively.

2.4 Discussion

In this study we have presented a new agro-climatic zoning system, based on the correlations between elevation and temperature combined with the reference evapotranspiration and rainfall. Our evaluation of the current traditional climate zoning system based solely on altitude and temperature revealed that temperature or altitude have less impact than rainfall on crops that are well adapted to the given locality. The performance or the productivity of the crops adapted to the local semi-arid environment mainly depends on the duration (in days) of the rainy period in which the reference evapotranspiration is correlated with a given amount of rainfall (Benoit, et al., 1977; Simane and Struik, 1993; Ati et al., 2002). From this we derived the parameters that define the concept of the growing period. This ultimately leads to crop climatic suitability zoning.

Because crop plants have certain heat unit requirements in order to reach certain stages, the effect of temperature on crop plants cannot be ignored (Raes, et al., 2009a). However, the temperatures in the Giba catchment are suitable for most of the existing cropping pattern. For example, under the present practice, the period of low temperature that occurs during October, November and December corresponds to the time of physiological maturity and therefore taking into account the current cropping practice, it can be generalized that temperature imposes few limitations on crop production in the study area.

The reason the ET_o was low during the main rain season at all the stations in the Giba catchment was because of the high cloud cover and low vapour pressure. The low ET_o values during the main rain season has both advantages and disadvantages for crop production. The advantage is that the crop water requirement during July and August is low. The disadvantage is the greater risk of disease because of high humidity. Generally, ET_o is less variable than rainfall. Tilahun, (2006b) reported that in the semi-arid tropics the temperature and reference evapotranspiration do not vary greatly and therefore what governs the effect of climate on crops is the variable element of rainfall.

The third climate parameter for indicating crop suitability that we considered in this study was rainfall. The duration of the rainy period in the Giba catchment ranges from 60 to 100 days, which is very short compared with the time the crop spends in the field (3 to 4 months). Thus most crops grown in the Giba catchment suffer from moisture stress during their growth.

The growing period from pentads 33 to 38 corresponds to the time of sowing and early crop establishment for barley depending on the onset of rain. The rainy season in semi-arid Africa usually starts with small rains followed by dry spells (Barron et al., 2003; Raes et al., 2004). The period (pentads 33 to 38) has been facing unacceptably higher numbers of false starts (germination fails due to insufficient rain). The farmers call such false starts 'Aramts' or 'Afakus'. In the period, the long-term 80% dependable rainfall hardly crosses the 0.5 ET_o per pentad (Figure 2.3) and is erratically distributed (Figure 2.4 (b)). Many agriculturists in the catchment reported that every three to four years crops had failed due to a false start (Araya, 2005). Through experience, farmers have developed two risk-avoidance mechanisms: i. replanting with a quickly maturing crop ii. dry planting drought-resistant crops adapted to the area. Dry planting succeeds if the rain comes early: a severe dry spell at the start of growing season usually leads to crop failure. An assessment of dry planting over twenty years showed a failure rate of about 25 to 30% (Araya, 2005). If the first crop fails, farmers replant with a different variety or crop, but sometimes they leave the land fallow if they do not have enough draught power. Barley is normally sown on dry soil or after one to two showers of rain. However, the time of sowing in the 1st period (pentads 33-38) varies slightly from station to station in the study area. At Abyadi and H/selam the sowing times were earlier than at the other stations in the study area (see Figure 2.5).

The 2nd period (pentads 39/40 to 49/50) represents the peak rainy period, which coincides with the crop vegetative stage in the case of barley and to the time of sowing and vegetative stage in the case of teff. The period generally has more rainfall: in most cases the 80% dependable rainfall is close to or above the potential evapotranspiration (see Figure 2.3) and the probability of dry spells is low. Teff is normally planted in the peak rain period in order to ensure successful seed germination and establishment. However, as in most plants, the vegetative stage is relatively resistant to shortage of water. During its vegetative growth, teff encounters high humidity and low temperature, and sometimes waterlogging. This usually results in slow growth, but unlike barley, teff tolerates waterlogging. In barley fields, problems with aeration associated with excess water in poorly drained low-lying soils are commonly observed during this period, resulting in stunted growth and sometimes total crop failure. As reviewed by Setter and Waters (2003), soils with less than 10% air porosity are associated with waterlogged conditions. Grain yield of barley was reported to reduce when the crop is waterlogged at early growth of the crop (2 to 6 weeks after planting) than at mid or late stage (after 10-14 weeks) (Setter and Waters, 2003). There are few records of failure of teff or barley caused by a false start in the 2nd period. At the end of the 2nd period (around pentad 50) rainfall has almost ceased and is characterized by high variability and long and frequent dry spells (Figure 2.4 (a) and (b)).

In the 3rd period (pentads 50/51 to 54), crops depend on reserves of soil moisture and start to suffer from moisture stress. Both barley and teff crops reach at the heading stage, which is very sensitive to drought stress. Late-sown crops are particularly likely to be exposed to these types of late season drought. Therefore, most crop loss due to moisture stress occurs in the 1st and 3rd periods, hence we recommend paying more attention to the problem by planning a better rainwater management strategy for the 1st and 3rd periods.

In general, the rainfall in the Giba catchment varies within and between seasons. Others have also reported great spatial and temporal seasonal rainfall variability (Simane and Struik, 1993; Araya, 2005; Tilahun, 2006a; Bewket and Conway, 2007).

All this demonstrates that rainfall is the most important climatic determinant of crop-growing conditions in the Giba catchment. Therefore, understanding the rainfall distribution within and between seasons as well as the onset and cessation of the rain contributes to knowledge of the LGP and indirectly indicates the climatic suitability of the crop. Studies have verified that a difference of 10 – 20 days in LGP produces differences not only in yield but also in the farmers' choice of crops and crop varieties (Araya and Stroosnijder, in preparation). For example, there are some differences in cropping pattern between the west and east of the Giba catchment. The minimum LGP (60 days) occurs in the north-east of the catchment, an area where the main crops grown are quick-maturing crop varieties of barley and teff. On the other hand, some medium-maturing varieties of barley wheat, maize, teff and horse bean are grown in certain areas in the south-west of the catchment, where the LGP is longer (80 to 100 days). Therefore, in semi-arid regions, a climate classification like the one we present here is vital to ensure that the farmers grow crop varieties according to their climatic requirements. Taking into account the climate change scenario, mechanisms for adapting to climate change could be established by considering the agro-climatic zones. Long- and short-term cropping strategies will be developed and this will lead to agricultural sustainability and food security in the region.

2.5 Conclusion

To conclude, the Ethiopian traditional method of climate classification based on temperature and altitude was found to be less relevant to crop suitability zoning in semi-arid regions of Northern Ethiopia. This is because within this semi-arid drought-prone environment the rainfall is more important for crop growth than temperature. In the tropics the annual ranges of temperature and reference evapotranspiration are small. However, temperature may also be helpful when determining the crop-growing degree days. For this reason, in this paper we have combined rainfall and evapotranspiration with temperature and altitude, and have used this comprehensive agro-climatic input to generate a crop suitability classification system. Using this agro-climatic system, we classified the Giba catchment into two LGP zones and combined these with five traditional climate zones to give eight agro-climatic zones. We conclude that areas WD1, K3, and K1 of the of the Giba catchment are moderately suitable for medium-maturing varieties of teff whereas areas WD2, K2 and D2 are moderately suitable for quick-maturing teff varieties. D1 and WD1 are suitable for medium-maturing barley varieties whereas D2 and WD2 are suitable for quick-maturing varieties. Using this method, the most important climate elements are integrated to easily demonstrate and demarcate the crop suitability of an area at a scale smaller than a sub-catchment. Our climate classification system may help farmers to cope better with drought stress and help agronomists to adapt crops in line with climate change scenarios. This climate classification may also have a positive impact on environmental sustainability.

Chapter 3

Assessing drought risk and irrigation need in northern Ethiopia

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Assessing drought risk and irrigation need in northern Ethiopia

Abstract

Long-term climate data of four stations in the northern Ethiopia were analysed in combination with information from local farmers and documented materials. From this analysis, a suitable drought-assessing technique was developed and site-specific needs for supplementary irrigation were explored. Results showed that our technique for assessing drought and crop failure corresponded well with farmer observations. The three major causes of crop failure (dry spells, short growing period and “total lack of rain”) which were explicitly listed and ranked by the local farmers were found to match the analysed data well. The agro-meteorological variables with the most severe consequences were “short growing period” and “total lack of rain”. To prolong the growing period, supplementary irrigation is recommended in the month of September for three of the stations (Maychew, Mekelle and Adigudom) because: (1) rain frequently stops in early September or late August and crops have no other source of water for the rest of the growing period; (2) sufficient surface runoff can be harvested in July and August to be stored in farm ponds and used in September (3) more cultivable land can be irrigated if supplementary irrigation is scheduled only for the month of September and (4), giving supplementary irrigation in September can cut yield reduction by over 80% and crop failure by over 50%, except at Alamata. At Alamata, supplementary irrigation must be scheduled for July. The conditions experienced during the famine years of the early 1980s were primarily caused by the continued total rain failure over multiple years. Giving supplementary irrigation in July or September would probably not have mitigated the effects of these droughts, especially at Alamata and Maychew stations.

3.1 Introduction

The Ethiopian economy is based on agriculture. It is also the source of income for about 80% of the labor force in Ethiopia (Bewket and Conway, 2007). Natural rainfall is the major source of water for agriculture. Assessing seasonal or dekadal[*] rainfall characteristics based on past records is essential to evaluate drought risk and to contribute to development of drought mitigation strategies such as supplementary irrigation.

Rainfall variability has been reported to have significant effect on the country’s economy and food production for the last three decades. There have been reports of rainfall variability and drought- associated food shortages (Tilahun, 1999; Bewket and Conway, 2007). In most cases, what determines crop production in semi-arid areas of Africa is the distribution rather than the total amount of rainfall, because dry spells strongly depress the yield (Barron et al., 2003; Segele and Lamb, 2005; Meze-Hausken, 2004).

Early onset of the rainy season leads to crop germination, since most farmers sow in dry soil. If a long dry spell follows, the seedlings die – a “false start” (Ati et al., 2002; Raes et al., 2004; Kipkorir et al., 2007) – and often the crop must be resown. The major causes of crop failure in northeastern Ethiopia are frequent dry spells of about 10 days length, as well as a shorter growing period due to replanting or late onset and/or early cessation of rain (Segele and Lamb, 2005, Araya et al., 2010a). Reliable estimation of onset and cessation of

[*] We use the term dekad for a period of 10 days

rain could help optimize rainwater use in semi-arid areas (Sivakumar, 1992; Ati et al., 2002; Raes et al., 2004; Kipkorir et al., 2007; Mugalavai et al., 2008).

Dry-spell analysis has been carried out in various parts of Africa. Many authors define a dry spell as *n* consecutive days without appreciable rainfall (Stern, 1980; Sivakumar, 1992; Sharma, 1996; Ceballos et al., 2004; Gong et al., 2005). In many studies, days with rainfall less than 0.1 mm per day are considered a dry spell. The severity of dry spells depends on their frequency and duration and on the crop stage during which they occur. However, sometimes such analysis may not be useful for assessing whether the crop water demand will be met, for three reasons: (i) it does not consider the evaporative demand of the atmosphere; (ii) a day of rainfall with little agronomic effect may be counted as a wet day and (iii) effective rainfall is not considered.

Given that agriculturists are mainly concerned with actual crop water stress, the analysis would be more meaningful if it considered dry spells in relation to meeting crop water demand (Barron et al., 2003). Moisture deficit and the crop-growing risks and suitability of rain-fed agriculture can be evaluated on the basis of relationships between rainfall and reference evapotranspiration (Tilahun, 2006; Araya et al., 2010a). However, effective rainfall, not total rainfall has to be considered, because in semi-arid northern Ethiopia a substantial amount of the rainfall is lost as runoff (Araya and Stroosnijder, 2010). Crop water stress becomes severe when the available water meets less than half the crop water demand (Doorenbos and Kassam, 1979). Thus, one way of analysing dry spells is to describe the dekadal effective rainfall in relation to the dekadal reference evapotranspiration. A dry spell in our case is thus any dekad in which effective rainfall is less than 50% of the dekadal reference evapotranspiration, whereas a wet spell is any dekad in which effective rainfall exceeds 50% of the dekadal reference evapotranspiration.

There are many definitions of drought, but from the viewpoint of local people, drought is any season with low rainfall in relation to crop water demand that results in poor crop harvest or total crop failure and/or livestock suffering or dying from because of feed shortages as a consequence of poor rainfall distribution/amount. Dry spells affect a crop when only a small amount of soil water is available to the crop due to reduced soil water holding capacity.

A dry spell can occur at the start, mid, or late season of the crop. When dry spells occur at the late season stage of the crop, the growing season is shortened. Late season drought has been reported to reduce yields significantly at Mekelle in northern Ethiopia (Araya et al., 2010a). Despite the risk of drought and the vulnerability of the people to the recurrent drought, little has been done to develop techniques for assessing drought risk and to determine how and which variables are related to crop failure circumstances in the northern Ethiopia.

There are various techniques for assessing and predicting drought. Each has merits and limitations (Alley, 1984; Guttman, 1991; Heddinghaus and Sabol, 1991; Guttman, 1998). In this study we set out to develop a simpler technique that can be used to assess the occurrence of past drought (crop failure) years easily and adequately for northern Ethiopia.

Drought can be mitigated by various agronomic and water conservation methods and with supplementary irrigation. The objectives of this paper are: (1) to analyse critically the quality of past growing seasons in northern Ethiopia in order to elucidate the main causes of crop failures (2) to develop a simple suitable drought assessment technique and (3) to study the probability of occurrence of drought and indicate site-specific time and quantity recommendations for supplementary irrigation as a drought-coping strategy. Data from four rainfall stations in northern Ethiopia, each with 30 to 46 years of observation, and on two major crops: barley (*Hordium vulgare*) and teff (*Eragrostis tef*) were studied.

3.2 Materials and methods

3.2.1 Site and data description

The study site is located in northern Ethiopia (longitude 39° 5′- 39° 8′ and latitude 12° 3′-13° 7′) and has four climate stations (Figure 3.1). The climate is characterized by bimodal rainfall. About 70 - 80% of the rain falls in the Kiremt season (June to September) (Araya et al., 2010a). There is great inter-annual spatial and temporal rainfall variation. The mean minimum and maximum temperature range is from 8 °C to 30 °C, with small annual variations. In all months except the month of August, the dekadal reference evapotranspiration exceeds the mean dekadal rainfall.

In this area, the agriculture is mixed crop and livestock farming. Land degradation and deforestation are among the major problems caused by human factors in the area (Hurni, 1990; Nyssen et al., 2000; Meze-Hausken, 2004). The fertility of the agricultural lands is deteriorating. In this area of Ethiopia the soils are shallow (<0.5 m) and have poor water-holding capacity.

The major crops in the study area are barley, teff, sorghum, chick pea and wheat. Early-maturing and drought-resistant crop cultivars are widely grown (Meze-Hausken, 2004). The growing period starts in early July and ends in early to late September, with a rainy period of a maximum of 80 days (Araya et al., 2010a). More than 95% of the arable land is cultivated without irrigation.

The site was chosen not only due to availability of relatively long series of meteorological data but also because recurrent drought is common in this part of the country. As the farmers in this area have frequently experienced drought, their perceptions of drought and crop failure are valuable to consider when analysing climatic data.

Daily weather data such as rainfall, sunshine, temperature, humidity and wind were obtained from the Ethiopian Meteorological Services Agency. Seasons with missing daily values were excluded from the analysis. The homogeneity of all dekadal, monthly, seasonal and annual rainfall records were proved based on Buishand (1982).

Two stations had shorter periods (30 years) of observation than the other two (44 and 46 years) (Table 3.1). There have been reports of climatic variability over the region (Tilahun, 2006; Araya et al., 2010a). Therefore the comparisons of stations for different kinds of analysis were done using only the years common to all stations (1978 – 2008). However, full data sets from each station were also used to describe the situation, especially when evaluating the drought assessment technique.

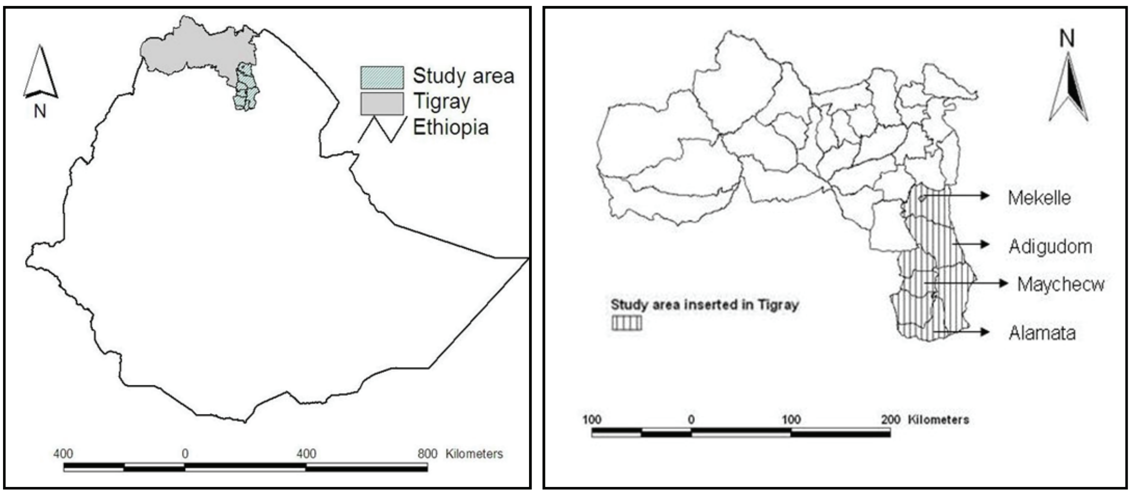

Figure 3.1. Map of the study area in Tigray region in north Ethiopia.

Table 3.1. Details of the four rainfall stations in north Ethiopia used in this study.

Station	Altitude (m)	Years of observation	Number of years with no data
Alamata	1700	1975-2008	2
Maychew	2800	1953-2008	11
Mekelle	2112	1960-2008	2
Adigudom	2050	1978-2008	1

3.2.2 Farmers' information

About 500 farmers in the study area, in teams or as individuals, were invited to characterize and classify past growing periods. They were able to list most of the years with abundant rainfall and many of the drought years, including the infamous 1984/85 drought. In addition, data was gathered from the Ministry of Agriculture and the statistical authority offices. We compared our analysed information with that from the farmers. We designated farmers' data "observed" data and compared it with the analysed data (''calculated'') from the four climatic stations.

Farmers and extension workers were asked to list and then rank the cause of crop failure in the study area. Our ranking of the analysed data was then compared with the farmers' rankings.

3.2.3 Analysis of onset, cessation and length of growing period (LGP)

The onset and cessation of the rainy period were determined from the rainfall-reference evapotranspiration relationship. This approach was presented in Ati et al. (2002) and was validated with slight modification for this region by Araya et al. (2010a). Accordingly, onset was assumed to occur; (1) after 15 June when long-term cumulative 5-day rainfall is greater than or equal to the cumulative half of the 5-day reference evapotranspiration and (2) a greater ratio of rainfall to reference evapotranspiration for at least two consecutive pentads during which period the rainfall sum exceeds 25 mm and within 30 days there is no dry spell of more than 7 consecutive days.

Similarly the growing period was assumed to cease after 20 August (1) a week after half of the 5-day cumulative rainfall is less than the 5-day cumulative reference evapotranspiration and (2) this must be followed by a dry period of more than 10 days. The length of the growing period (LGP) was considered as the period from the onset to the cessation of rain. Frequency analyses were performed for both onset and cessation of the rainy period and were grouped as early, normal and late over the observation period for each of the stations. A frequency analysis was also performed for LGP.

3.2.4 Analysis of reference evapotranspiration, dry and wet spell data analysis

Dekadal reference evapotranspiration (D_{ETo}) was computed using the Hargreave's equation for all stations in the study area. In addition, for those stations with full data sets, the D_{ETo} was computed using the FAO-Penman–Monteith method. The estimates of Hargreaves's equation were compared with the estimates of FAO-Penman–Monteith at one of the stations (Mekelle) where wind speed, humidity, temperature and sunshine hours are measured. Since the estimates with the limited data sets are less accurate (they differed slightly from the estimates calculated from the full data set), the ratio method was then used to calibrate the estimates of the Hargreaves equation for all stations in the study area. Validation revealed that ET_o values estimated with FAO Penman–Monteith at another station (Maychew) in the study area where wind speed, humidity, temperature and sunshine hours are measured agreed well with the corresponding calibrated estimates of the Hargreaves's equation for the same station. FAO Penman-Monteith analysis was carried out using ET_o software (FAO, 2009).

Dekadal rainfall and reference evapotranspiration during the growing period from the 1 July to 30 September were computed. Effective rainfall per dekad (Barron et al., 2003) was also calculated based (Equation 3.1) on the following relationship:

$$D_{Eff} = D_{Rain}(1 - 0.25) \qquad [3.1]$$

Where:

D_{Eff} is the dekadal effective rainfall (mm).

Effective rainfall in this case is the amount of rainfall infiltrated into the soil.

D_{Rain} is dekadal rainfall.

The factor 0.25 accounts for the estimated average runoff of 25% (Araya and Stroosnijder, 2010).

Dry spell occurrence in a dekad was analysed and presented in two ways:

(*i*). When the ratio of dekadal effective rainfall to the dekadal reference evapotranspiration was <0.5 in any one of the dekads between onset and cessation of rain.

(*ii*). The percentage frequency of dry dekad was computed and evaluated for given sets of effective rainfall thresholds (10, 20, 30, 40 and 50 mm). Such analysis reveals how dry or wet the dekad was in relation to those five amounts of effective rainfall (Sivakumar, 1992). For most of the stations in the study area, at least 20 mm of effective rainfall in a dekad was considered to be the threshold for meeting the 50% dekadal evapotranspiration. Any reduction or increment beyond this threshold level demonstrated how the frequency of a dry or a wet dekad changes with the amount of effective rainfall. The probability of a dry dekad (Equation 3.2) in relation to a set amount of effective rainfall was calculated as:

$$P_d = \left[\frac{n}{N}\right]100 \qquad [3.2]$$

Where:

P_d, is probability of a dry dekad receiving less than a given threshold of effective rainfall.

n is the number of seasons with a dry dekad, based on the given threshold limit

N is the total number of seasons.

Similarly, wet spells described in dekads were analysed and presented in two ways:

(i) a wet dekad was deemed to occur when the ratio of D_{Eff}/D_{ETo} > 0.5 (ii) the probabilities of wet dekads were also calculated according to equation 3.3.

$$P_w = \left[\frac{n}{N}\right]100 \qquad [3.3]$$

Where:

P_w is the probability of a wet dekad receiving effective rainfall above a given threshold.

n is the number of seasons with a wet dekad.

N is the total number of seasons.

The frequency of wet dekads was computed and evaluated for thresholds above a given amount of effective rainfall (10, 20, 30, 40 and 50 mm).

A false start was defined as occurring when the ratio of dekadal effective rainfall to the dekadal reference evapotranspiration is > 0.5 in the onset dekad followed by a dekad s^{-1} < 0.5 in the dekad s^{-1} following the onset dekad. This condition was evaluated for up to 30 days following sowing. The occurrence of a false start can also be evaluated by considering the relative transpiration or evapotranspiration rate over the 30-day period following sowing (Raes et al., 2004; Kipkorir et al., 2007). As most farmers in northern Ethiopia sow their seeds in dry soil, the seed will germinate only when the rainfall wets the top 0.1 to 0.2 m of the soil (Araya, 2005). According to local farmers, a false start (locally called '*Afakus*' or '*Aramst*') occurs when a dry period longer than a dekad occurs after germination. Thus we assumed failure or false start when a D_{Eff} did not meet at least half of the D_{ETo} over the 10-day period following sowing. But if onset of rain was late, we considered the 1st rain after sowing as onset, as long as the seed had not been in the soil for over 10 days (seeds may also fail to germinate if they stay too long in the soil).

The inter-annual dekadal rainfall variability is shown by the coefficient of variation:

$$CV = \left[\frac{S}{X}\right]100 \qquad [3.4]$$

Where:
CV is the coefficient of variation.
X is the average long-term rainfall over the given dekad.
S is the standard deviation of the dekadal rainfall.

Since rainfall in semi-arid environments is erratically distributed and unreliable, analysing dependable rainfall is vital (Tesfaye and Walker, 2004). This helps to understand to what extent the rainfall meets the evaporative demand of the atmosphere in 1, 2, or 3 years out of a total of 4 years. Thus, for each station the 25%, 50%, and 75% dekadal dependable rainfall was compared with the dekadal mean reference evapotranspiration. The dependable precipitation was determined using the Weibul's method and was best-fitted using the normal distribution with r^2 of greater than 0.85. The analysis was done using the RAINBOW program (Raes et al., 1996).

3.2.5 Seasonal drought and trend

Seasonal drought indices were calculated based on equation 3.5.

$$DI = \left[\frac{M - Z}{S}\right] \qquad [3.5]$$

Where:
DI is dekadal average drought index for the season.
M is the average of the ratio of dekadal effective rainfall to dekadal reference evapotranspiration for each season.
Z is the long-term average ratio of dekadal effective rainfall to dekadal reference evapotranspiration.
S is standard deviation from the average ratio of the long-term dekadal effective rainfall to dekadal reference evapotranspiration.

A drought index above 1 was set at 1 because excess water was considered as loss. This assumption is particularly valid in shallow soils with low water-holding capacity as is the case in northern Ethiopia. The season was deemed to be dry when DI was < -0.5 and/or when the number of wet dekads was less than 6 for Maychew, Mekelle and Adigudom and less than 5 for Alamata (due to the effect of high temperature on shortening of the growing period); it was deemed to be a normal season when DI was > -0.5 and when the number of wet dekads was $\geq$ 6/5; and wet when DI was > 0.5 and when the number of wet dekads was > 7.

Seasons shorter than 6 wet dekads in Maychew, Mekelle and Adigudom were considered to be crop failure seasons. In the Alamata area, the crops mature earlier due to the high temperature, so here seasons shorter than 5 wet dekads were considered to be failures. We designated seasons with < 6/5 and > 5/4 wet dekads as 1^{st} class short growing seasons (1^{st} CSGS). They have a small number of growing days that can lead to yield reduction or yield loss but do enable the farmers to obtain some biomass yield for their livestock. By contrast, season's < 5/4 wet dekads were deemed to be total failures ("total rain failure") and grouped in this study as 2^{nd} class short growing season (2^{nd} CSGS).

A time series (1978 – 2008) trend analysis was carried out on the basis of the calculated drought indices.

3.2.6 Irrigation need

Before estimating irrigation water requirement of teff and barley, we analysed the length of growing period (LGP) for teff and barley at the stations in the study area, because knowledge of the LGP would help calculate the crop water requirement for the period during which the crop is in the field. The LGP of the crops was estimated from their degree days and interviews with farmers. Teff and barley require about 85 to 90 days (920-1105 degree days) to mature (Araya et al., 2010b, and c). Degree days (Equation 3.6) were calculated as presented in McMaster and Wilhelm (1997):

$$DD = \sum_{i}^{n} \left[\frac{T_{\min} + T_{max}}{2} - T_b \right] \qquad [3.6]$$

Where:

DD is the accumulated degree day (^{o}C day).

T_{min} is the mean minimum daily air temperature (^{o}C).

T_{max} is the mean maximum daily air temperature.

T_b is the base temperature below which crop development does not progress (^{o}C). T_b was assumed to be 7 ^{o}C (unpublished).

Dekadal crop water requirement for teff and barley from planting to maturity was then calculated according to equation 3.7.

$$ET_c = k_c \times ET_o \qquad [3.7]$$

Where:

ET_c is dekadal crop water requirement (mm).

k_c is crop coefficient.

ET_o is dekadal reference evapotranspiration (mm).

Irrigation water requirement was computed according to equation 3.8

$$In = ET_c - DR_{75\%} \qquad [3.8]$$

Where:

In is irrigation water requirement (mm).

$DR_{75\%}$ is the 75% dependable rainfall for the dekad (Garcia, et al., 2003).

3.3. Results

3.3.1 Dry spells and rainfall variability

Table 3.2 shows the long-term mean dekadal effective rainfall and coefficient of variation for the stations in the study area. A CV > 30% is an indicator of large rainfall variability. The decadal rainfall variability in the study area was high.

Probabilities of receiving a minimum of 10, 20, 30, 40, and 50 mm of effective rainfall per dekad are presented in Figure 3.2a-d. The mean seasonal dekadal reference evapotranspiration was 52 mm for Alamata, 41 mm for Maychew, 38 mm for Mekelle and 38 mm for Adigudom. The probability of receiving more than 40 mm effective rainfall per dekad at most of the stations ranged from 20 to 50% for dekads in July, 40 to 70% for dekads in August, and 0 to 30% for dekads in September. At Mekelle station the probability of receiving more than 40 mm effective rainfall in the dekads in August was higher than in the other three stations. At all stations the probability of receiving 40 mm effective rainfall in the dekads in September was lower.

Table 3.3 shows probability of occurrence of a dry dekad below the threshold limits of 10, 20, 30, 40 and 50 mm effective rainfall for the four stations. Assuming 20 mm as threshold limit, the probability of a dry dekad occurring at the stations in July and August varied from 20 to 64 % in Alamata; from 15 to 43% in Maychew; from 0 to 27% in Mekelle; and from 17 to 48% in Adigudom, whereas the probability of occurrence of a dry dekad for the dekads in September over the corresponding stations were 64 – 100% in Alamata; 48 – 82% in Maychew; 59 - 100% in Mekelle and 47 - 100% in Adiguom. At all stations the probabilities of occurrence of dry dekad increased sharply after the 2nd dekad of September and was higher at Mekelle and Adigudom (83 - 100%) than at Alamata and Maychew (55 - 76%).

Figure 3.3 shows three levels of dependable rainfall for all the stations: 25% (the rainfall equalled or exceeded in 1 out of a total of 4 years), 50% (the rainfall equalled or exceeded in 2 out of a total of 4 years) and 75% (the rainfall equalled or exceeded in 3 out of a total of 4 years. Although 9 dekades were analysed, the numbers of wet dekads in the study area were < 8. The rainfall received in three out of four years (75% dependable) was lower than the mean reference evapotranspiration for the respective dekad in at least 7 of the 9 growing dekads, except for the Mekelle station which met this condition for only 4 dekads. The number of dekads during which the 50% dependable rainfall exceeded reference evapotranspiration was 3 for Alamata, 4 for Maychew, 6 for Mekelle and 5 for Adigudom. This implies that the rainfall received per dekad has been unreliable and too low to meet the water requirement of most cereals. Mekelle station meets the condition in 6 dekads out of the 9 growing dekads and received more rainfall than the other stations, whereas at Alamata the condition was met in only 3 of the 9 growing-season dekads.

Figure 3.4 shows time series of mean annual drought indices. The early 1980s were drought years (indices -0.6 to -1.5) while the 1990s and later were normal. In most years after 1990, the pattern and trend of the drought indices were similar for all stations, but before 1990 there were different patterns for the different stations.

Table 3.2. Long-term (1978 – 2008) mean dekadal effective rainfall and coefficient of variation for four rainfall stations in north Ethiopia.

Month	Dekad	Alamata			Maychew			Mekelle			Adigudom		
		Effective rainfall (mm)	SD (mm)	CV (%)	Effective rainfall (mm)	SD (mm)	CV (%)	Effective rainfall (mm)	SD (mm)	CV (%)	Effective rainfall (mm)	SD (mm)	CV (%)
July	J1	20	22	110	25	21	87	41	28	70	27	21	77
	J2	26	21	82	38	30	78	42	21	49	42	29	69
	J3	41	38	94	50	35	70	65	38	59	55	38	69
August	A1	51	31	61	55	26	48	60	30	50	56	43	77
	A2	52	35	68	56	35	62	57	33	57	58	47	81
	A3	43	30	69	43	28	64	51	33	64	49	40	81
September	S1	20	16	79	24	17	70	22	27	121	27	29	107
	S2	8	7	95	14	13	92	4	8	171	3	7	261
	S3	12	11	89	12	17	135	1	1	142	1	2	327
Summer seasonal mean		29.8	23.8	84.8	34.9	25.9	82.8	37.9	22.1	80.6	34.1	27.9	139.2

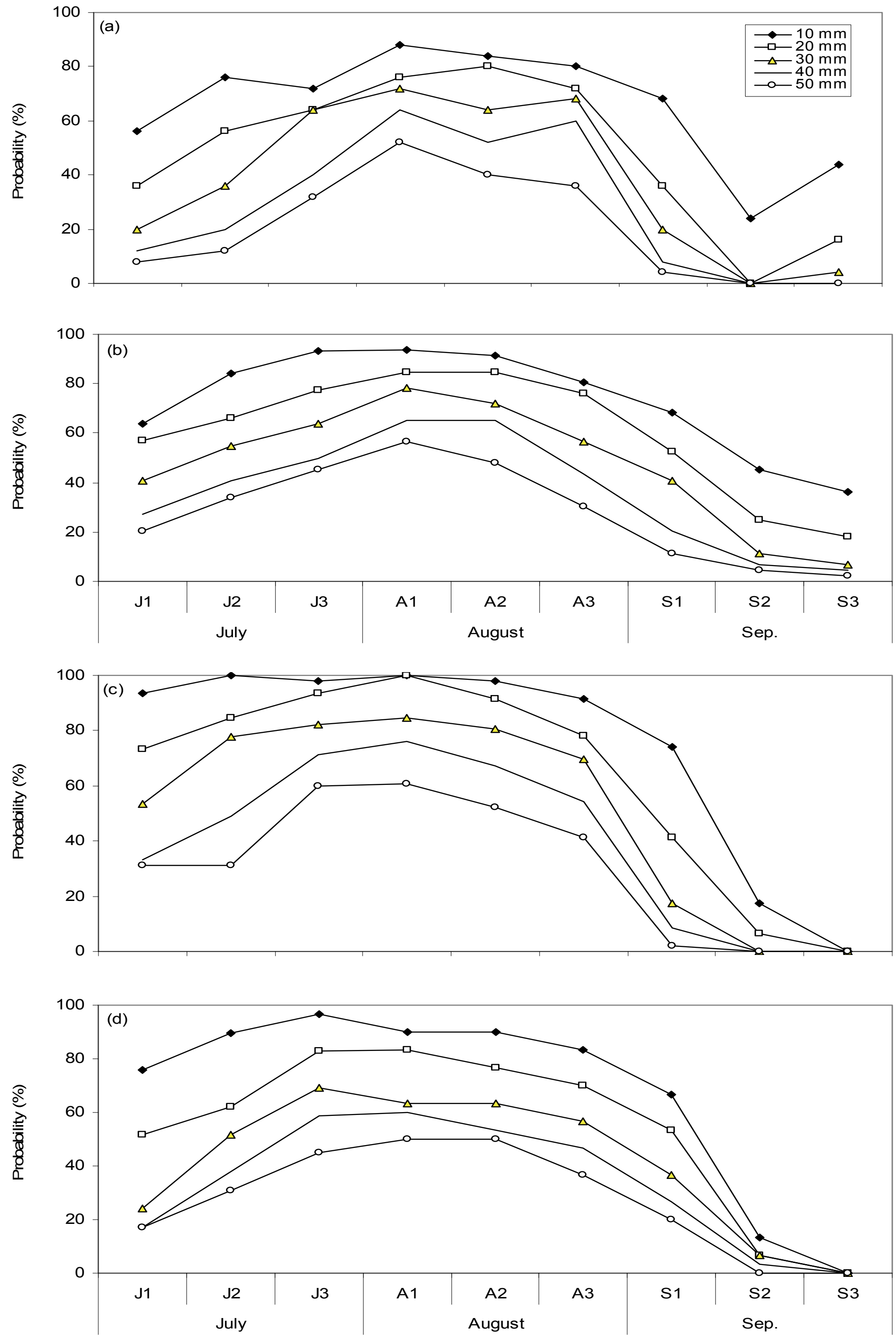

Figure 3.2a-d. Probabilities (%) of receiving a minimum of 10, 20, 30, 40, and 50 mm rainfall in a dekad during the growing season (July-September) for four stations in north Ethiopia: (a) Alamata, (b) Maychew, (c) Mekelle and (d) Adigudom.

Table 3.3. Probabilities (%) of occurrence of a dry spell in a dekad below a threshold limits of 10, 20, 30, 40 and 50 mm effective rainfall for four stations in north Ethiopia.

		Alamata					Maychew				
Month	Dekad	10 mm	20 mm	30 mm	40 mm	50 mm	10 mm	20 mm	30 mm	40 mm	50 mm
	J1	44	64	80	88	92	36	43	59	73	80
July	J2	24	44	64	80	88	16	34	45	59	66
	J3	28	36	36	60	68	7	23	36	50	55
	A1	12	24	28	36	48	7	15	22	35	43
August	A2	16	20	36	48	60	9	15	28	35	52
	A3	20	28	32	40	64	20	24	43	57	70
	S1	32	64	80	92	96	32	48	59	80	89
September	S2	76	100	100	100	100	55	75	89	93	95
	S3	56	84	96	100	100	64	82	93	95	98

		Mekelle					Adigudom				
Month	Dekad	10 mm	20 mm	30 mm	40 mm	50 mm	10 mm	20 mm	30 mm	40 mm	50 mm
	J1	7	27	47	67	69	24	48	76	83	83
July	J2	0	16	22	51	69	10	38	48	62	69
	J3	0	7	18	29	40	3	17	31	41	55
	A1	0	0	15	24	39	10	17	37	40	50
August	A2	2	9	20	33	48	10	23	37	47	50
	A3	9	22	30	46	59	17	30	43	53	63
	S1	26	59	83	91	98	33	47	63	73	80
September	S2	83	93	100	100	100	87	93	93	97	100
	S3	100	100	100	100	100	100	100	100	100	100

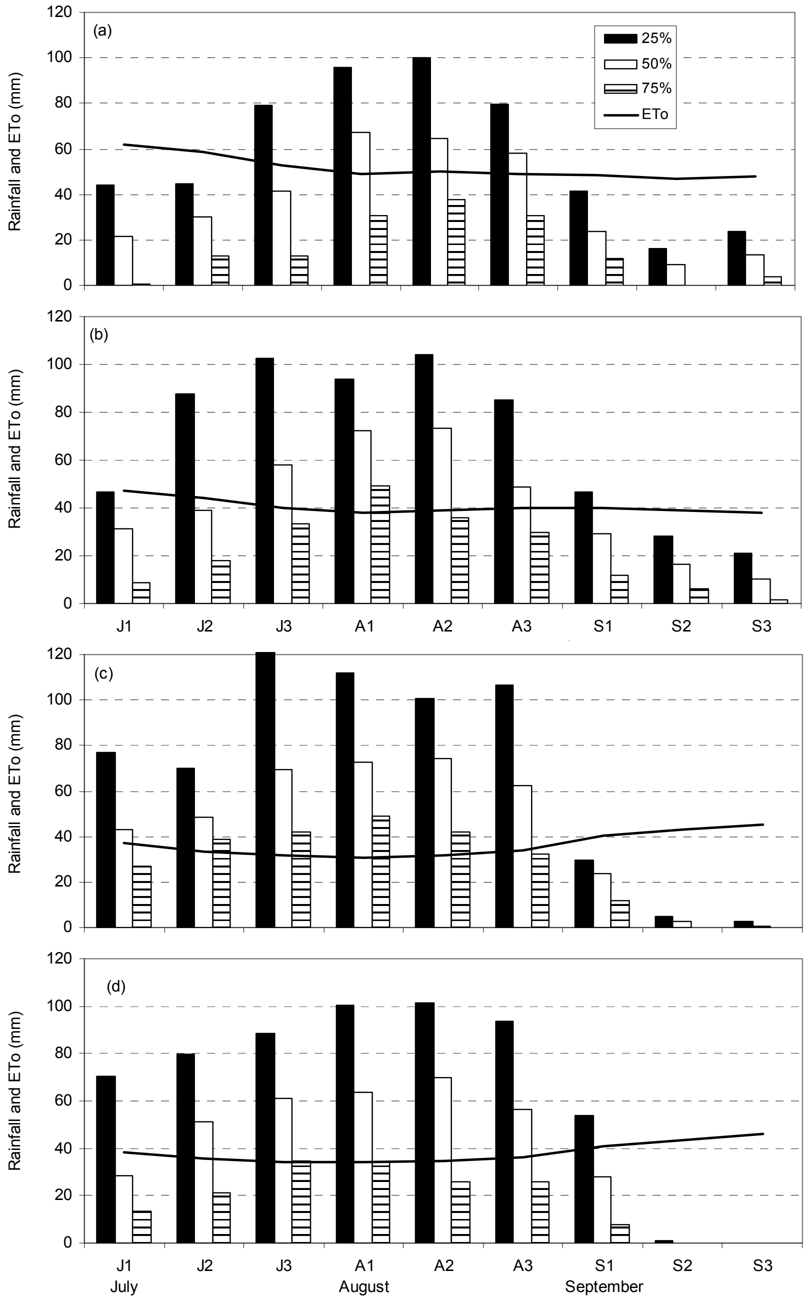

Figure 3.3a-d. Long-term (1978 – 2008) 25%, 50% and 75% dependable rainfall versus mean dekadal reference evapotranspiration for (a) Alamata, (b) Maychew, (c) Mekelle and (d) Adigudom in north Ethiopia.

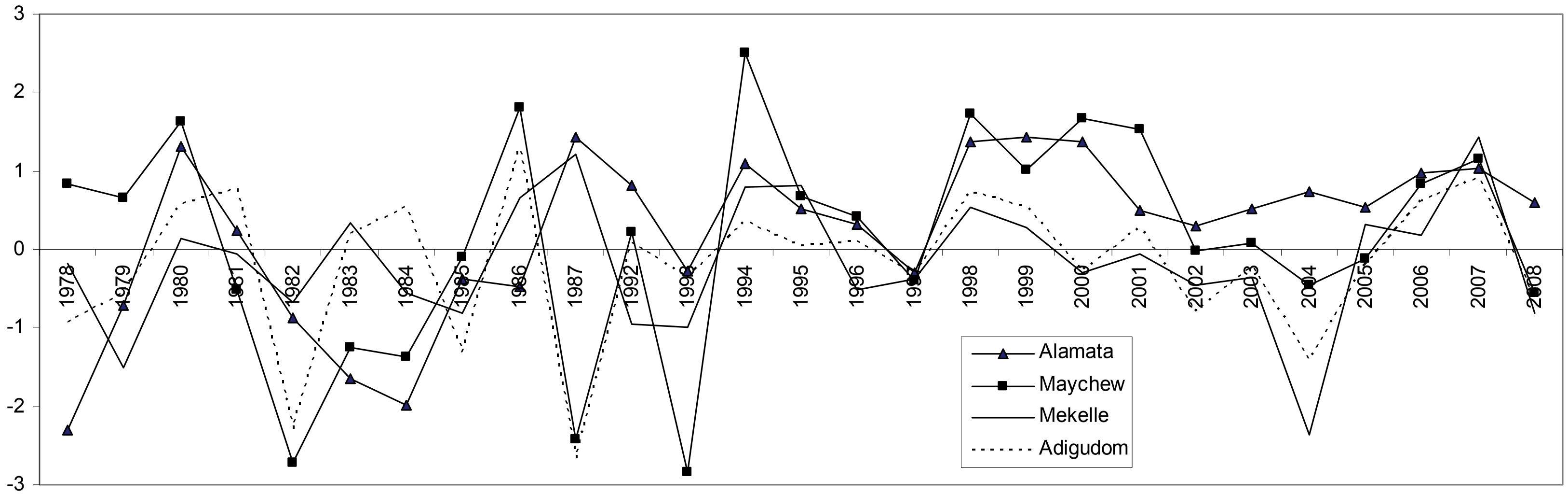

Figure 3.4. Time series mean (1978 - 2008) dekadal drought indices for four rainfall stations in northern Ethiopia: (Filled triangle, Alamata; filled box, Maychew; straight line, Mekelle; dotted line, Adigudom).

3.3.2 Onset, cessation, length of growing period and crop failure

Probabilities for onset, cessation and length of growing period, calculated for the period 1978 – 2008, are presented in Table 3.4. The farmers' sowing practices were compared with the analysed onset and it was found that the analysed onset agreed well with the farmers' sowing practice. The onset at Mekelle was less variable than that at the other stations; the onset at Alamata was the most variable. According to the survey, the farmers' sowing practices can be grouped into three: July 1 – 10 (early); July 11 - 20 (normal) and July 21 - 30 (late). In contrast to the Alamata and Maychew areas, in the Mekelle area farmers do not deliberately sow late: they sow late only if they do not have enough labour or oxen to sow on time.

Table 3.4. Probabilities (%) of the long-term (1978 – 2008) onset and cessation of rainy period.

Growing season	Dekad	Alamata	Maychew	Mekelle	Adigudom
Onset	July1-10	24	41	89	50
	July 11-20	28	22	11	18
	July 21-30	20	11	0	11
	Failure	24	26	0	21
Cessation	Aug.21-30	25	18	41	25
	Sep.1-10	46	43	44	46
	Sep.11-20	4	7	4	4
	Sep.21-30	0	4	11	4
	Failure	25	28	0	21

Failure: is a season with very poor rainfall distribution (no onset and cessation).

The most frequent cessation of growing period was September 1 - 10. The cessation of growing period over the study area was more variable than the onset of the growing period. Contrary to the findings for the onset of growing period, at Alamata the cessation of growing period was less variable than at the other stations. Early cessations were more frequent at Mekelle than at the other stations.

The LGP of the major crops (teff and barley) was calculated to be 60 days at Alamata, 87 days at Maychew, and 85 days each at Mekelle and Adigudom. The LGP calculated from the degree days agreed well with the actual duration of crop-growing period in the study area. However, the length of growing period (LGP) for the major crops grown in the study area was too long to match the long-term season LGP analyzed on the basis of the difference between onset and cessation. For example, teff and barley require more than 80 days (from sowing to maturity) but most of the analysis of length from onset to cessation falls below 70 days.

Table 3.5 shows percentages of occurrence of drought, normal and wet seasons over the past years as determined with the technique described in section 2.5. The estimated crop failure due to drought was 50% at Alamata, 48% at Maychew, 36% at Mekelle and 59% at Adigudom (Table 3.5). Dry spells can occur at any time between sowing and maturity. Long and frequent dry spells at sowing and/or during flowering time may drastically reduce the crop yield.

Table 3.5. Percentage of occurrence of drought, normal and wet years determined using the technique described in the text (section 3.2.5).

Stations	Drought	Normal	Wet	Years
Alamata	50	43	7	1978-2008
Maychew	48	41	10	1978-2008
Mekelle	36	61	4	1978-2008
Adigudom	59	36	5	1978-2008

The contribution of dry spell to crop failure was 8% at Alamata, 23% at Maychew, 40% at Mekelle and 8% at Adigudom stations (Table 3.6). Obviously, false starts resulting from early season dry spells also contributed to the total crop failure: in the study area the contribution was up to 20%.

Table 3.6 Percentage of contribution to total crop failure of the three variables, ''short growing period'', ''dry spell'' and ''total failure of rain'' determined using the technique described in the text (section 3.2.5).

Stations	Short growing season (1st CSGS)	Dry spell	Total failure of rain (2nd CSGS)
Alamata	31	8	61
Maychew	46	23	31
Mekelle	50	40	10
Adigudom	23	8	69

The contribution of the 1st class shortening of growing period to crop failure was about 31% at Alamata, 46% at Maychew, 50% at Mekelle and 23% at Adigudom. The early cessation of growing period contributed to the occurrence of the 1st class shortening of growing period about 33% at Alamata, 17% at Maychew, 67% at Mekelle and 63% at Adigudom whereas the late start of rain contributed to the occurrence of 1st class shortening of growing period about 58% at Alamata, 63% at Maychew, 25% at Mekelle and 38% at Adigudom.

The contribution of the 2nd class shortening of growing period to crop failure was 61% at Alamata, 31% at Maychew, 10% at Mekelle, and 69% at Adigudom. At Mekelle there was more 1st class shortening of growing period and less 2nd class shortening of growing period than at the other stations in the study area.

The three variables for crop failure, "short growing period", " dry spell" and "total failure of rain" that were mentioned by the farmers were ranked differently across the stations (Table 3.7).

Table 3.7. Farmers' rankings of the three variables ''short growing period'', ''dry spell'' and ''total failure of rain'' causing crop failure in north Ethiopia.

Causes of crop failure	Alamata	Maychew	Mekelle	Adigudom
Short growing period(1st CSGS)	2	1	1	2
Dry spell	3	3	2	3
Absence of rain(2nd CSGS)	1	2	3	1

1 = very severe; 2 = moderately severe; 3 = slightly severe

We compared our data with the farmers' ranking and found strong agreement (the ranking of all classes agreed for all stations). There was also excellent correspondence between the long-term observed and calculated drought assessment results (Table 3.8). The analysis showed that the droughts over the early 80s in the study area were continuous. Hence, the primary cause of the famine of the 1984/85 was cumulative effect of drought during the previous years and the year under consideration. The Mekelle area was less affected by such drought (Table 3.8) than the other three stations.

3.3.3 Irrigation need

The dekadal irrigation water requirement of teff and barley are presented in Figure 3.5a and b and Table 3.9. Teff and barley need more irrigation water in the dekads in September than in the other months for all stations except Alamata. For example, the irrigation water requirement for the dekads in September for barley and teff ranged between 10 and 30 mm, while the irrigation water requirement for the dekads in August was estimated to be less than 10 mm and for the dekades in July ranged between 0 and 20 mm, except at Alamata.

Table 3.8. Calculated and observed seasonal anomalies in relation to crop performance at two stations in north Ethiopia. The calculated results are based on the drought indices and NWD values whereas the observed results are based on information from farmers and other documents. Note that 1984 at Mychew is the 4th consecutive dry year with crop failure.

	Maychew					Mekelle			
Years	Indices	NWD	Calculated	Observed	Year	Indices	NWD	Calculated	Observed
1953	0.9	7	N	S	1960	1.0	8	W	S
1954	1.6	8	W	S	1961	0.8	7	N	S
1955	-1.8	2	D	F	1962	0.6	7	N	S
1956	1.1	9	W	S	1969	0.7	7	N	S
1957	-0.3	5	D	F	1970	0.2	6	N	S
1958	0.1	6	N	S	1971	-0.6	6	D	F
1959	1.2	9	W	S	1972	0.2	7	N	S
1961	0.6	7	N	S	1973	0.1	6	N	S
1964	1.0	7	N	S	1974	-1.1	5	D	F
1965	0.2	5	D	F	1975	0.9	8	W	S
1971	-1.7	2	D	F	1976	0.8	8	W	S
1972	-1.0	2	D	F	1977	1.1	8	W	S
1973	0.3	6	N	S	1978	-0.2	6	N	S
1974	0.0	6	N	S	1979	-1.5	6	D	F
1975	-3.0	0	D	F	1980	0.1	6	N	S
1976	0.5	6	N	S	1981	-0.1	6	N	S
1977	0.7	7	N	S	1982	-0.7	6	D	F
1978	0.4	7	N	S	1983	0.3	7	N	S
1979	0.3	5	D	F	1984	-0.6	6	D	F
1980	0.8	6	N	S	1985	-0.8	5	D	F
1981	-0.3	4	D	F	1986	0.5	6	N	S
1982	-1.4	1	D	F	1987	0.7	7	N	S
1983	-0.6	5	D	F	1988	1.2	7	N	S
1984	-0.7	3	D	F	1992	-1.0	5	D	F
1985	0.0	5	D	F	1993	-1.0	5	D	F
1986	0.9	9	W	S	1994	0.8	7	N	S
1987	-1.2	2	D	F	1995	0.8	7	N	S
1991	0.1	5	D	F	1996	-0.6	6	D	F
1992	0.1	6	N	S	1997	-0.4	6	N	S
1993	-1.4	1	D	F	1998	0.5	7	N	S
1994	1.3	7	N	S	1999	0.3	7	N	S
1995	0.3	6	N	S	2000	-0.3	6	N	S
1996	0.2	6	D	S	2001	-0.1	6	N	S
1997	-0.2	4	D	F	2002	-0.4	7	N	S
1999	0.5	7	N	S	2003	-0.3	5	D	F
2000	0.8	7	N	S	2004	-2.4	4	D	F
2001	0.8	8	W	S	2005	0.3	7	N	S
2002	0.0	5	D	F	2006	0.2	7	N	S
2003	0.0	6	N	S	2007	1.4	8	W	S
2004	-0.2	5	D	F	2008	-0.8	6	D	F
2005	-0.1	4	D	F					
2006	0.4	5	D	F					
2007	0.6	7	N	S					
2008	-0.3	3	D	F					

NWD = number of wet dekads, D = dry season, N = normal season, W = wet season,

S = success crop, F = Failure crop

Of the total irrigation water requirement in the growing period, the proportion required by teff in September was 0% at Alamata, 51% at Maychew, 98% at Mekelle and 67% at Adigudom. Each of the three dekads in September constituted about 10 - 41% of the teff total irrigation water need in the season. Compared with the other stations, the Alamata area required a larger proportion of the total water requirement in the growing period in July. At Alamata, the irrigation water requirement in September was zero (Table 3.9) because the crop had already matured in early September due to the fast development enhanced by high temperatures.

For barley, out of the total seasonal irrigation needs, the proportion of irrigation water requirement in September was 0% at Alamata, 60% at Maychew, 92% at Mekelle and 72% at Adigudom. The dekadal irrigation water requirement for barley over the growing period for the study area is presented in Figure 3.5b. Generally, the total irrigation water need of teff and barley was substantially lower at Mekelle than the other stations.

Table 3.9 Seasonal irrigation requirements (mm) and the percent of water requirement in July, August and September for teff and barley in north Ethiopia.

Crop	Units	Alamata	Maychew	Mekelle	Adigudom
Tef	Total seasonal irr. water req. (mm)	148	115	74	115
	July (%)	83	37	0	16
	August (%)	18	12	2	17
	September (%)	0	51	98	67
Barley	Total seasonal irr. water req. (mm)	135	107	83	114
	July (%)	81	18	0	2
	August (%)	19	24	8	26
	September (%)	0	60	92	72

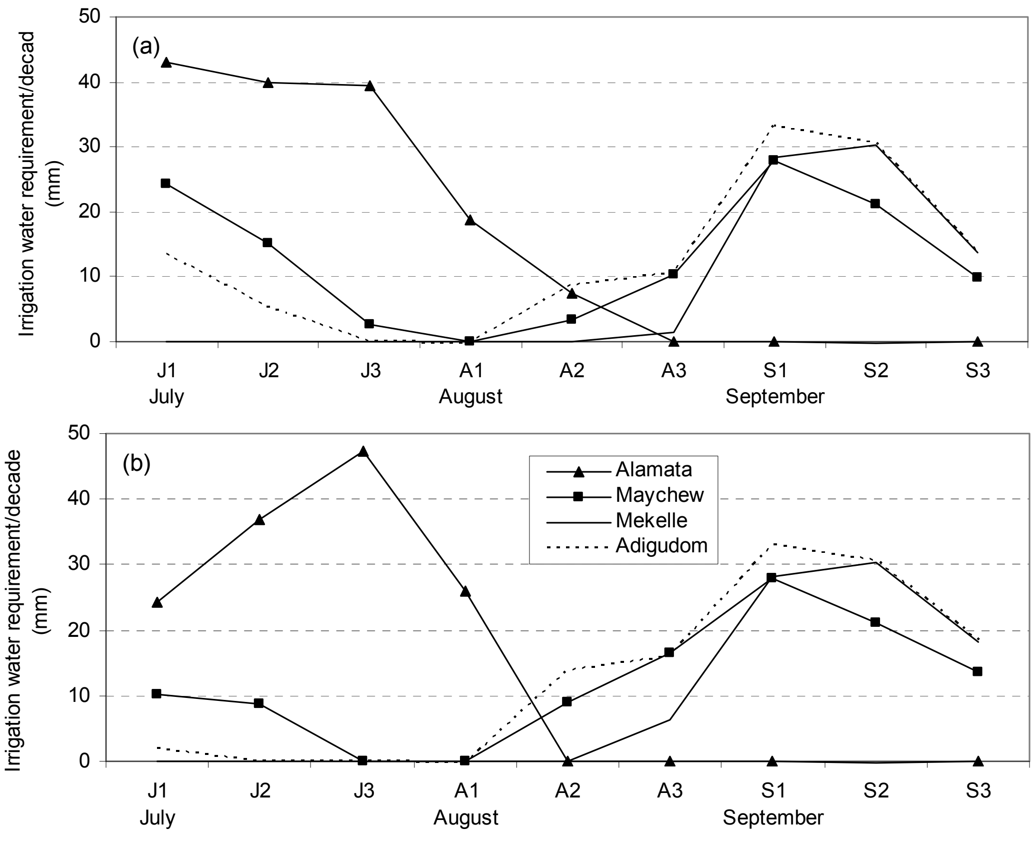

Figure 3.5a and b. Dekadal irrigation water requirement for 4 stations in north Ethiopia, (a) for tef and (b) for barley.

3.4 Discussion

3.4.1 Drought and rainfall characteristics

Rainfall over northern Ethiopia has been known to be variable (Meze-Hausken, 2004; Segele and Lamb, 2005) and not enough to meet the crop water demand (Araya et al., 2010c). This study also found great rainfall variability (CV more than 30%) and in most of the cases, the dekadal 75% dependable rainfall during the crop growing period was lower than the dekadal ETo which means that to secure their harvests, farmers need to explore the options for supplementary irrigation.

Some previous rainfall trend reports have indicated a declining trend of Kiremt rains (June – September) in north central and central Ethiopia (Seleshi and Demaree, 1995; Osman and Sauerborn, 2002). However, Conway (2000); Seleshi and Zanke (2004); Meze-Hausken (2004) and Seleshi and Camberline (2006) reported an absence of a declining trend in northeastern, northwestern and central parts of the country. Bewket and Conway (2007) did not find a consistent trend in daily rainfall characteristics over the Amhara region of northern Ethiopia either. However, the results of these studies were affected by the number of years and the type of years chosen for the analysis (Bewket and Conway, 2007). The indices we calculated with the drought assessment technique described in this paper showed a decreasing trend in the 1970s and 1980s and a normal to slightly above average trend in the years after 1990 (Figure 3.4). In addition, data for the 1960s at one of the stations (Mekelle) indicated that the trend in that decade was very different from the trend in the 1970s and 1980s (data not shown).

Most of the major meteorological factors that contribute to rainfall variability over Ethiopia are not well known. Recently some studies have been carried out to elucidate the large-scale factors influencing Ethiopian rainfall (Bewket and Conway, 2007). For example, some studies showed an association between the El Nino-Southern Oscillation (ENSO) and sea surface temperatures (SST) and Kiremt rainfall (Gissila et al., 2004; Segele and Lamb, 2005; Korecha and Barnston, 2007; Diro et al., 2010). Segele and Lamb (2005) verified that normal kiremt onset and variable cessation in the northeastern Ethiopia were associated with neutral ENSO years whereas warm ENSO events were correlated with late onset of kiremt and a short growing period. They also found that kiremt cessation anomalies were associated with SST in the nearby western Indian Ocean and Arabian Sea, such that late kiremt cessation of rain correlates more strongly with warm SST in the western Indian Ocean and Arabian Sea than with the SST of the Atlantic Ocean.

3.4.2 Effect of length of growing period

One of the essential features of the Ethiopian *Kiremt* season is the northward movement of the inter-tropical convergence zone (ITCZ) (Segele and Lamb, 2005; Korecha and Barnston, 2007). The southeasterly trade winds blowing across the equator in the eastern Atlantic Ocean and western Indian Ocean arrive in Ethiopia as southwest monsoons (Shanko and Camberlin, 1998). In early September, the weather system is characterized by weakening of the eastern Atlantic and western Indian Ocean monsoon system and the cessation of rains due to the southward retreat of the moist and unstable air mass, ITCZ. The dominance of the dry northeasterly winds towards northern Ethiopia increases after early September. Segele and Lamb (2005) have stated that most of the dry spells in northeastern Ethiopia occur towards the end of the growing period, particularly in September. A shorter growing period exposes the critical flowering and yield formation stage of crops to long dry spells (Araya et al., 2010a), resulting in substantial yield losses.

To fully characterize and understand the climate, especially the nature and occurrence of drought over northern Ethiopia, the characteristics of the seasons in terms of the onset and cessation of rains, the length of growing period and the occurrence of dry spells were assessed. Onset of rain over the study area was less variable than the cessation. Segele and Lamb, (2005) also described the *Kiremt* onset in northeastern Ethiopia, which includes the study area, as the latest and least variable in the country. The most frequent onset over the study area is from July 1 - 10. In contrast with the onset of the growing season, its cessation is more variable over the study area. This agrees with the finding by Tessema and Lamb (2003) that from1965 to 1999 the timing of the cessation of rain varied in the northeast part of the country that includes the study area. We found higher probabilities of early cessations over the study area in general. The impact of this was more pronounced at Mekelle and Adigudom than at the other two stations. It seems that the shortening of the growing period as a result of early cessation is a major cause of yield reduction and crop failure in the study area. This conclusion is backed up by the farmers ranking the shortening of the growing period as the main factor limiting crop production.

In section 3.2.5 the short growing periods were subdivided into 1st and 2nd class short growing periods. The 1st class short growing season is rain failure that can lead to reduction or loss of yield but allows farmers to obtain some crop biomass for their livestock. A 2nd class short growing seasons is one with total rain failure that results in total crop failure; these are less frequent than the 1st class ones. If consecutive 2nd class short growing seasons occur, the result may be famine, as happened in 1984/85. The 2nd class short growing seasons are probably the result of larger scale or global climate influence, whereas the 1st class short growing seasons are frequent and are less intense and can be mitigated more easily. First class short growing seasons were more frequent at Mekelle, whereas the 2nd class short growing season was more pronounced at Alamata and Adigudom stations.

Most of the devastating north Ethiopian drought years that occurred during 1979 - 1987 were caused by the 2nd class short growing seasons ("total rain failure"). The contribution of 2nd class short growing seasons to crop failure during the long-term observations in the study area ranged between 10% and 69% and was least for Mekelle and most for Adigudom (Table 3.6). In Alamata and Adigudom, the prime cause of crop failure was "total rain failure" (2nd class short growing season). The total rain failure might have resulted from a shift in seasonal rainfall due to large-scale climate influence, but the fact that the stations were not uniformly affected at the same scale suggests that small-scale climate influences could also be important. The total rain failure (2nd class growing season) in the early 1980s was very severe and the population was very vulnerable due to the cumulative effect of consecutive rain failure. Millions of Ethiopians were affected and nearly a million people died of famine in 1984/85. Over half of the victims of this drought were from the study area (unpublished data). Almost all the farmers in the study area, particularly in Alamata and Maychew areas, reported that the effects of the famine were exacerbated by other factors. Governance was poor: there was poor preparedness for disaster – even foods pledged from donors were suspended; the movement of relief workers was restricted; and most people were discriminated against and neglected (associated as supporters of the opposition group). The low economic status of the rural population increased their vulnerability to the risk. The lack of knowledge about how to avoid risk was also a factor.

3.4.3 Dry spell and false start

In previous studies, a dry spell has had various definitions in terms of the time of occurrence and effect, depending on the purpose of the study. We studied dry spells in dekads because of the importance of these 10-day periods in crop production. A dry spell of 10 days in the study area causes great stress to crops because the water-holding capacity of the soils has been reduced by severe land degradation (Hurni, 1990; Nyssen et al., 2000). A dry dekad may occur any time between the onset and the cessation of the rainy season. It can be expressed in terms of percent frequency of dry dekad below a given threshold amount of effective rainfall received (mm). Table 3.3 shows the probabilities of occurrence of a dry dekad under threshold rainfall limits of 10, 20, 30, 40, and 50 mm rainfall. Regardless which threshold limit is chosen, the results showed that a dry dekad is less likely to occur in August than in July and September. Despite the extremely low probability that dry spells would occur at Mekelle (Table 3.3), dry spells were the 2nd most important agro-meteorological variable causing crop failure, ranked only after 1st class short growing season. This study showed that about 36% of the long-term seasons in the Mekelle area were in drought years (Table 3.5). In these drought years, dry spells contributed to about 40% of the crop failure that occurred at the station (Table 3.6). Longer dry spells may be related to large-scale or small-scale weather systems. Segele and Lamb (2005) verified that long and consecutive dry spells were strongly related to major downturn in dew point, abnormally high temperatures, and easterly winds throughout the troposphere beneath a weak tropical easterly jet. The increased probability of dry dekads at all the stations in late August and thereafter might be related to southward shift of the inter-tropical convergence zone (ITCZ).

In Zimbabwe and Kenya, crop failure due to false start has been evaluated with a relative transpiration and evapotranspiration rate over a 30-day period following sowing (Raes et al., 2004; Kipkorir, 2007; Mugalavai et al., 2008). We evaluated the risk of a false start in a given season by determining the DEff/DETo in the onset dekad and in the dekads following the onset. An onset dekad with indices > 0.5 followed by dekad s^{-1} with indices < 0.5 was assumed to result in false start. Since farmers in the study area sow their crops in dry soil, the result indicated higher probability of false starts. The risk of a false start was reported to be about 9.9% in Kenya (Kipkorir et al., 2007) but as much as 20% at one of our stations (Maychew), the lowest being 8% for the Alamata and Adigudom stations. Though resowing is an option, the growing period will be shorter. Our study confirms earlier findings of high frequencies of false starts in north eastern Ethiopia (Araya, 2005).

3.4.4 The new drought assessment technique

The established relationship of effective rainfall and reference evapotranspiration together with the number of wet dekads in a given season seems to be a suitable and a reliable indicator of crop failure over the years. There was an excellent relationship between the observed (information obtained from farmers and documents) and the calculated indices (see Table 3.8, Maychew and Mekelle). The technique uses easily accessible information such as rainfall, average runoff, evaporating power of the atmosphere and the number of wet dekads in a particular season. To produce reliable results, the numbers of wet dekads over that season must be related to the length of growing period for the commonest crops. The technique is more suitable where soil water-holding capacity has been reduced due to land degradation, as is the case in our study area.

3.4.5 Supplementary irrigation needs

Crops suffer from various lengths of dry spells because (1) the rainwater is not available due to low soil water-holding capacity as a consequence of land degradation (Stroosnijder, 2009); (2) the rainy season is too short when compared to the length of crop growing period; (3) the rainfall is far below normal or is totally absent (total rain failure).

To mitigate the effect of dry spells, to avoid a false start and to prolong the growing period, supplementary irrigation can be used. The irrigation water need should be calculated taking account of rainfall, reference evapotranspiration, crop development and soil type (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979). Accordingly, we tried to assess the irrigation requirement of the two major crops in the study area.

The main reasons that the total irrigation water requirement of teff and barley in July was higher at Alamata than at the other stations (Table 3.9) were: (1) the relatively low amount and erratic nature of rainfall and (2) the high daily temperature and, hence, the high evaporative demand in Alamata compared to that at the stations with lower temperatures.

Although the percent of irrigation water requirement at Mekelle for the month of September was higher than for the other stations, the total seasonal amount of irrigation water needed in Mekelle was only half of what was needed in Maychew and Adigudom because at Mekelle the rainfall in July and August is higher and better distributed than at the other stations. Supplementary irrigation is advised for the three stations (Maychew, Mekelle and Adigudom) during the month of September because: (1) most frequently rain ceases in early September or in late August (that is during flowering and yield formation which is the most sensitive period of the crop to water stress) and crops have no other source of water for the remaining part of growing period (2) sufficient runoff can be harvested in July and August to be stored in ponds for irrigation during the month of September (Araya et al., 2006a); (3) larger areas of cultivable land can be irrigated if the supplementary irrigation is scheduled only for September and (4) with the exception of Alamata, more than 80% of the yield reduction and more than 50% of the crop failure can be avoided when the rainwater in the season is integrated with the provision of supplementary irrigation in September (flowering and yield formation period). Over 50% of the drought years (in the three stations) were resulted from water stress that occurred at the critical period of the crop (in September). In the case of Alamata, supplementary irrigation must be scheduled in the month of July.

In every season, surface runoff can be collected using household ponds for supplementary irrigation. The average gross capacity of a household pond constructed in the study area is about 180 m^3 (Araya et al., 2006). Given the conventional systems used, this amount could be enough for an area of 0.08 - 0.1 hectare if the supplementary irrigation is planned to be applied for the month of September only. Under present conditions, irrigation in Ethiopia is limited to some vegetable and fruit crops because the water use efficiency of the main cereal crops is less than that of vegetables (Araya et al., 2006). But crop production needs to be intensified by introducing modern water supply and application systems to cereals as well.

False starts could be avoided by irrigating crops during their establishment. However, if farmers have limited access to water for irrigation at the beginning of the rains, they should delay sowing until rainfall meets more than half of the evaporative demand of the atmosphere (at least the top 10 – 20 cm should be moist) or they should irrigate.

Growing quickly-maturing cash crops such as chickpea may also help to avoid complete failure because they normally grow at the end of growing period, utilizing unused soil water reserves. Such crops are recommended when the seasonal rain starts too late and when there is little possibility for irrigating the crops.

3.5 Conclusions

Our method to assess drought risk proved to be a suitable and reliable indicator of crop failure, especially for areas where the soil's water-holding capacity has been reduced by land degradation, as is the case in north Ethiopia. There was a good correlation between the observed information (obtained from farmers and documents) and the data we analysed.

In the period 1978 – 2008, about 36 - 59% of the seasons in the study area were drought seasons (crop failure). This was attributed to three major agro-meteorological factors: (1) intra-seasonal dry spells, (2) 1st class short growing season and (3) 2nd class short growing season or total failure of rains mainly caused by shifts in large- and small-scale weather systems. Dry spells were common during the rainy season. In addition, crop failure as a result of false starts was also common. In general, the probability of dry spells causing crop failure was not as great as the risk of a too short growing period.

The most promising way to minimize drought resulting from 1st class short growing seasons and dry spells is to give supplementary irrigation in the dekads in September. More than 80% of yield reductions attributable to water stress and more than 50% of the crop failures attributable to this stress could have been avoided by irrigating adequately during the dekads in September – except in Alamata, where irrigation should have been in July. It may prove difficult for the farmers in Alamata to meet the high requirements for supplementary irrigation in July, as water resources in the area are limited, especially, if the months before July are dry. Therefore, alternative options such as groundwater need to be explored in order to meet the crop water demand in July.

Failure of rain associated with large-scale climate distortion resulted in devastating droughts in the study area in the 1980s. The 1984/85 famine was principally the effect of the year-to-year cumulative occurrence of 2nd class short growing seasons. It is unlikely that the droughts during the early 1980s at the Alamata and Maychew stations could have been mitigated by supplementary irrigation in only the month of July or September.

For optimal use of rainwater, we recommend that farmers sow their crops after the soil has received enough moisture and that in the Maychew, Mekelle and Adigudom areas they give their crops supplementary irrigation in September. Growing quickly-maturing crops will enable the farmers to better utilize the rains in the growing period. We strongly advise extension workers and other responsible government bodies to follow these recommendations.

Chapter 4

Crop coefficient, yield response to water stress and water productivity of teff (*Eragrostis tef* (Zucc.))

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Crop coefficient, yield response to water stress and water productivity of teff (*Eragrostis tef* (Zucc.)

Abstract

In the semi-arid region of Tigray, Northen Ethiopia a two season experiment was conducted to measure evapotranspiration, estimate yield response to water stress and derive the crop coefficient of teff using the single crop coefficient approach with simple, locally made lysimeters and field plots. During the experiment we also estimated the water productivity of teff taking into account long-term rainfall probability scenarios and different levels of farmers' skills. During the experimental seasons (2008 and 2009), the average potential evapotranspiration of teff ranged from 260 to 317 mm. The total seasonal water requirement of teff was found to lower in contrast to the assumptions of regional agronomists that teff water requirement is comparable to that of wheat and barley (375 mm). The average single crop coefficient values ($k_{c)}$ for the initial, mid and late season stages of teff were 0.8 - 1, 0.95 - 1.1 and 0.4 - 0.5, respectively. The seasonal yield response to water stress was 1.04, which indicates that teff exhibits a moderately sensitive and linear response to water stress. The results suggest that teff is likely to give significantly higher grain yield when a nearly optimal water supply is provided. The study showed that, in locations where standard equipment is not affordably available, indicative (rough) crop evapotranspiration values can be obtained by using field plots and employing locally made lysimeters. The difference in economic water productivity (EWP) and the crop water productivity (CWP) for teff were assessed under very wet, wet, normal, dry and very dry scenarios. In addition two groups of farmers were evaluated, a moderately (I) and a highly skilled (II) group. The results showed that higher EWP and CWP were obtained under very wet scenario than very dry scenario. There was also a 22% increase in EWP and CWP under group II compared to group I farmers. The increase was due to a 22% reduction in unwanted water losses achieved through use of improved technology and better irrigation skills. Both EWP and CWP can be used to evaluate the pond irrigation water productivity (IWP) for a given climate, crop and soil type, and skill and technology level of the farmer. For special crops like teff extra criteria may be needed in order to properly evaluate the pond irrigation water productivity. During the experimental seasons, a high IWP for teff was attained when about 90% of the optimal water need of the crop was met. IWP can be used as an indicator as how much supplementary irrigation has to be applied in relation to the rainfall and other sources of water supply in order to assure greatest yield from a total area. However, the supplemental irrigation requirement of the crops may vary with season due to seasonal rainfall variability.

4.1 Introduction

The main cause of instability in food security in Ethiopia is the dependency on erratic rainfall (Helmut, 1990), as witnessed by the drought-induced food crises experienced in the last two decades. Teff is the staple food crop and principal source of carbohydrates for the majority of the Ethiopian population. Its production is critical for national food security. It is a gluten-free food crop grown predominantly by smallholders, which has attracted much interest in the international market (Spaenij-Dekking et al., 2005). It has high demand and market value, which makes farmers get more revenue than other crops. Teff straw is valuable as fodder since it is protein-rich, and it is preferred by cattle, making its market price relatively high (Ketema, 1997).

Teff is adapted to dryland farming in Ethiopia and is considered a drought-resistant crop. Despite its adaptation to dryland conditions, one of the major yield-limiting factors in teff production is water shortage. Increasing the on-farm efficiency of rain water usage would benefit not only the smallholders who grow it but would also improve food security in the whole country and bring in revenue from international sales.

Teff is normally not sown until the peak of the rainy period, which in Tigray is from the third week of July to the first week of August (Araya et al., 2010a). Wet sowing is preferred to avoid false start, to improve seedling establishment (Araya et al., 2010a) as well as to reduce shoot fly infestation. Often, the rainy period ends 40 to 50 days after the normal planting time of teff, but the duration of teff's growing period ranges from 80 to 85 days. Considering a normal season, the occurrences of late-season dry spells are more pronounced than intra-seasonal (within the rainy season) dry spells. The occurrence of late-season dry spells coincides with the critical crop growth stage, in particular, flowering and yield formation stages. Given that rain ceases in the middle of the growing stage, supplemental irrigation may be necessary for optimum growth (Araya et al., 2010b).

Rainwater harvesting (RWH) and management, especially on-farm storage ponds for supplemental irrigation offer an opportunity to mitigate the recurrent dry spells (Fox and Rockstrom, 2003; Ngigi et al., 2005). In the last 10 years, the government of Tigray promoted the construction of household ponds and more than 20,000 were constructed so far. There are possibilities to improve crop production by using on-farm storage ponds however water management has been one of the major problems. Teff's water requirement has not been studied in detail and is commonly assumed by local agronomist to be similar to that of wheat and barley (personal communication).

To estimate evapotranspiration accurately lysimeters should be used (Liu et al., 2002; Kang et al., 2003). However, they are very expensive and rarely available in Ethiopia. To address this problem, in our study we used a combination of field plots and locally made lysimeters. The single crop coefficient approach can be used to estimate the crop coefficient (Allen et al., 1998; Kang et al., 2003). The single crop coefficient is simple and applicable for the planning and designing of irrigation projects as well as for less frequent water application (Kang et al., 2003; Garcia et al., 2003). Hence, this method was the most suitable for our teff investigation, given the local constraints in the experimental conditions.

In order to increase the irrigation area coverage, there is need to increase the source of irrigation water supply and/or to improve the productivity of the irrigation scheme. The latter is sounder under the present condition because water management has become a problem as the farmers do not know enough about teff's water productivity. As water scarcity demands the maximum use of every drop of water, there is a need to calculate the water productivity of crops (Pereira et al., 2002; Bessembider, et al., 2005; Fereres and Soriano, 2006).

Enhancing water use efficiency in irrigated agriculture includes increasing output per unit of water, reducing water loses and prioritizing water allocation (Howell, 2001). The sustainable use of water has to consider maximizing yield per unit of water rather than maximum yield per unit of area (Fereres and Soriano, 2006). Evaluations of irrigation schemes based on economic water productivity (EWP) and crop water productivity (CWP) are the essential indicators of efficiency of water use. However, many farmers, especially in northern Ethiopia, failed to take into account such important elements. In this study we have introduced these two elements (EWP and CWP) to study teff water productivity under the present pond water use. The crop productivity per unit water aspect should be analysed in addition to the economic aspect because increasing crop production per unit of water does not necessarily increase the farmer's income due to the non-linearity of crop yield with the price of products

The objectives of this paper are to measure evapotranspiration and derive the crop coefficient of teff using a single crop coefficient approach from a simple, locally affordable field and locally made lysimeter; to determine the yield response to water stress and to estimate and evaluate teff water productivity under the present pond water use taking into account the long-term rainfall probability scenarios and skill and technology of the farmers.

4.2 Materials and methods

4.2.1 Experimental site

The experiment was conducted in 2008 and 2009 (August to October) in northern Ethiopia at Mekelle (latitude 13^{o} 29' N long 39^{o} 35'E, 2130 m.a.s.l) (Figure 4.1).

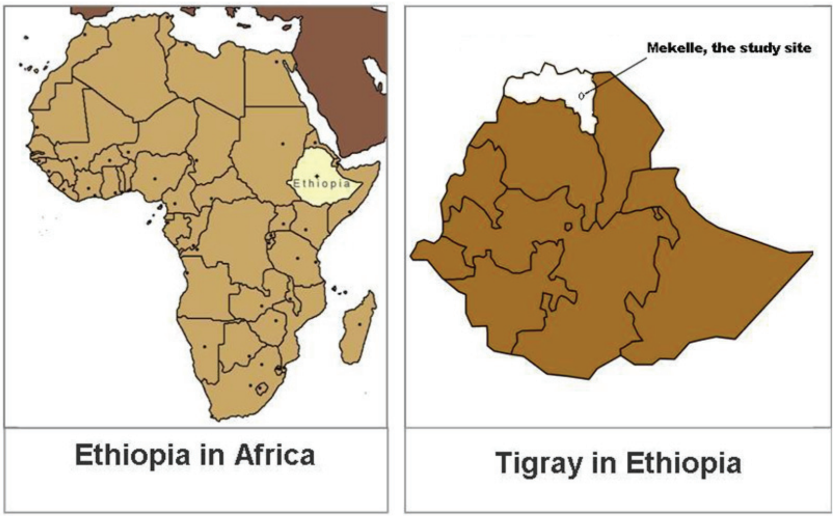

Figure 4.1. Map of the study site (Mekelle area) in reference to Tigray region of Ethiopia.

The soil at the experimental site is a Cambisol with total nitrogen of 1.22 g kg^{-1} and available phosphorus, 5.84 mg kg^{-1} (Habtegebrial et al., 2007). The texture of the surface soil (0 to 0.3 m) is silty clay. The water content at field capacity for the soil depth 0 - 0.2 m is 27 vol% and for 0.2 - 0.3 m is 32 vol%. The corresponding values for the permanent wilting point are 14 and 14.3 vol%.

Climate data such as rainfall, humidity, temperature, wind speed, sunshine hours and radiation were obtained from the weather station at Mekelle University campus (about 200 m away). Daily reference evapotranspiration (ET_o) was computed using the FAO-Penman-Monteith equation employing the full data sets with the help of the ET_o software (FAO, 2009). The daily reference evapotranspiration ranges from 2 to 5.5 mm per day. The daily rainfall, daily reference evapotranspiration and applied irrigation are presented in Figure 4.2a & b. At the site, the long-term (1960-2009) average annual precipitation is about 600 mm, 70% of which falls during the *kiremt* season (June to September). The long-term 80% dependable rainfall meets the reference evapotranspiration for about four dekads during July and August (Araya et al., 2010a). The mean annual reference evapotranspiration is about 1700 mm. The long-term mean minimum and maximum temperatures are 12 ^{o}C and 28 ^{o}C, respectively.

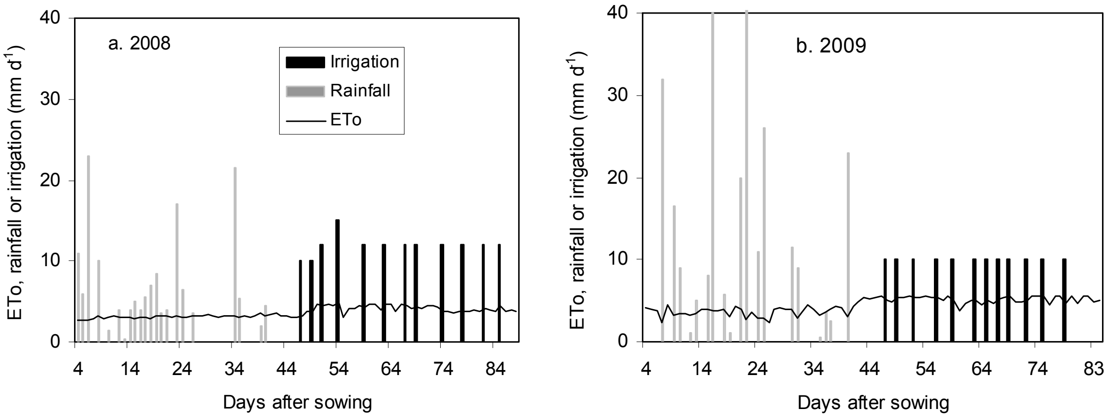

Figure 4.2. Estimated ET_o, measured rainfall and applied irrigation at the field during the cropping season in 2008 (a) and 2009 (b).

4.2.2 Field layout and measurements

In 2008 and 2009, field experiment was set up to determine the evapotranspiration and calculate the crop coefficient values of teff. Two dominant early maturing teff cultivars were grown with supplementary irrigation conditions. Each treatment was replicated three times, arranged randomly in a uniform environmental condition. The plot size was 4.0 m x 5.0 m and plots were hydrologically isolated from each other by soil bunds 0.2 to 0.3 m tall. The distance between plots was 1.5 m. The cultivars were sown by broadcasting in early August at a rate of 30 kg per hectare and harvested in October. All crop management techniques followed the regional recommended practices. Accordingly, DAP (Di-ammonium phosphate) and urea fertilizers were applied at a rate of 100 kg per hectare each (64 kg N and 46 kg P per hectare); N was applied in split: half at sowing and the other half a month after sowing. Three hand weeding were carried out; shoot flies were controlled using insecticide (applied once). Rooting depth for the dominantly grown teff varieties were measured using the conventional technique: the root lengths were measured using a ruler after roots washed out of soil samples in the site. The maximum measured rooting depth of the early maturing experimental teff cultivars was about 0.3 m. Studies showed that the majority part of teff roots of many teff varieties were limited between 0 and 0.3 m, (Taddesse, 1969; 1975; Araya et al., 2010b) out of these, early maturing types were reported to have the shortest root depth (Ayele et al., 2001). The plant population was 923 plants m^{-2}; leaf area index, crop cover, development phases and yield for optimal growing condition were presented in Araya et al. (2010b). After maturity, dry biomass and grain yield were determined from subplots of 2 x 3 m.

4.2.3 Measuring Teff evapotranspiration (ET_c) and potential evapotranspiration (ET_o)

Locally made lysimeters

In 2008, data were collected using three locally made lysimeters which (Figure 4.3), were put in the middle of the teff field. About 1000 m^2 area of teff field was kept at field capacity and the three locally made lysimeter were installed 3 to 5 m apart. The locally made lysimeters had a diameter of 0.6 m and were 0.6 m tall. They were designed to replace the more expensive lysimeters and were suitable for teff since the maximum rooting depth for teff in our experimental sites was only 0.3 m. The locally made lysimeters had a solid base with an outlet for collecting drained water through a perforated iron sheet. On top of this sheet was about 0.06 m of gravel followed by a layer of about 0.06 m thick sand, covered with a 0.005 m thick sisal sheet. Deep percolation (drainage) beyond the root zone was collected in a receptacle under the locally made lysimeters and measured using a calibrated cylinder.

The locally made lysimeters were placed in the field containing the holes left after the original soil column had been carefully removed using a sharp-edged metal ring of the same diameter as the locally made lysimeters. The rim of the installed locally made lysimeters was set flush with the soil surface. Then the soil column was replaced in the locally made lysimeters with minimal disturbance, on top of the sisal cover. The locally made lysimeters were positioned exactly similar to the field condition. Teff was sown in the locally made lysimeters and kept at field capacity throughout the growing period.

Soil water balance

Time domain reflectometry (TDR) with Trime-FM3 soil moisture measuring system (Eijkelkamp, 1996) was used to measure the soil moisture profile in the field plots and field locally made lysimeter. One thin-walled glass fibre access tube was installed per plot (6 plots) and per locally made lysimeter (3 locally made lysimeter), to depths of 1 m and 0.5 m, respectively. The tube probe was connected to the FM3 meter and lowered into the tube so that measurements can be carried out to the desired depth.

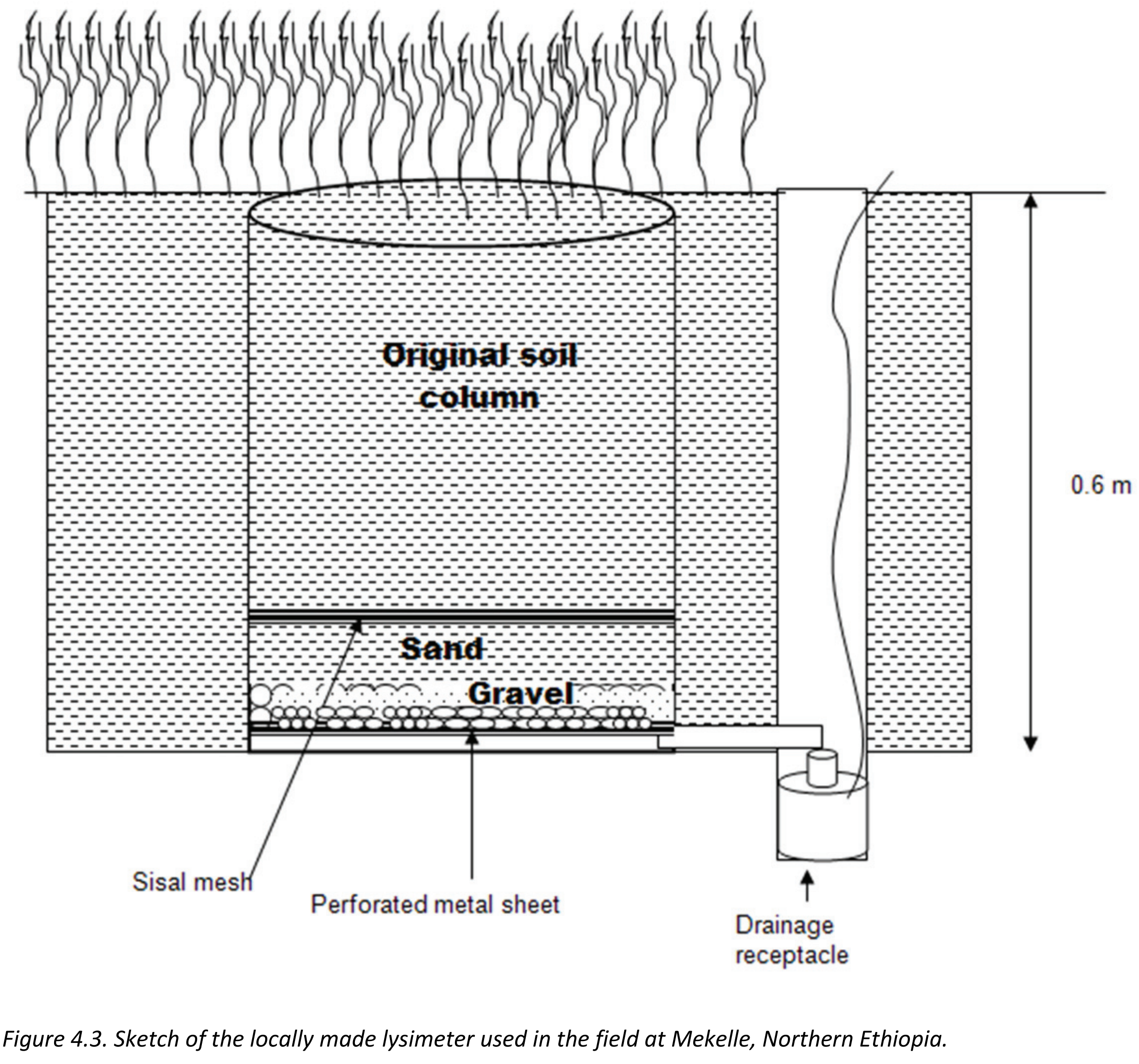

Figure 4.3. Sketch of the locally made lysimeter used in the field at Mekelle, Northern Ethiopia.

In 2009 only field plots were used without the locally made lysimeters. TDR was observed on alternate days at 0.1 m intervals. Gravimetric soil moisture was measured and used for the calibration of the TDR measurements. All the field plots were positioned uniformly on a 2% slope and runoff was collected in a barrel installed at bottom end of each plot. In both the field and the locally made lysimeters experiments a depth of about 10 to 20 mm irrigation water was applied every 3 to 5 days interval. Irrigation in the locally made lysimeter was applied using a calibrated container whereas irrigation in the field was applied by gravity from a well known temporary storage structure using a pipe. Drainage was collected at the drainage receptacle (Figure 4.3) below the locally made lysimeter and was negligible; the effect of groundwater was ignored because the water table was deeper than 100 m; the effect of lateral soil water movement was assumed uniform throughout the plots and hence ignored; the runoff was collected in a barrel placed at the bottom end of each plot. Surface runoff from each experimental plot was entered directly into the barrels by gravity. The runoff collected was emptied manually after measurements were taken. The runoff volume was measured using a calibrated container. Run on was prevented by dykes.

Daily teff evapotranspiration was computed and averaged for the weeks during the experimental seasons to give the weekly ET_c based on Equation 4.1 (Allen et al., 1998).

$$ET_c = I + P - D - Ro \pm \Delta S \qquad [4.1]$$

Where:

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

I is irrigation (mm).

P is rainfall (mm).

D is drainage (mm).

Ro is runoff (mm).

4.2.4 Assessment of the Single crop coefficient of Teff (k_c)

The average weekly ET_c and ET_o values were used to produce weekly k_c values using Equation 4.2 as presented in Doorenbos and Pruitt (1977); Allen et al., (1998) and Liu et al., (2002). Mean teff crop coefficient (k_c) values for the weeks of the growth stages were then obtained.

$$k_c = \frac{ET_c}{ET_o} \qquad [4.2]$$

Once k_c values are obtained, crop water requirement of teff can be calculated using Equation 4.3.

$$ET_c = k_c \times ET_o \qquad [4.3]$$

4.2.5 Assessing yield response factor to water stress

The effect of water stress on yield of teff is indicated by the yield response factor (k_y), calculated based on Equation 4.4 (Doorenbos and Kassam, 1979):

$$\left(1 - \frac{Y_a}{Y_m}\right) = k_y \left(1 - \frac{ET_a}{ET_m}\right) \qquad [4.4]$$

Actual evapotranspiration (ET_a) represents both transpiration and evaporation and is a direct indicator of actual soil water content and actual yield (Moran et al., 1996; Barron et al., 2003). The potential teff yield (Y_m) and potential teff evapotranspiration ET_m which is equal to ET_c, were obtained from plots without any water constraint; actual yield (Y_a) and actual evapotranspiration (ET_a) for teff were obtained from plots grown under rainfed with limited supplementary irrigation conditions. Values for k_y above 1 indicate that the crop is sensitive to moisture stress, whereas values below 1 indicate that the crop can tolerate moisture stress.

4.2.6 Assessment of the effectiveness of supplemental irrigation and the effect of skill and technology on irrigation water requirement

As ponds are the common types of irrigation water source widely used for agriculture, a survey was conducted to study teff's EWP and CWP under the present pond irrigation water use in the study area. About 48 household ponds were selected for the survey (Araya et al., 2006). Pond capacity, the irrigation method, soil types and teff cropping period and skill of the farmer was assessed.

Rainfall data over the 1960 - 2009 was statistically analysed. Test of homogeneity was applied and the seasonal rainfall data was proven to be consistent. The dependable 10 day period (decadal) rainfall over the record period (> 20% (very wet), 40 - 20% (wet), 60 - 40% (normal), 80 - 60% (dry) and < 80% (very dry)) was computed. Mean precipitation of each scenario was obtained. About 25% of the 10 day period (decadal) rainwater was assumed to be runoff loss (Araya and Stroosnijder, 2010). Effective rainfall was calculated by subtracting the runoff from the decadal rainfall of each scenario. Hence, the net irrigation water requirement of teff was computed following Equation 4.5.

$$NIWR = ET_c - R_p \times (1 - 0.25) \qquad [4.5]$$

Where:

NIWR, is net irrigation water requirement.

R_p is the mean 10 day period (decadal) dependable rainfall (scenarios) for each corresponding scenario.

As the distance between irrigable area and pond was so short and the type of irrigation method was a direct water application (such as using pipes), only field application loss was assumed to occur. Field application losses include unwanted deep percolation below the root zone and runoff. It is affected by the type of irrigation system used, soil type and the skill of the farmer (Doorenbos and Pruitt, 1977). Given that water is a scarce resource in this part of the region, the field application loss needs to be taken into account. Gross irrigation (GIWR) requirement was thus estimated from the field application efficiency and net water requirement using Equation 4.6.

$$GIWR = \frac{NIWR}{F_E} \qquad [4.6]$$

Where:

F_E is field application efficiency.

Two groups of farmers were considered in the calculation of irrigation water requirement:

Group I: considers moderately skilled farmer irrigating by direct water application system (pipes) with a teff crop grown in medium textured soils as in the study area. Assuming these conditions, the field application efficiency was estimated to be 70% (Doorenbos and Pruitt, 1977).

Group II: Considers highly skilled farmers applying irrigation during cool climate (e.g. applying irrigation at night in tropics minimizes evaporation) using a modern technology in medium textured soils, the field application efficiency was estimated to be 90%. This condition is unlikely to exist under the present farmer's socio economic condition but we have included it for comparison to demonstrate how this difference would affect water management and hence water productivity and net irrigable area. Further assumptions were taken: the two groups of farmers were given equal amount of water (127 m^3) and optimal irrigation was assumed to be applied. Then the net irrigable area and water productivity were compared.

The net irrigable area by the household pond was estimated based on Equation 4.7.

$$TIA = \frac{NPC}{GIWR} \qquad [4.7]$$

Where:
TIA is total irrigable area (ha).
NPC is the net pond capacity (m^3).
GIWR is teff gross irrigation water requirement (m^3 ha^{-1}).

4.2.7 Assessment of water productivities of Teff

Teff economic water productivity (EWP) was calculated as the gross income in USD per gross water supplied in m^3. EWP was computed based on the following information obtained at the study site: the size of irrigable area, maximum obtainable yield and the gross income gained from the sale of grain (main product) and straw (bi-product) considering the average seasonal local market price (USD) as shown in Equation 4.8. The gross income is the product of the average price of teff per kg for the season and the average grain yield per given irrigable area plus the product of the price of teff straw per kg for the season and the average straw yield per given irrigable area.

$$EWP = \frac{GI}{GIWR} \qquad [4.8]$$

Where:
GI is gross income from the sale of grain and straw (USD).
GIWR is gross irrigation water requirement (m^3 ha^{-1}).

Teff water productivity (CWP) was also estimated using Equation 4.9.

$$CWP = \frac{GY}{GIWR} \qquad [4.9]$$

Where:
GY is yield (kg ha^{-1}).
CWP, is crop water productivity (kg m^{-3}).

Irrigation water productivity (IWP) was estimated based on Equation 4.10.

$$IWP = \frac{GYI - GYr}{IR} \qquad [4.10]$$

Where:
GYI, grain yield of irrigated teff (g m^{-2}).
GYr, grain yield of rainfed teff (g m^{-2}).
IR, is applied irrigation (mm).

4.3 Results and discussion

4.3.1 Teff evapotranspiration (ET_c) and reference evapotranspiration (ET_o)

Soil water in the root zone was kept nearly at field capacity throughout the growing season (Figure 4.4). The excess water during the first 15 days after planting was drained out of the field plots in the form of runoff.

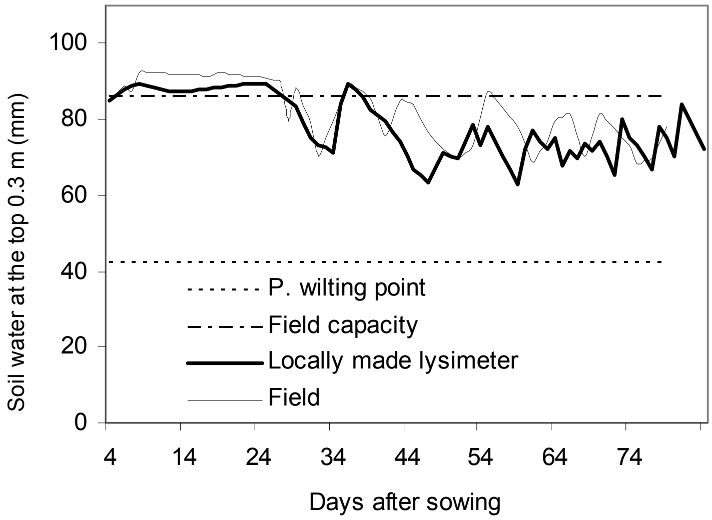

Figure 4.4. The soil water (mm) in the top 0.3 m for field plots and locally made lysimeters.

The estimated ET_c values in the field and in the locally made lysimeters were very closely related, as was shown by the strong (R^2 = 0.97) relationship between the ET_c field and ET_c locally made lysimeter during the experimental period at the site (Figure 4.5b).

The mean seasonal ET_c of the cropping season in 2009 was slightly higher (290 mm) than 2008 (270 mm). Table 4.1 shows the mean weekly ET_c sum and the corresponding teff growth stage during the experimental season in 2008. The maximum ET_c observed in one of the plots in 2008 was 317 mm per season.

The ET_c calculated using Equation 4.3 based on the long-term mean climate data of 46 years was higher (338 mm) than the ET_c obtained during experimental seasons in 2008 and 2009. This increase was mainly caused by the reduced humidity and increased temperatures. However, the measured teff ET_c values were lower than that of barley (375 mm) ET_c measured at the same climate and site (unpublished data). In addition, for most of the cereals, the seasonal crop evapotranspiration documented in FAO publications are higher than 300 mm. This implies that with a given amount of water, it may be possible to irrigate a relatively larger area of teff field than other cereal's field.

The ET_c increased from the initial stage to the mid season stage. High ET_c was measured in the period between 35 to 70 days after planting in both years (Table 4.1; Figure 4.5a&c) attributable to an increase in green leaf canopy transpiration and a slight increase in reference evapotranspiration, which again resulted from reduced humidity and higher temperature.

Table 4.1. The weekly sum of reference evapotranspiration and potential teff evapotranspiration and the corresponding crop stage.

DAP	ET_o (mm per week)	ET_c (mm per week)	Crop stage
7	19	17	Initial
14	21	19	Initial
21	22	20	Dev.
28	22	22	Dev.
35	22	24	Dev/Mid
42	24	26	Mid
49	26	28	Mid
56	30	33	Mid
63	31	34	Mid
70	31	28	Mid/Late
77	27	14	Late
84	27	5	Late

DAP, days after planting.

Under rainfed condition, teff suffered from late season dry spells in the region because the length of rainy period is shorter than the crop growing period (Araya et al., 2010ba). However, the crop resists drought better than many field crops such as maize. Ayele et al. (2001) also reported that one important drought resistance mechanism of teff is the maintenance of high osmotic adjustment as its survival strategy under drought stress conditions. Tefera et al. (2000) also reviewed that osmotic adjustment, leaf water loss and leaf canopy temperatures are potential drought resistance mechanisms of teff. These drought resistance mechanisms of teff has shown significant variation among cultivars which could be used as selection criteria (Tefera et al., 2000).

Figure 4.5a & c show the relationship between the daily mean evapotranspiration (ET_c) and reference evapotranspiration (ET_o) for the weeks during the experimental period in 2008 and 2009, respectively. During the initial stage, ET_o was higher than the ET_c measured both at the field and locally made lysimeter (Figure 4.5a). This was mainly attributed to low canopy cover at the early stage of the crop. ET_c is affected by climate, management, crop type and stage (Doorenbose and Pruitt, 1977). Growing conditions such as fertilizer and water were assumed optimal. However, the watering frequency might have affected the evaporation component of the ET_c. ET_c was slightly higher than ET_o during the late vegetative and grain filling stage because the crop has attained high canopy cover and maximum rooting depth, which enables the crop to use the soil water in the root zone for its transpiration while minimizing evaporation. During the later stage of the crop, ET_o slowly declined but relatively higher than ET_c whereas ET_c declined quickly because leaves turn yellow and start to dry and fall and ultimately transpiration stopped.

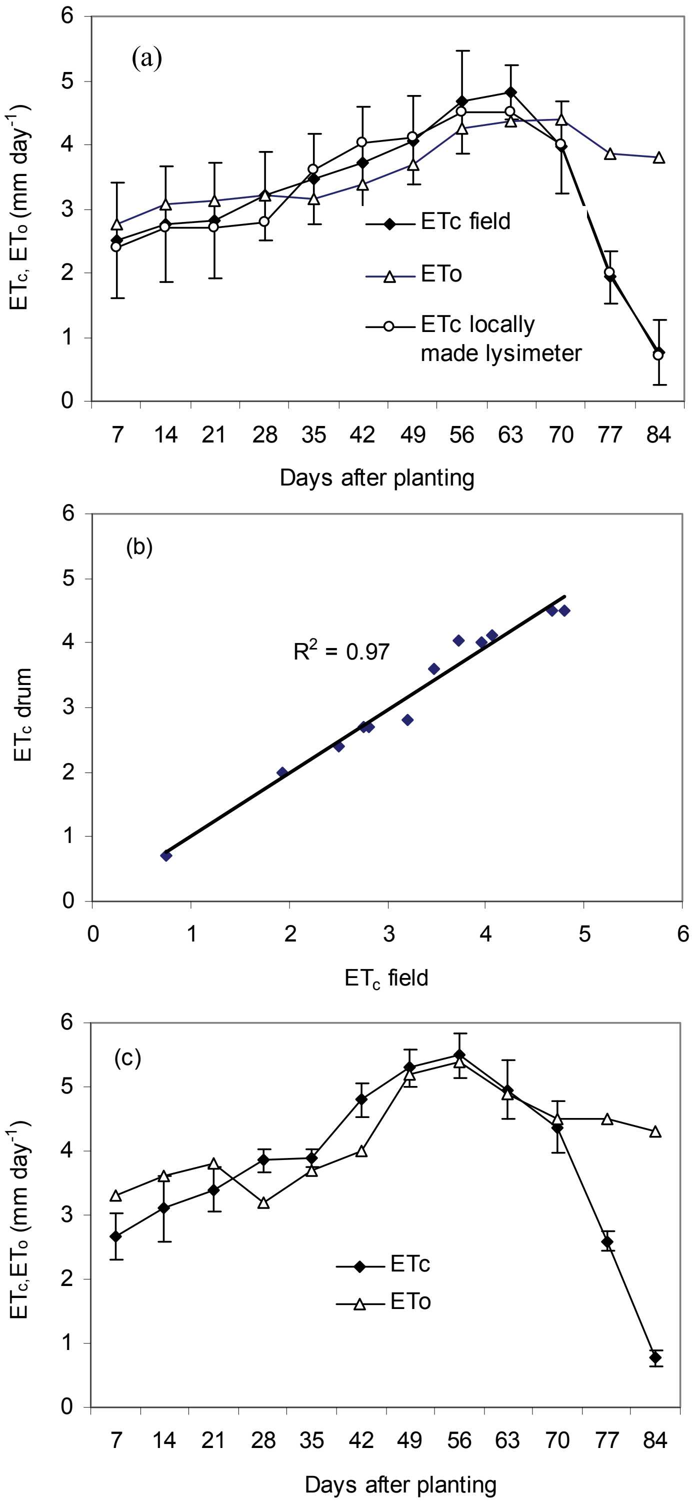

Figure 4.5. (a) The relationship between the measured daily mean ET_c for the field plots (filled diamond) and locally made lysimeters (blank circle) versus daily mean ET_o (blank triangle) for the respective weeks during the experimental season in 2008; (b) the regression between daily mean ET_c at the field plots and locally made lysimeters (filled diamond) for the respective weeks during the experimental season in 2008; the straight line is linear regression line (c) the relationship between daily mean ET_c (filled diamond) at the field and ET_o (blank triangle) for the respective weeks during the experimental season in 2009.

4.3.2 Crop coefficient (k_c)

The single crop coefficient value of teff for 2008 and 2009 are presented in Figure 4.6. The k_c values increased from initial to mid season stage and decreased during the later season of the crop. Like the ET_c, the k_c showed an increase in trend in the vegetative stage (15 to 34 days after planting) and remained almost constant during the mid season stage (35 to 67 days after planting) and started to decline during the late season stage (after 68 days after planting). The estimated single crop coefficient values for teff were 0.8 - 1.0, 0.95 - 1.1 and 0.4 - 0.5 for initial, mid and late season stages, respectively (Table 4.2).

These values are slightly lower than the values for wheat and barley (common cereal crops) as reported by Doorenbos and Pruitt (1977); Doorenbos and Kassam (1979), Allen et al. (1998), however, a relatively higher k_c value was observed for teff during the initial stage. This may be due to teff requiring wet conditions during its establishment period (Araya et al., 2010a). In addition, evapotranspiration during the initial stage is dominated by the evaporation component and thus affected by the frequency and amount of the watering and evaporative power of the atmosphere (Allen et al., 1998).

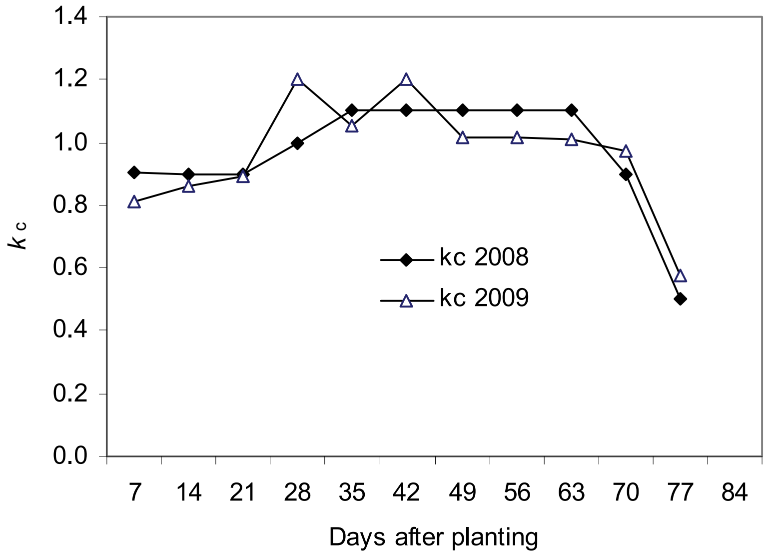

Figure 4.6. Weekly mean crop coefficient values of teff during the experimental season in 2008 (filled diamond) and 2009 (blank triangle).

Table 4.2 k_c values for teff growth stages in 2008 and 2009 at Mekelle, Tigray, Ethiopia.

Growth stage	initial	vegetative	mid	late
Number of days	14 -16	18 - 21	33 - 35	16
Ground cover	10%	10-90%	90-100%	Senescence
k_c	0.8-1.0	Linear interpolation	0.95-1.1	0.4-0.5

4.3.3 Yield response to water stress

Quantifying the yield response factor clarifies whether it is better to grow teff on a smaller area under optimum water application rather than to grow it on a larger area where it receives less water. The seasonal yield response factor (k_y) based on Equation 4.4 for teff is given in Table 4.3. A k_y value 1.04 indicates that teff grain responds moderately to water stress.

Table. 4.3 Yield response (k_y) of teff to water stress.

Crop parameter	Water supply		
	Optimal	Limited	k_y
ET_c (mm per season)	317	160	
Yield (kg ha^{-1})	1818	878	1.04

Under conditions of limited water supply and with water deficit equally spread over the total growing season, the yield decrease for teff will be greater than for those crops with ky < 1. This implies, when maximum total production for the project area is being aimed at, that the available water supply would be best directed toward nearly meeting the optimal water requirements of teff. Teff grain water use efficiency was reported to be higher under a nearly optimal water condition than under water stress condition however the opposite has been reported if teff is to be grown for its straw only (Araya et al., 2010b).

Teff yield seems to be dramatically reduced especially if optimal water is not applied at the early establishment and flowering stage of the crop. In this research, we did not investigate the sensitivity of each growing stage to drought stress in detail: we recommend this be addressed in future research. The data presented in Figure 4.7 shows that teff grain yield responded almost linearly (R^2 = 0.93) to the amount of water applied and then forms a plateau over a larger range of supplementary irrigation. There was very little increase in yield with further large increase in water supply after about 90% of the water requirement of the crop is met (Figure 4.7).

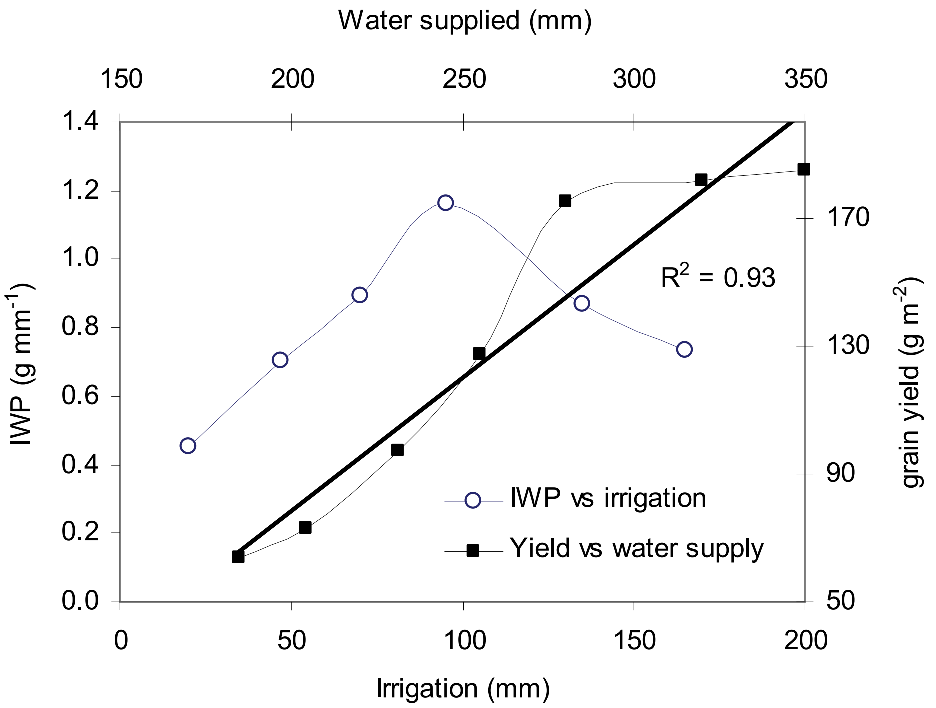

Figure 4.7. The relationships between applied irrigation and teff irrigation water productivity (IWP) (1^o axis; with unfilled circle) and the relationship between yield and water supply (irrigation + rainfall) (2^o axis; filled box) during the experimental seasons at Mekelle, Ethiopia.

4.3.4 Water productivity of teff

The ponds under the present condition have the capacity to irrigate a very small plot of land which varied depending on the type of crop, soil, skill and technology and climatic condition. The net pond capacity in the study area is about 127 m^3 (Araya et al., 2006).

Assuming optimal water application, the irrigable area calculated for group I farmers (farmers with moderate skill and technology condition) under the five rainfall scenarios (> 20%, 40 - 20%, 60 - 40%, 80 - 60%, and < 80%) were 624, 467, 442, 409 and 343 m^2, respectively, and the corresponding irrigable land under group II farmers (highly skilled farmers equipped with modern technology) were estimated to be 803, 601, 568, 526, and 442 m^2, respectively (Table 4.4). There was a 22% increase in irrigable area under group II compared to group I farmers. The increase in irrigable land was due to 22% reduction of unwanted water losses (reduced field application loses) achieved as a result of using improved technology and better irrigation skill.

The mean potential grain and straw yield of the teff cultivars for the experimental seasons in the study site was 1818 kg ha^{-1} and 7800 kg ha^{-1}, respectively. The mean seasonal price of grain and straw of teff for the study area was 0.8 USD kg^{-1} and 0.0919 USD kg^{-1}, respectively.

Teff water productivity (CWP) calculated under very wet, wet, normal, dry and very dry scenarios for group I farmers were 0.89, 0.67, 0.63, 0.59 and 0.49 kg m^{-3}, respectively. The corresponding CWP scenarios for group II farmers were 1.15, 0.86, 0.81, 0.76, and 0.63 kg m^{-3}, respectively. The increase in CWP with increase in rainfall was attributed to the reduced supplemental irrigation water requirement which enabled the farmer under very wet scenario to supplement relatively larger cultivable land when compared to farmer under very dry scenario where the limited pond water is used almost for full irrigation. Group II farmers were also able to gain advantage of their skill and technology in minimizing the application loses consequently there was substantial improvement in CWP. This study demonstrated that upgrading skill and technology of the farmers in water management (such as reducing field application loses) has significant contribution in saving the limited water in dryland areas.

The economic water productivity (EWP) from growing teff for each levels of climate scenarios (> 20%, 40 - 20%, 60 - 40%, 80 - 60%, and < 80%) under group I farmers were 1.07, 0.8, 0.76, 0.70, 0.59 USD m^{-3}, respectively, whereas the corresponding EWP for group II farmers were 1.37, 1.03, 0.97, 0.90 and 0.76 USD m^{-3}, respectively. In all climate scenarios there was a 22% increase on group II farmers that can be taken as advantage over the group I. The advantage gained was mainly due to increase in size of irrigable area as a result of minimizing field irrigation application losses (improved water management).

In both groups, the highest EWP was obtained in case of very wet condition with lower supplementary irrigation whereas the lowest EWP corresponds to the very dry scenario. This was sourced from an increase in the size of irrigable area due to reduced irrigation application per unit area under very wet condition compared to very dry climate scenario.

The calculated EWP and CWP for teff using the household pond irrigation water is much lower when compared to EWP and CWP data of other vegetables crops such as tomato and onion as documented in previous studies (Araya et al., 2006) because the yield of these vegetables from an equivalent area is much higher than the yield of teff. The EWP estimations used in this study do not consider the export values of teff because of lack of recorded data. In future, study on similar issues needs to include export prices of teff. The EWP values have strong relationship with price of the product hence may vary with time as supply and demand changes. Therefore, the evaluation of teff in terms of EWP under the present pond water use is not highly attractive when compared with the vegetable crops.

Table 4.4 Estimated EWP and CWP for two groups of farmers under five seasonal rainfall scenarios.

Parameters and indicators	Group I farmers					Group II farmers				
	Very wet	Wet	Normal	Dry	Very dry	Very wet	Wet	Normal	Dry	Very dry
NIWR (mm)	142.4	190.3	201.1	217.5	258.8	142.4	190.3	201.1	217.5	258.8
GIWR (m^3 ha^{-1})	2035	2719	2873	3108	3698	1582	2114	2234	2417	2876
TIA (ha)	0.062	0.047	0.044	0.041	0.034	0.080	0.060	0.057	0.053	0.044
Grain (USD m^{-3})	0.710	0.530	0.510	0.470	0.390	0.918	0.684	0.648	0.603	0.504
Straw (USD m^{-3})	0.350	0.260	0.250	0.230	0.190	0.450	0.342	0.324	0.297	0.252
EWP (USD m^{-3})	1.070	0.800	0.760	0.700	0.590	1.368	1.026	0.972	0.900	0.756
CWP (kg m^{-3})	0.890	0.670	0.630	0.590	0.490	1.152	0.864	0.810	0.756	0.630

TIA, total irrigable area; EWP, economic water productivity; CWP, crop water productivity; NIWR, net irrigation water requirement; GIWR, gross irrigation water requirement.

Looking at the result of pond water use scenarios considered in this study and the primary objective of harvested water by the ponds (supplementary irrigation), it seems wise to give priority to crops with higher EWP and CWP so that cost of investment could be quickly regained as well as more food per applied water could be obtained. Under water scarce environment, EWP and CWP could be improved through: crop choice, reducing unwanted water loses, improving productivity and marketability. Farmers choose to grow teff in places where continuous water source for irrigation could be accessed such as from seasonal or perennial streams or rivers. Teff has relatively higher local market price and social acceptance when compared to most cereal crops grown in Ethiopia. In addition, the crop is becoming popular in an international market for its gluten free food source (Ketema, 1997). Therefore, for very special crops like teff, further extra criteria such as social acceptance, storage, production cost, export values, health benefits, and other factors may be crucial to consider for appropriate evaluation.

Irrigation substantially increased the teff grain yield. Teff yield increases with more irrigation up to a certain level after which yield response to additional water showed a plateau (Figure 4.7). This study indicated that about 100 mm supplementary irrigation water corresponds to the maximum IWP of teff. The supplementary irrigation (100 mm) plus the rainfall fulfils about 90% of the optimal water requirement of the crop. In north China, Zhang et al. (1999) obtained a maximum IWP of 1.5 g mm^{-1} for winter wheat by applying 135 mm of supplementary irrigation. In this region, since the rainfall amount and distribution vary from season to season, the supplementary irrigation requirement of the crop also varies. Therefore regardless of the change in seasonal rainfall it is necessary to look for water source for supplementary irrigation so that to assure at least 90% of the seasonal water requirement of the crop is met. However, satisfying only seasonal water demand does not guarantee the highest IWP because the application of irrigation water has to consider intra-seasonal dry spells during the growing season. This study showed excess and too small supplementary irrigation results in low IWP (Figure 4.7).

4.4 Conclusions

The evapotranspiration of teff was measured to derive the crop coefficient of this important staple food crop using a single crop coefficient approach from a simple, locally affordable field and locally made lysimeter. To determine the yield response to water stress and to estimate and evaluate teff water productivity under the present pond water use taking into account the long-term rainfall probability scenarios and skill and technology of the farmers.

The teff potential evapotranspiration during the 2008 and 2009 experimental seasons ranges from 260 to 317 mm. However, when examined based on long-term climate data, it reached approximately 338 mm. This was mainly due to the variation in climate especially in ET_o.

Teff water requirement was found to be approximately 15% to 30% lower than that of barley (unpublished). This is in contrast to the subjective assumption of many agronomists in the region that teff water requirement is as high as that of wheat and barley. The k_c values for the initial, mid and late season stages of teff were 0.8 - 1, 0.95 - 1.1 and 0.4 - 0.5, respectively.

The seasonal yield response to water stress was 1.04, which indicates that teff has a moderately sensitive and linear response to water stress. Teff is likely to give significantly higher grain yield when a nearly optimal water supply is attained. Hence, if maximum total grain production is an objective, the best use of available water supply would be to meet the water requirements of teff as much as possible.

The method used for estimation of crop evapotranspiration value in this study only gives rough estimates. Therefore we recommend the use of any of the standard (such as use of standard lysimters) methods. However, in places where standard materials are not affordably available, indicative values can be obtained by cautiously using field plots and employing locally made materials as demonstrated in this study.

IWP can be used as an indicator of how much supplementary irrigation is needed to be applied in relation to the rainfall and other sources of water supply in order to assure greater yield from a total area. However, the supplemental irrigation requirement of the crops may vary with season due to seasonal rainfall variability. In this experiment high IWP of teff was attained when about 90% of the optimal water need of the crop was met. Therefore, supplementary irrigation has to be applied to ensure at least 90% of the crop water demand is attained. Excess (unwanted loss of water) or too little (severe water shortage) irrigation water application may result in low IWP.

The capacities of the household ponds are very small hence any method that enables a reduction in unwanted water loses would improve the productivities of these ponds in water scarce environments. For example, the supplementary irrigation with pond irrigation varies with climate, crop and soil type and water management skill of the farmer.

The calculated EWP and CWP for teff under highly skilled farmers were higher than moderately skilled farmers. There was at least a 22% increase both in EWP and CWP due to minimizing irrigation field application loses through the use of improved technology and skill. Also the EWP and CWP of teff under very wet climate were much higher than very dry climate. Therefore, the EWP and CWP criteria could be used as a tool for decision making in growing crops under limited water condition.

The yield produced per unit of pond water for teff is even under highly skill farmers lower than the common vegetables grown in the region. In addition, as documented in previous studies, the EWP of teff under the local market is less attractive than other vegetables. However, teff is an exceptionally important food crop in the country. The pond water productivity evaluation of a special crop like teff needs to include additional criteria for appropriate evaluation such as: the production cost, social acceptance, good storage characteristics, health benefits, export values and so on. However, for common crops only EWP and CWP may be used to evaluate the productivity of pond irrigation. EWP and CWP can be improved among others through crop choice, upgrading the water management skills of the farmer and improving the market windows and marketability of the crop.

Chapter 5

Simulating yield response to water of teff (*Eragrostis tef*) with FAO's AquaCrop model

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Simulating yield response to water of Teff (*Eragrostis tef*) with FAO's AquaCrop model

Abstract

In a semi-arid environment, the main challenge for crop production is water deficit. FAO's AquaCrop model, which simulates yield response to water, has been calibrated to explore alternative water management strategies in teff cropping. To calibrate and evaluate this model, we used independent data sets of the cropping season 2008 and 2009 in the northern Ethiopia. The teff crop cover, biomass and soil water simulated by the model agreed well with the observed data. The model revealed that the grain-water use efficiency of teff increased when supplementary irrigation after the start of flowering was increased from 0 to 95 mm. The Biomass-water use efficiency showed the opposite trend: it decreased. The implication of these results is that if land is not a constraint, and if the intention is to grow teff for its biomass, the best option is to use the available water to grow teff with deficit irrigation. But when the major intention is to produce grain, the best option is an optimum irrigation application. Furthermore, it can be concluded that the AquaCrop model can be used to explore management options to improve teff water productivity in the area.

5.1 Introduction

Teff (*Eragrostis tef* (Zucc.)) is the staple food crop for the majority of the Ethiopian population. More than half of the area under cereals in Ethiopia is for teff production (Ketema, 1997; Habtegebrial et al., 2007). Because it is in high demand and thus has a high market value, farmers earn more from growing teff than growing other staple crops. At present, most teff is produced by smallholders who rely on natural rainfall.

Rainfall fluctuations play a significant role in determining the national economy of Ethiopia because many economic activities in this country depend heavily on rain-fed agriculture. Consequently, one of the main obstacles to developing sustainable agriculture in Ethiopia is seasonal crop water shortage. As a result of its dependence on erratic rainfall for food production, Ethiopia is very vulnerable to soil water deficit. Under current conditions, the average national teff yield in the dryland areas is less than 0.8 tons ha^{-1} (Teffera et al., 2000; Balesh et al., 2005). Given that teff is the staple food crop, its production is critical for the national food security. So, increasing the efficiency of rain water use would improve the country's food security.

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 useful to avoid cropping risks (Tsubo 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 daily 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 in general, because it can be used to explore and evaluate alternative management that improves water productivity and achieves more efficient water use (Bessembinder, et al., 2005). It might also be applied by extension specialists, relief organizations, and policy makers, to predict yields.

In this study, two seasons and two sites field experiment data were used to evaluate the performance of the AquaCrop model version 3.0, released in 2009. The calibration of the model was done using measured canopy cover, biomass, and soil water data. Most of the soil, crop and climate parameters needed for calibration of the model, were obtained from field measurements.

5.2 Materials and methods

5.2.1 Study site

Data from two sites in northern Ethiopia were used: Mekelle and Ilala. Their coordinates are 13^o 3'N and 39^o 6'E, and 13^o 4'N and 39^o 4'E, respectively. Among the crops grown in the area are cereals, such as barley (*Hordeum vulgare*), wheat (*Triticum* sp.), and teff (*Eragrostis tef)*.

The Mekelle and Ilala areas are typical of the teff-growing areas of northern Ethiopia. Their climate is cool semi-arid (Koppen's classification, in Gonfa, 1996). There are two rainy seasons in this region: the main one from June to September and a short rainy season from March to May. The dry period is from October to February. Mean annual rainfall is 600 mm in Mekelle and 650 mm in Ilala; the values for reference evapotranspiration are 1700 and 1750 mm, respectively. Mean monthly minimum and maximum temperatures during the crop growing months are 11.5 ^{o}C and 23.2 ^{o}C for Mekelle and 14.8 ^{o}C and 25.8 ^{o}C for Ilala.

5.2.2 Climate data collection and analysis

The climate data for the Mekelle and Ilala sites were obtained from local meteorological stations

The daily reference evapotranspirations (ETo) of Mekelle and Ilala site for the growing season 2008 and 2009 were computed using full set of data based on FAO Penman-Monteith method as described in Allen et al. (1998) with the help of the ETo calculator (FAO, 2009). Daily weather data of sunshine hours, wind speed, relative humidity, and temperature and rainfall were obtained from both experimental sites.

Rainfall and irrigation during the growing seasons at the two locations are depicted in Figure 5.1a-c. The rainy period of the two seasons was very short (36 to 40 days after planting). At Mekelle, the total rainfall from sowing to harvest was 184 and 278 mm in 2008 and 2009 respectively. The August rainfall in both seasons of the two locations was well distributed but rain ceased in early September. Supplemental irrigation was applied for some of the treatments starting from cessation of rain.

5.2.3 Soil data of the experimental sites

The soils at Ilala (Vertisol) and Mekelle (Cambisol) areas represent the two major soil types on which teff is grown in Ethiopia. The physical soil characteristics used as data input for the AquaCrop model are given in Table 5.1. The soil was at maximum field capacity during the time of sowing and early establishment. All soil data inputs were measured in the field.

Table 5.1 Physical soil characteristics of the Mekelle and Ilala sites.

Site	Depth (m)	Moisture content (vol %)			BD	Ksat	CN
		FC	WP	Sat	(g cm^{-3})	mm day^{-1}	-
Mekelle	0.0-0.1	27	14	46	1.55	250	87
	0.1-0.2	27	14	50	1.55	250	
	0.2-0.3	42	22	52	1.45	175	
Ilala	0.0-0.3	37.7	19.3	54	1.29	100	90

FC, field capacity; WP, wilting point; Sat, water content at saturation; Ksat, saturation hydraulic conductivity; and BD, bulk density.

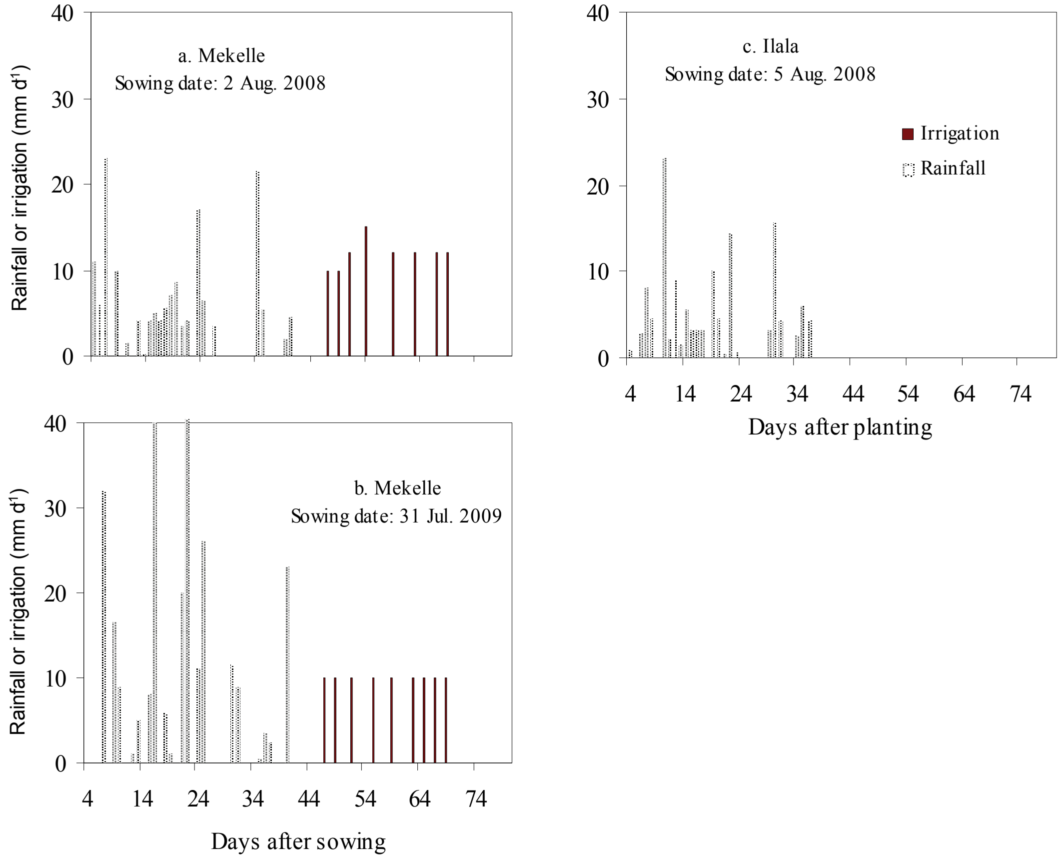

Figura 5.1a-c. Daily rainfall for Mekelle site during the cropping season 2008 (a) and 2009 (b) and Ilala site during the cropping season 2008 (c).

5.2.4 Field experiment and crop data collection

Two common teff varieties were grown at Mekelle site; 'DZ-974' (improved) and a local variety, named '*Keyh*'. The varieties received similar irrigation treatments: supplementary irrigation after start of flowering 8, 6, 4, 2, and 0 times in the cropping season 2008. Each treatment was replicated four times (Table 3), and thus the total number of plots were 40. The plots, which were arrayed uniformly on a 2% slope, were in a randomized complete block design. Each plot was 4.0 m x 5.0 m, spaced 1.5 m apart. The individual plots were hydrologically isolated by means of soil bunds.

The sowing date was in the 2^{nd} of August and harvested in October. The seeding rate was 0.024 tons ha^{-1} considering 70% germination rates (approximately 1900 successful plants per m^2). In all treatments in 2008, 60 kg N and 46 kg P per hectare were applied. Other cultural practices were based on regional recommendations.

In 2008, aboveground biomass observation was made every 10 days from an area of 0.25 m^2. The biomass was dried with an oven drier for 48 hrs at 60 ^{o}C and then weighed.

Leaf area index was estimated using two methods:

a) By multiplying the plant population by the leaf area per plant as described in Kar et al. (2006). Area of the leaf was measured using CI-202L portable laser leaf area meter from 10 plants every 10 days. Counting plant population was carried manually from 0.1 m^2 every 10 days.

b) The LAI-2000 plant canopy analyser (Li-Cor Inc., 1992) was also used in measuring the LAI every 10 days. The values from the two methods were compared. It was proved that similar values were obtained in both methods and hence the values from LAI-2000 plant canopy analyser were taken.

Canopy cover was estimated from treatments that received eight and two irrigation in 2008 based on the method described in Riche (1975) and the type used by Geerts et al. (2008) and Farahani et al. (2009) Equation 5.1.

$$CC = 1 - \exp^{(-0.65*LAI)} \qquad [5.1]$$

Where:
CC is canopy cover.
LAI is the leaf area index.

Grain yield was measured after maturity, from pooled samples from an area of 2 x 3 m in each plot. The grain was dried and then weighed on a sensitive balance. As there was no significant difference between the two teff varieties in many characteristics such as phenological development and canopy cover the average of the two varieties were considered in the simulations. We noticed that some of the plots were attacked by animals. Hence, statistically erroneous yield values were avoided from the analysis.

In 2009, the local variety 'keyh' was sown at Mekelle in late July. The seeding rate, fertilization and other cultural practices were similar to the described above for 2008. The water treatments were: 0, 4, and 9 irrigations after the start of flowering. The plot size was 20 m^2 replicated four times. Plots were in randomized complete block design. The total numbers of plots were 12. Samples of final biomass and grain yield were collected at maturity from an area of 2 x 2 m in each plot.

Similar experiment was also conducted at Illala site under rainfed conditions during the 2008 cropping season. The individual plots were 6.0 m x 4.0 m, spaced 1.5 m apart. Plots were hydrologically isolated from each other by means of soil bunds. Here, DZ-974 and the local teff variety, 'keyh', were sown: on August 5 in 2008. The rainfed treatment was replicated three times. Samples of final biomass and grain yield were collected at maturity from an area of 2 x 3 m in each plot.

Date of sowing and dates of 90% emergence was recorded. Flowering and duration of flowering, maximum canopy cover, senescence and maturity observations were also made. Senescence was assumed to be reached when the canopy cover start to decline whereas maturity date was assumed when the canopy cover reached nearly zero (Heng et al., 2009). Root observation was done in the field at about maximum canopy cover and at maturity from four locations. The conventional destructive technique of root length measurement (from roots washed out of soil samples) was used. Teff root reached maximum at about 50 days after planting. Canopy cover per seedling was estimated (1.5 cm^2). The phenology was calculated in calendar days (Table 5.2). Maximum coefficient and actual crop evapotranspiration was derived from a separate experiment in the site.

5.2.5 Soil water data collection and analysis

To study the field water balance, changes of incoming and outgoing water fluxes were measured for all plots both under rainfed and irrigated fields in the Mekelle and Ilala sites.

At the lower side of each plot, a barrel was placed to collect all runoff. The measured runoff was used to calibrate the curve number to be used in the AquaCrop model. The curve numbers that best fitted the measured runoff were 87 for Mekelle and 90 for Ilala.

A Time Domain Reflectometry (TDR) (Eijkelkamp, 1996) depth probe was used to measure the soil moisture content at the Mekelle site. One glass fiber access tube was installed in each plot (40 plots). TDR observations were taken every other day at 0.1 m intervals to a depth of 0.7 – 1 m. The gravimetric method was used occasionally for calibration purposes. At the Ilala site, all soil moisture measurements were derived from the gravimetric method.

Table 5.2. The different treatments (rainfed and irrigation condition) and the crop phenology in calendar days at Mekelle and Ilala sites during the 2008 and 2009 cropping season.

Site	No. of irrigations	Planting date	Planting density Plants per m^{-2}	Emergence	Date of start of flowering	Physiological maturity	Date of harvest	Rainfall after sowing (mm)	Amount of irrigation (mm)	Dates of irrigation
Mekelle (2008)	8	2/08/08	923	8 Aug.	17/09/08	Oct. 28.	Nov. 5	184	10, 10, 12, 15, 12, 12, 12, & 12, respectively Total = 95 mm	17, 19, 21, 24, 29, /09-08 and 3, 7, 9, /10-08
	6	2/08/08	923	8 Aug.	17/09/08	Oct. 28.	Nov. 5	184	10, 10, 12, 15, 12 ,& 12 respectively Total = 69 mm	17, 19, 21, 24, 29, /09- 08 and 3, /10-08
	4	2/08/08	923	8 Aug.	17/09/08	Oct. 28.	Nov. 5	184	10, 10, 12, & 15, respectively = total 45 mm	17, 19, 21, and 24, /09-08
	2	2/08/08	923	8 Aug.	17/09/08	Oct. 28.	Nov. 5	184	10, 10, Total = 20 mm	17, 19, /09-08
	0	2/08/08	923	8 Aug.	17/09/08	Oct. 28.	Nov. 5	184	-	-
Ilala (2008)	0	5/08/08	923	11 Aug.	20/09/08	Oct. 15	Oct. 25	187	-	-
Mekelle (2009)	9	31/07/09	923	5 Aug.	13/09/09	Oct. 28.	Nov. 15	277.6	10 mm each Total = 90 mm	17, 19, 20, 24, 27 /09-09 and 1, 3, 5, & 7, /10-09
	4	31/07/09	923	5 Aug.	13/09/09	Oct. 28.	Nov. 15	277.6	10 mm each Total = 40 mm	17, 19, 20, 24 /09- 08
	0	31/07/09	923	5 Aug.	13/09/09	Oct. 28.	Nov. 15	277.6	Total = 0 mm	-

Soil samples were taken at 0.15 m depth every 10 days. For Mekelle experimental site, TDR calibration was performed by comparing the soil water measured with the TDR against the value obtained from the gravimetric method. Soil water (kg kg^{-1}) was converted to its corresponding volumetric value by multiplying it by its bulk density (Wiyo et al., 2000). The TDR calibration showed a coefficient of determination of 0.73 and standard error of 0.09. The TDR data was corrected using the regression equation 5.2.

Soil water content (vol %) = 3.85 + 0.837 x TDR value (vol %) [5.2]

In the soil water analysis averages of the observed TDR values of the same treatment were taken but we detected some erroneous measurements that were possibly caused by misplacement of the TDR access tubes in the field. Therefore, extreme values were avoided from the analysis.

In both seasons, the crop has started flowering when the rain ceased. 10-15 mm of irrigation was applied after the rainy season ended. The number of irrigations was pre-determined; the interval was 3 to 4 days. The irrigation was supplied through a pipe and stored temporarily in a well-known volume container. Then water was applied manually from the container to each plot.

Water content beyond the root zone was considered as drainage. Water drained to below the teff root zone was estimated from TDR observations/gravimetric methods. The total measured drainage value was compared with the simulated result.

5.2.6 Water use efficiencies (WUE)

According to Bessembinder et al. (2005), water productivity definitions depend on the aim and scale of the study however using transpiration as a denominator would make the definition valid at all scales. Oweis and Hachum (2006) also stated that yield per unit of water consumed could be used as an important indicator of the water productivity.

Accordingly our aim is to understand if optimal or deficit irrigation could be used to improve grain or biomass yield in teff under scenarios of unlimited arable land in the semi-arid area of Ethiopia. In addition, we would like to assess the productivity of the water supplied to the crop in the growing season (rainy season or supplementary irrigation) in terms of water consumed per unit of water supplied. This was termed as green water use efficiency (Stroosnijder, 2009). As Bessembinder et al. (2005) already suggested we used a validated water response model to estimate the transpiration for computation of water use efficiencies.

(i) Grain water use efficiency (Grain-WUE) was computed based on Equation 5.3.

$$Grain-WUE = \left[{GY}/{\sum T} \right] \qquad [5.3]$$

Where:

GY is grain yield kg ha^{-1} (measured).

T is transpiration determined using AquaCrop model but was converted into m^3 ha^{-1}.

(ii) Biomass water use efficiency (Biomass –WUE) was calculated using Equation 5.4.

$$Biomass-WUE = \left[{BY}/{\sum T} \right] \qquad [5.4]$$

Where: BY is final aboveground biomass in kg ha^{-1} (measured).

(iii) Green water use efficiency (Green-WUE) was computed based on Equation 5.5 where P, is seasonal precipitation from planting to maturity (mm) and I is the total depth of applied irrigation (mm) (Stroosnijder, 2007 and Stroosnijder, 2009). Green-WUE is usually expressed in percent.

$$Green-WUE = 100 * \left[\sum T \big/ _{P+I} \right] \qquad [5.5]$$

5.2.7 Description of AquaCrop model

A detailed AquaCrop model description is available in Steduto et al. (2009) and Raes et al. (2009a). The model evolved from concepts of seasonal or stage yield response to water as described in Doorenbose and Kassam (1979) to a concept of normalized crop water productivity in which case relationships used are based on daily time step (Steduto et al. 2009). AquaCrop calculates the water storage in various soil horizons from the inputs (rainfall, irrigation) and outputs (runoff, evaporation, transpiration, and deep percolation). Infiltration and internal drainage are estimated by an exponential drainage function that takes into account the initial wetness and the drainage characteristics of the various soil layers. The evapotranspiration is separated into evaporation and transpiration by the model. The model estimates the yield from the daily transpiration, considering key physiological characteristics of the crop. The effects of water stress on stomata conductance, canopy senescence, and leaf growth are expressed through indicators which vary from 0 to 1. For example, for greater yield needs high carbon dioxide fixation through high stomata conductance and high transpiration (Blum, 2009). The model reproduces the canopy cover from daily transpiration taking into account some important physiological characteristics of the crop such as leaf expansion growth and canopy development and senescence (Steduto et al., 2009). Unlike many models, AquaCrop expresses its foliage development through canopy cover instead of leaf area index. The daily transpiration is used to derive daily biomass gain through the normalized crop water productivity (NCWP). NCWP is calculated based on Equation 5.6 and is expressed in g m^{-2} (Steduto et al., 2006). The conservative water productivity parameter in the model is normalized in order to make the model applicable to diverse location and seasons including future climate scenario (Steduto et al., 2006; Steduto et al., 2009; Hsiao et al., 2009).

$$NCWP = \frac{BY}{\sum \left(T \big/ _{ET_o} \right)} \qquad [5.6]$$

5.2.8 Model calibration

We calibrated the model with a measured data of the treatment eight irrigations. As the rainfall was good in distribution up to the time of flowering, the treatment with eight irrigations after the cessation of rainfall in 2008 was close to the optimal water requirement of teff in the area. The parameters obtained in model calibration were used for validation. The calibrated model was tested with the data measured at Mekelle experimental sites: 6, 4, 2, and no irrigation and 9, 4, and no irrigation after the start of flowering in the cropping season 2008 and 2009 respectively. The model was also tested with the data measured at Ilala experimental site in 2008.

The calibration for canopy cover was crucial. The change in canopy cover over the growing period was measured in the field as described in section 5.2.4. We used the options in the model to estimate the initial canopy cover (CC_o) from sowing rate, seed weight, seed number and estimated germination rate. Teff has very low initial canopy cover per seedling (1.5 cm^2). The canopy expansion rates were automatically estimated by the model after we enter some of the phenological dates such as dates to maximum canopy cover, senescence, maturity and emergence. The canopy growth coefficient (CGC), canopy decline coefficient (CDC) and the stress indices for water stress affecting leaf expansion and early senescence are the most important canopy cover parameters. The water stress parameters and curve shapes were changed manually around the default value to reproduce the measured values of canopy cover. Finally by trial and error, we obtained good estimates of CGC and CDC.

Simultaneously, NCWP was estimated based on Equation 5.6 but slight changed as transpiration was not separated from evapotranspiration. We used the linear regression of the aboveground biomass and actual evapotranspiration normalized for reference evapotranspiration cumulated to the time of each biomass sampling as described in Farahani et al., (2009). This holds true since the ratio of transpiration to evapotranspiration increases with the increase in canopy cover (Kato et al., 2004). Actual evapotranspiration (ET_a) was determined in a separate experiment. Suitable soil water depletion threshold value for stomata closure and its shape were assessed around the obtained slope value of Equation 5.7 by trial and error. Finally, best fit of the measured sequential aboveground biomass was obtained at NCWP value of 20 g m^{-2} with R^2 of 0.99.

$$BY = 15.1 \times \sum \left({}^{ET_a}\!/_{ET_o} \right) - 313 \qquad [5.7]$$

5.2.9. Model validation

Data from the 6, 4, 2 and no irrigation treatments in 2008 and all three (9, 4 and 0) irrigations treatments in 2009 were used for validating the model. The validation data set consisted mainly of final aboveground biomass and grain yield. Accordingly, comparisons were made between the observed and simulated values of corresponding treatments for final aboveground biomass and grain yield. The goodness of fit of these comparisons was evaluated using graphic and statistical tests. Comparisons of the simulated against the observed time progression canopy cover, sequential aboveground biomass and soil water data sets were also made for rainfed (no irrigation) treatments in 2008.

The coefficient of determination (R^2), root mean square of error (RMSE), and model efficiency were used in evaluating the goodness of fit. Model efficiency (ME) was calculated based on Equation 5.8, (Loague and Green, 1991). ME is a measure of the robustness of the model.

$$ME = \frac{\sum_{i=1}^{n}(O_i - MO)^2 - \sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - MO)^2} \qquad [5.8]$$

Where:

O and S are observed and simulated values for each of n study cases.

MO is the mean observed value.

ME ranges from negative infinitive to positive 1; the closer to 1, the more robust the model.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Oi - Si)^2} \qquad [5.9]$$

RMSE (Equation 5.9) indicates to what extent the model over- or underestimated the observation whereas the R^2 shows the amount of variance explained by the model as compared to the observed data. R^2 ranges from 0 to 1. The value closer to 0 is the best estimate.

5.3. Results

5.3.1. Calibration and validation of the model

Figure 5.2a shows the average observed soil water plotted against the results simulated by the model under nearly optimal condition at Mekelle site. There was a perfect match between the simulated and observed soil water. Mild water stress occurred from the time of senescence to maturity during which slight mismatches were observed. Figure 5.2b and 5.2c show comparisons of the simulated and observed soil water under rainfed conditions at Mekelle and Ilala sites respectively. The model has slightly underestimated the soil water during the severe water stress period particularly at Mekelle site (Figure 5.2b).

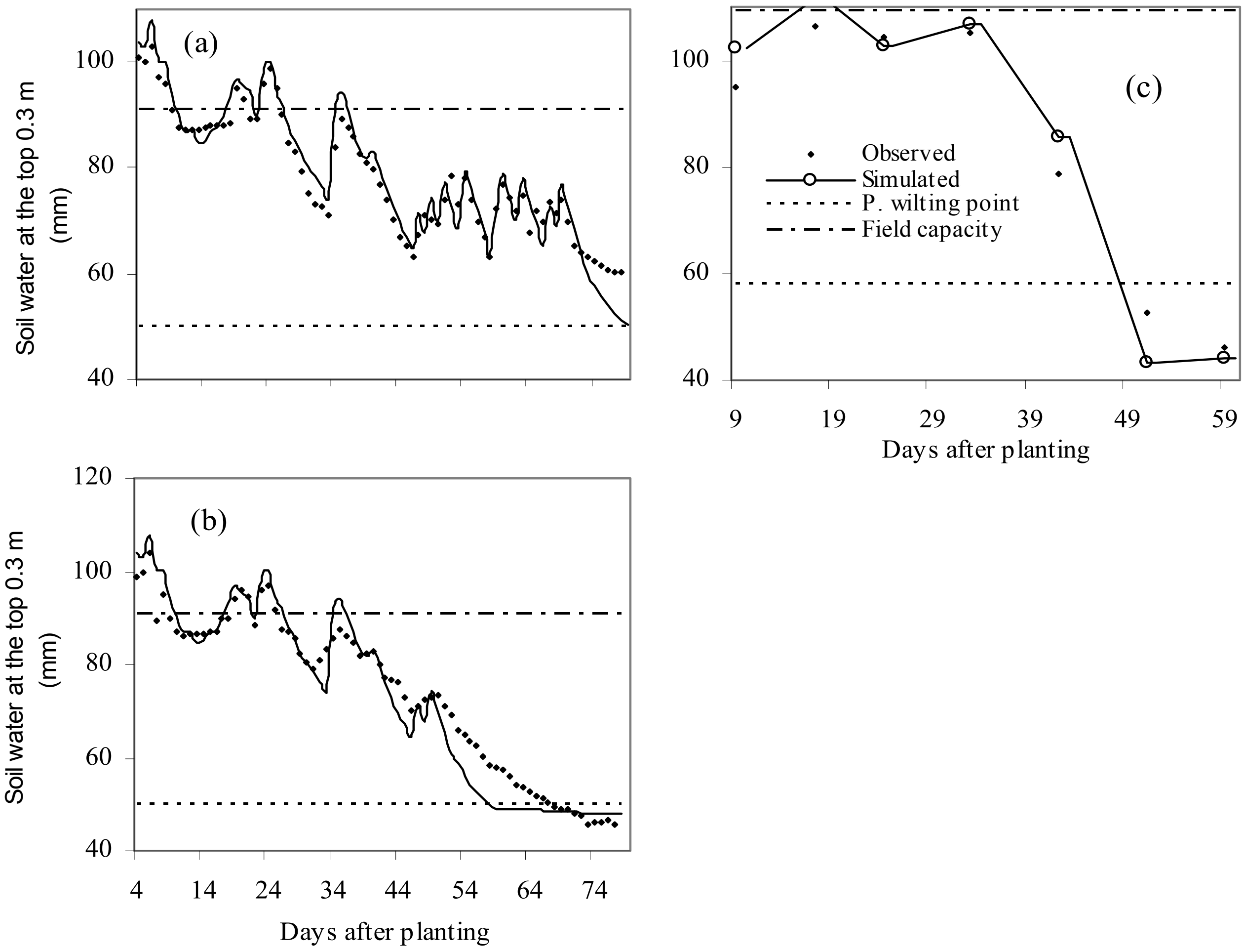

Figure 5.2a-c. Observed and simulated soil water at the top 0.3 m (mm) for treatment with eight irrigations (Mekell site) (b) two irrigation (Mekell site) (b) and no irrigation (Ilala site) (c) during the cropping season 2008. Only seven soil water observations were taken for Ilala site whereas several observations were made for Mekelle site. Soil water observations were taken starting from four days after planting.

The simulated canopy cover correlated strongly with the observed data. There was no significant difference between the simulated and observed canopy cover (Figure 5.3a). Figure 5.3a represents the canopy cover for irrigated (eight irrigation) and rainfed treatments in the cropping season 2008. The canopy cover for rainfed treatments showed rapid decline when compared with the irrigated treatment (Figure 5.3a).

Figure 5.3b shows the simulated and observed sequential aboveground biomass in irrigated (eight irrigation) and rainfed conditions. In both treatments, the simulated sequential aboveground biomass agreed well with the observed values.

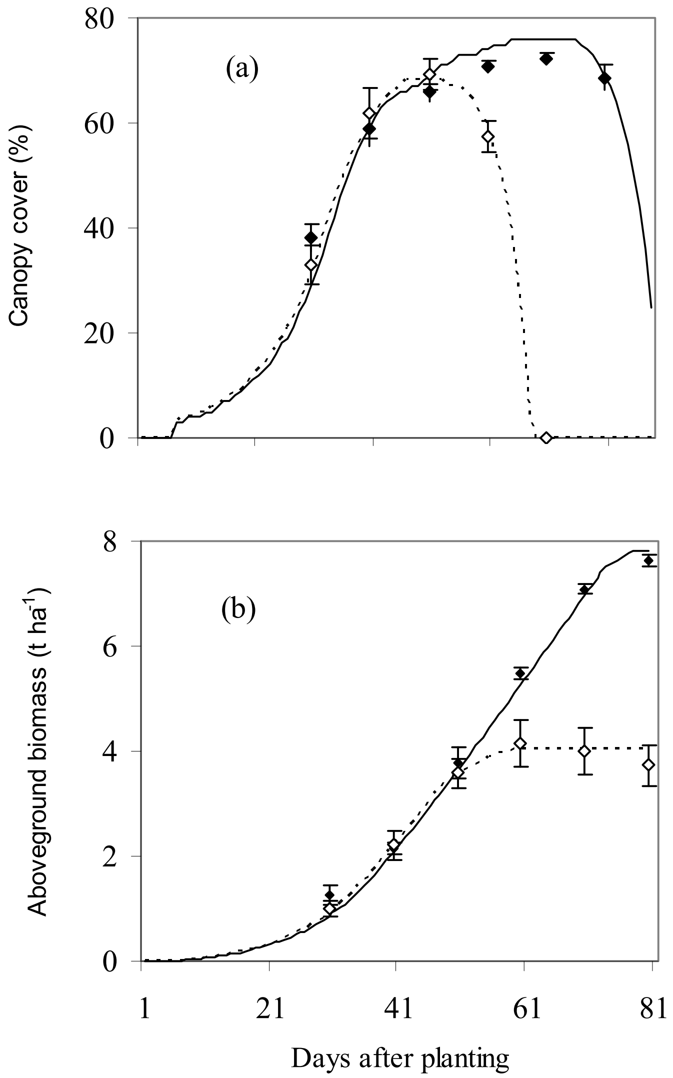

Figure 5.3a & b. The simulated (line) as compared with the observed (diamond) canopy cover progression (a) and aboveground biomass accumulation (b) at different growth stages for treatment with eight irrigations (filled diamond) and rainfed (open box) in the cropping season 2008. Vertical bars are standard deviation. The eight irrigation and rainfed treatments were used for calibration and validation respectively.

The water stress key physiological variables were changed around the default values to reproduce the observed sequential canopy cover and biomass data. Crop data inputs used in the model for simulation of teff productivity are shown in Table 5.3.

Table 5.3. Crop parameters used in AquaCrop to simulate teff productivity.

Description	Value	Units	Interpretation
Canopy cover per seedling at 90% emergence (CC_o)	0.15	Cm^2	
Canopy growth coefficient (CGC)	9.9	%	Increase in CC relative to existing CC per day
Maximum canopy cover (CC_x)	80	%	Well covered
Maximum crop coefficient	0.95	-	At max. canopy
Canopy decline coefficient (CDC) at senescence	16.2	%	Decrease in CC relative to CC_x per day
Water productivity	20	gram m^{-2}	Biomass per m^2
upper threshold for canopy expansion	0.2	-	Above this leaf growth is inhibited
lower threshold for canopy expansion (P_{lower})	0.5	-	Leaf growth stop completely at this *P* value.
Leaf expansion stress coefficient curve shape	3.5	-	
upper threshold for stomatal closure	0.7	-	Above this stomata begins to close
Stomata stress coefficient curve shape	4.5	-	
Canopy senescence stress coefficient (P_{upper})	0.79	-	Above this canopy senescence begins
Senescence stress coefficient curve shape	3.5	-	Moderately convex.
Reference harvest index (HI)	25	%	Common for good condition
Duration of flowering	16	days	-
Duration of yield buildup	35	days	-
Total growing period	85	Days	Emergence to maturity
Coefficient, adjustment of HI to water stress during flowering	0.85		Upper threshold to failure of pollinations
Coefficient, HI increased due to inhibition of leaf growth before flowering	1.0		Maximum HI increased by inhibition of leaf growth before flowering
HI decreased caused by water stress during yield formation.	5.0	-	HI reduced by inhibition of stomata at yield formation.

HI, harvest index.

Figure 5.4 shows the 1:1 linear correlation between observed and simulated dry final aboveground biomass and grain yield. The simulated aboveground biomass and grain yield agreed well with their corresponding observed data for all treatments. Table 5.4 shows the statistical test of the model for aboveground biomass and grain yield. The moderately high R^2 (> 0.95) and ME values (0.82 - 1) and the moderate RMSE values (0.20 - 0.9) confirm that the model simulated the biomass and grain yield accurately. The simulated yield was well simulated under optimal and mild water stress conditions. However, the model has slightly under estimated the grain yield under severe water stress condition. Table 5.4 demonstrates that the yield simulation in water stressed treatments were not as good as those in well watered treatments.

Table 5.4. The root mean square of error (RMSE) and model efficiency (ME) and % of deviation for the measured final aboveground biomass and grain yield in 2008 and 2009.

		Biomass				Grain yield		
Site	Year	Treatment (no. of irrigation)	RMSE (t ha^{-1})	ME (-)	% deviation	RMSE (t ha^{-1})	ME (-)	% of deviation
Mekelle	2008	8	0.92	1.00	-0.60	0.21	0.83	+6.20
		6	0.64	0.82	+8.50	0.10	0.78	+4.60
		4	0.69	0.97	+3.70	0.11	1.00	-0.80
		2	0.25	0.92	-2.80	0.17	0.84	-16.50
		0	0.30	0.95	+3.10	0.11	0.90	-10.30
Ilala		0	0.21	0.93	+2.60	0.05	0.75	+8.50
Mekelle	2009	9	0.36	1.00	+0.70	0.06	1.00	+0.40
		4	0.52	1.00	-1.10	0.12	0.64	-18.70
		0	0.20	1.00	-0.10	0.11	0.85	-22.50

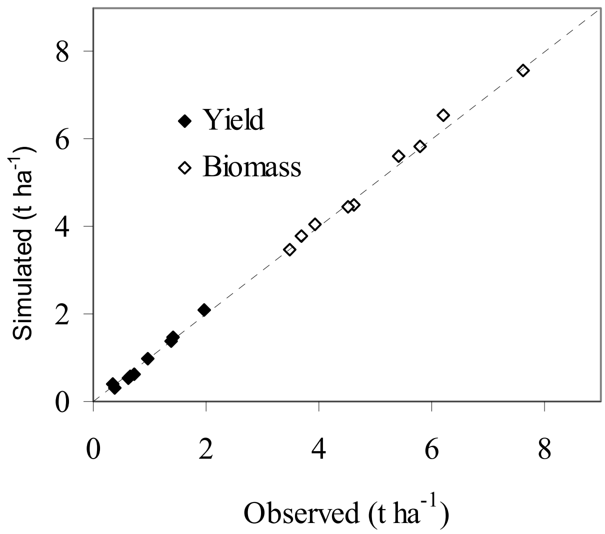

Figure 5.4. Simulated versus observed mean final dry aboveground biomass (open diamond) and grain yield (filled diamond) for Mekelle (n = 9) and Ilala sites (n = 1) for the 2008 and 2009 seasons. (---- 1:1 line); in both seasons R^2 > 0.95.

5.3.3 Water use efficiency (WUE)

The rainfall received in 2009 was higher in amount per rainy day than 2008. But the total actual transpiration in 2009 was lower than 2008 (Table 5.5).

Teff grain yield was improved when water supply increased in both years (Table 5.5). Grain-WUE increased with an increase in water supply up to eight irrigations indicating that a nearly optimum water supply may improve the grain yield of teff. Biomass-WUE, however, attained a maximum value in the two-irrigation and no irrigation treatment in 2008 and 2009 respectively (see Table 5.5).

The Green-WUE increased when water supply was improved. The values showed a minimum of 25% and a maximum of 50% for teff under rain-fed and well irrigated conditions respectively (Table 5.5). These figures are much better than those reported by Stroosnijder (2009) for sub-Sahara Africa (5-15%) and east Africa (20%). However, Green-WUE in 2009 was much lower than 2008.

Table 5.5. The HI, Grain-WUE and BM-WUE under various water level treatments at Mekelle and Ilala sites for the cropping season 2008 and 2009.

Site and year	Treat ment	T (m^3 ha^{-1})	Rain + Irr. (m^3 ha^{-1})	GY kg ha^{-1}	BY kg ha^{-1}	HI (-)	Grain-WUE (kg m^{-3})	BM-WUE (kg m^{-3})	Green-WUE (%)
Mekele	R+ 8	1399	2795	1950	7620	0.26	1.39	5.45	50
(2008)	R+ 6	1185	2556	1170	6220	0.19	0.99	5.25	46
	R+ 4	986	2316	970	5400	0.18	0.98	5.48	43
	R+ 2	759	2046	730	4630	0.16	0.96	6.10	37
	R+ 0	663	1846	640	3930	0.16	0.98	5.93	36
Ilala (2008)	R+0	690	1879	350	3700	0.09	0.51	5.36	37
Mekelle	R+9	1280	3670	1400	5800	0.24	1.09	4.53	35
(2009)	R+4	945	3176	610	4530	0.13	0.65	4.79	30
	R+0	696	2776	370	3480	0.11	0.53	5.00	25

Note that 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

5.4 Discussions

Teff is a C_4 plant (Teffera, et al., 2000). The obtained normalized crop water productivity (NCWP) for teff was lower than the default value for C_4 plants in the model. The possible reasons were: (i) Lower N uptake by the crop as a result of leaching and denitrification and/or lower N dose applied and (ii) short growing period of the crop.

Application of sufficient N fertilizer significantly increases transpiration and water use efficiency and hence improves yield (Jensen et al., 2003; Pala, et al., 2007). In line with this statement Raes, et al. (2009) out lined that lower N doses may lead to lower crop water productivity. The available information on teff nitrogen requirement is limited, complex and area specific. Habtegebreal et al. (2007) reported that biomass and grain yield increased linearly with increase in N up to 90 and 60 kg N per hectare respectively. The grain yield showed a decreasing trend when the N fertilizer increased from 60 to 90 kg ha^{-1}. N fertilizer beyond 90 kg ha^{-1} in teff was also reported to improve the aboveground biomass but in most cases difficult for management as the crop is susceptible to lodging (Teffera, et al., 2000). Lodging is the major yield limiting factors in teff under high rainfall and more fertile soils in Ethiopia (Teffera, et al., 2000). We applied 60 kg N per hectare, half at planting and the other half at 30 days after planting. The applied N was based on the general practice in the region which does not consider the difference in soil characteristics and rainfall condition. Leaching and denitrification may also have their share as N is a mobile nutrient (Teffera, et al., 2000; Jensen et al., 2003).

The second major reason for the lower NCWP is possibly due to the short growing period of the crop because plant synthesis accumulation is a function of time and many other environmental factors (Teffera, et al., 2000). Teff, unlike many C_4 plants, has short growing cycle.

Severe water stress (rainfed treatments) that occurred after the crop has reached at the end of vegetative stage or start of heading has induced fast senescence when compared with the non-stressed treatments. Consequently a rapid decline in canopy cover was noticed (Figure 5.3a). Similarly the aboveground biomass production was also reduced. Much of the reduction in biomass simulated for the rainfed situation (Figure 5.3b) must be the result of stress-induced early canopy senescence.

In AquaCrop, harvest index (HI) is simulated by a linear increase with time (Steduto, et al., 2009). HI in treatments with nearly optimal water condition (eight irrigations) increased with time and reached the reference level. But it didn't increase in rainfed treatments because it was stopped by water stress. Aggarwal et al., (1986) found similar HI trend in wheat with irrigated treatments. The adjustment of harvest index to water stress depends on the timing and extent of water stress (Steduto et al., 2009). Adjustments for pollination failure, for inhibition of stomata, for reduction in green canopy duration, for pre-flowering stress were taken into account in the simulation.

AquaCrop simulated the aboveground biomass accurately at different growth stages of the crop. The final aboveground biomass in the different irrigation treatment differed by far from each other but almost all of them fall in the 1:1 lines (Figure 5.4). Statistical evaluations also confirmed that the model is robust and accurate.

The model has also simulated the grain yield with good accuracy under optimal and mild water stress conditions (Figure 5.4). But it has slightly underestimated the observed yield under severe water stress treatments (rainfed). To some extent we managed to adjust the yield by changing the water stress and harvest index parameters to best fit the simulated yield with the observed. However, we noticed that some other factors such as the slight mismatches between the measured and simulated soil water as in Figure 5.2b, might have contribute to this minor difference. However, despite the slight difference, our statistical evaluation showed a moderately strong relationship with the observed data (Table 5.4; Figure 5.4).

In the eight and nine irrigations treatment, the grain yield and aboveground biomass were significantly higher when compared with other treatments. In addition, the treatments have relatively higher grain water use efficiency. However, they have moderate biomass-water use efficiency. This implies that in water-stressed conditions with no restriction of arable land and when the main aim is to produce fodder, biomass yield can be improved by applying less water (two irrigations after flowering) to a large area of irrigable land. But when the main aim is to produce grain, a nearly optimum irrigation application would be the best choice.

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 teff crops will be higher compared with teff crops that have encountered a shortage of water in the mid stage of its growth. The Green-WUE in 2009 was much lower than 2008 because the proportion of water used to the water supplied was much lower in 2009 when compared with the growing season 2008. Most likely the loss of more rainwater in the form of runoff has contributed to the relatively lower Green-WUE in 2009. To improve Green WUE in semi-arid Africa, the use of onsite area practices (such as mulch, conservation tillage and water-nutrient synergy), onsite line practice (such as hedgerows) and offsite practices (such as the use of water harvesting practices) were recommended (Stroosnijder, 2009). However, the practices have not been tested or documented for teff crop.

5.5 Conclusions

We found close agreement between the simulated and observed canopy cover both under rainfed and irrigated condition. The simulated aboveground biomass and grain yield was also in close agreement with the observed. These findings confirm that the AquaCrop model can be considered as a valid model. The statistical evaluations for biomass and grain yield also confirm the model's validity.

The Grain-WUE of teff was improved when supplied with eight irrigations compared to 9, 6, 4, 2 or no irrigations after start of flowering. However, two irrigations resulted in better Biomass-WUE as compared to other treatments. In other words, assuming that water is scarce and land is not limited, both grain and biomass gave significantly higher yield with optimum irrigations after start of flowering, though more biomass would have been gained if less irrigation had been applied to a larger area.

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 teff. However, there is no universal model; the applicability of key calibrated variables must be tested under different conditions (Farahani et al., 2009). As Hsiao et al. (2009) already indicated, further comprehensive refinements (calibration) may be important in order to include more characteristics of the crop in response to the diverse climate, cultivar, soil and agronomic (such as macro and micro nutrients interactions with water, variety, planting density and other environmental factors) conditions.

Chapter 6

Determination of local barley (*Hordeum vulgare*) crop coefficient and comparative assessment of water productivity for crops grown under the present pond water in Tigray, northern Ethiopia

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Determination of local barley (*Hordeum vulgare*) crop coefficient and comparative assessment of water productivity for crops grown under the present pond water in Tigray, northern Ethiopia

Abstract

An experiment was carried out in 2010 at Mekelle, in northern Ethiopia, to measure the evapotranspiration, to estimate barley crop coefficient (k_c), and to evaluate the water productivity taking into account the major crops grown under the present pond irrigation system. Four locally made lysimters were installed in the middle of barley field to measure barley evapotranspiration. The single crop coefficient approach was used to estimate barley crop coefficient. The average seasonal evapotranspiration of barley was 375 mm which is similar to many other cereal crops in the region. The single crop coefficient values for early, vegetative, mid and late crop stages were 0.6 – 0.8, 0.6 – 1.0; 1.0 – 1.05 and 0.3 - 0.4 respectively. The result showed that these crop coefficient values obtained in this experiment were similar to the crop coefficient values obtained in the past except for k_c initial. Therefore, the assumption that local barley crop coefficient values differ from that of the documented values was incorrect. Furthermore, the major reason for mismanagement of irrigation water in barley fields was not due to use of wrong crop coefficient values but could be due to inadequate irrigation technical skill and knowledge of the farmer. The average economic water productivity (EWP) of barley for the very wet, wet, normal, dry and very dry seasons scenario were 0.99, 0.7, 0.65, 0.57, and 0.44 USD m^{-3}, respectively, whereas the corresponding crop water productivity (CWP) values for grain were 1.53, 1.08, 1.0, 0.88 and 0.68 kg m^{-3}, respectively. The EWP and CWP of barley were compared with onion and tomato under pond water irrigation at the five climatic scenarios. The crop water productivity for tomato and onion were 85 – 87% and 76 – 78% higher than that of barley, respectively. The corresponding economic water productivity for tomato and onion were 87 – 89% and 81 – 82% higher than that of barley, respectively. We concluded that growing tomato and onion would bring more income or yield per m^3 of pond water supplied than growing barley. Evaluation of crops based on their water productivity would improve the productivity of irrigation schemes and ultimately improve food security in the arid and semi-arid areas where water scarcity is critical problem and irrigation is a necessity for crop production.

6.1 Introduction

Barley is a major staple food crop in the highlands of northern Ethiopia. The crop is used for preparing various types of traditional food such as *Kita, Kolo, Beso, Enjera, Giat*, and many others. Although the day to day survival is linked to barley, little focus has been given to improve the productivity of the crop in the dry land area.

The climate over the northern Ethiopia is characterized by uncertainties of rainfall both in distribution and in amount. The crop yield has been severely affected mainly due to water stress that occurs during part of its growing period (Araya and Stroosnijder, 2010; Araya et al., 2010 a & c).

In this region, the sustainable food production could possibly be ascertained through judicious use of water. According to Fereres and Soriano (2006) the sustainable use of water has to consider maximizing yield per unit of water rather than maximum yield per unit of area. To put this concept into practice requires at least: (i) detailed information on the crop water relations and crop water productivities and (ii) Water supply for agriculture has to be developed/ explored. The former deals mainly with different evaluation techniques such as the application of crop water productivity (Bessembider et al., 2005) that aims at the viability of irrigation projects. For example, the economic water productivities (EWP) and crop water productivity (CWP) are some of the most important elements that can be applied in the evaluation of irrigation project (Araya et al., 2011). Many farmers in the northern Ethiopia grow crops without considering the EWP and CWP for different cropping scenarios due to lack of local information on crop water relations and crop water productivities.

The second prerequisite for sustainable use of water was developing/ exploring water source for agriculture. Some efforts were made by the government to store rainwater through household pond storage system. The constructions of the household ponds have been intensified since a decade with the main objective of supplementary irrigation. Following the construction of household ponds, many farmers have started growing barley with supplementary irrigation. However, mismanagement of water has been among the major problems observed in many of the irrigated barley fields. This could be due to lack of information on water requirement of local barley. General crop coefficient values for various crops including for barley are available in Doorenbos and Pruitt (1977) and Allen et al. (1998). The documented *k*c values are used for all cultivars of the same crop and climate conditions across the world. We hypothesized that the crop coefficient for the local barley cultivars grown in the northern semi-arid Ethiopia differ from the documented values and hence we suggested that developing at least indicative local *k*c values could save the scarce water in dry environment like the case of northern Ethiopia. To obtain accurate local *k*c value requires the use of standard lysimeters. However, standard lysimeters are very expensive and not available in our region. To solve this problem, we used locally made lysimeter to measure evapotranspiration and derive crop coefficient values (indicative) for the local barley.

Crop coefficient is a function of crop evapotranspiration and reference evapotranspiration. There are two approaches of determining crop coefficient: the single and dual crop coefficient approaches. The dual crop coefficient approach splits the evapotranspiration into evaporation and transpiration. This method is used under research and in real time irrigation scheduling (Allen et al., 1998). In the single crop coefficient, the effect of crop transpiration and evaporation are combined into a single k_c value. This single crop coefficient values are used for planning of a typical irrigation management (Allen et al., 1998). In our study, the single crop coefficient approach was used to derive the indicative k_c values for *Saesea* a local barley crop under the local environmental condition.

The objectives of this research are to: (i) study the evapotranspiration and crop coefficient of local barley (*Saesea*) under local climate using locally made lysimeter, (ii) Evaluate the economic water productivity and the crop water productivity of barley in comparison with some major vegetable crops grown under the present pond water use conditions in the northern Ethiopia.

6.2 Materials and methods

6.2.1 Experimental site

The experiment was conducted in 2010 (February to May) in northern Ethiopia (lat 13^o 29' N and long 39^o 35'E, 2130 m above sea level (Figure 6.1). The water content at field capacity of the 0 - 0.2 m layer is 27 vol% and at 0.2 to 0.6 m is 37 vol%. The corresponding values for the permanent wilting points are 14 and 22 vol%, respectively. The maximum rooting depth for the local barley is 0.6 m (Araya et al., 2010a).

Climate data such as rainfall, humidity, temperature, wind speed, sunshine hours and radiation data were obtained from the weather station at Mekelle University (about 200 m far-off the study site). At the site, the long-term average annual precipitation is about 600 mm, 70 to 80% of which is received between the month of June and September while the other 20 to 30% is received between the month of February and May. Reference evapotranspiration (ET_o) was computed based on the full data set using FAO-Penman-Monteith equation and ET_o software program (FAO, 2009). The average annual reference evapotranspiration is about 1700 mm. The minimum and maximum temperatures are 11°C and 28°C respectively.

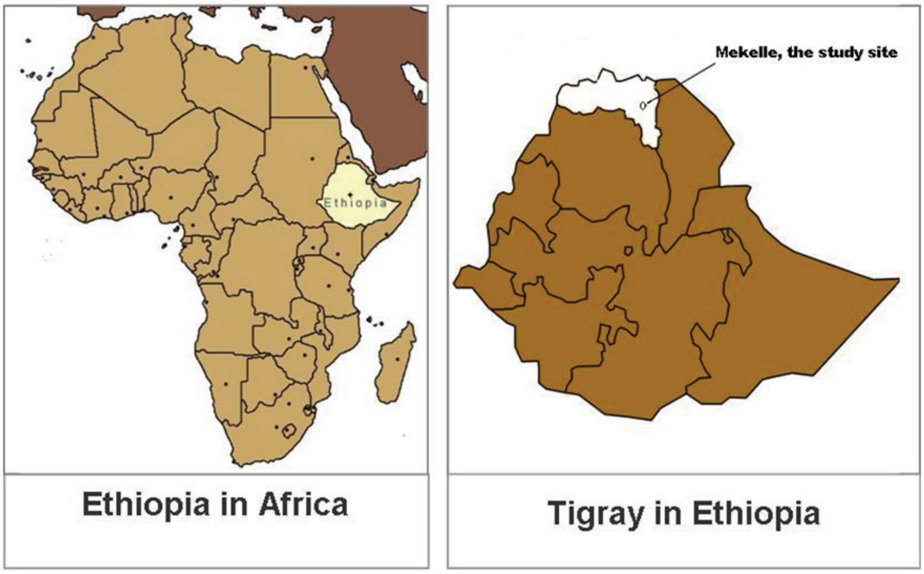

Figure 6.1. Map of Ethiopia and the study area in Tigray region.

6.2.2 Locally made lysimeters (hereafter drums) and crop details

Evapotranspiration data of barley was collected using four drums (Figure 6.2) which were installed at four representative positions of barley field. The design of the drums was similar to the one presented in Araya et al. (2011). The drums were installed about 5 m apart. The drums had a diameter of 0.6 m and depth of 1 m. They were designed to replace the more expensive lysimeters and were suitable for barley since the maximum rooting depth of the local barley was only 0.6 m and the final plant population was about 100 to 155 plant per m^2. The drums had a solid base with an outlet for collecting drained water through a perforated iron sheet. On top of this sheet was 0.1 – 0.15 m of gravel and 0.1 - 0.15 m sand, covered with a 0.01 m thick sisal sheet (Figure 6.2). Deep percolation beyond the root zone was collected in a receptacle under the drums and measured using a calibrated cylinder.

The drums were placed in the field containing the holes left after the original soil column had been carefully removed. To minimize the boundary effect, the rim of the installed drums was set flush with the soil surface. Then the soil column was replaced in the drums with minimal disturbance, on top of the sisal cover. The drum was positioned exactly similar to the field condition. The drums including the field were irrigated and left for some time to minimize variation from the field. The common barley cultivar (*Saesea*) was sown in the drum and at the field by broadcasting in early February at a rate of 120 kg per hectare. The field and the drum were kept at field capacity throughout the growing period. All crop management techniques followed the recommended practices; for example, DAP (Di-ammonium phosphate) and urea fertilizers were applied at a rate of 100 kg per hectare each (64 kg N and 46 kg P per hectare). The nitrogen in the form of urea was applied twice: half at sowing and the other half a month after planting. Crop biomass and yield were obtained after maturity.

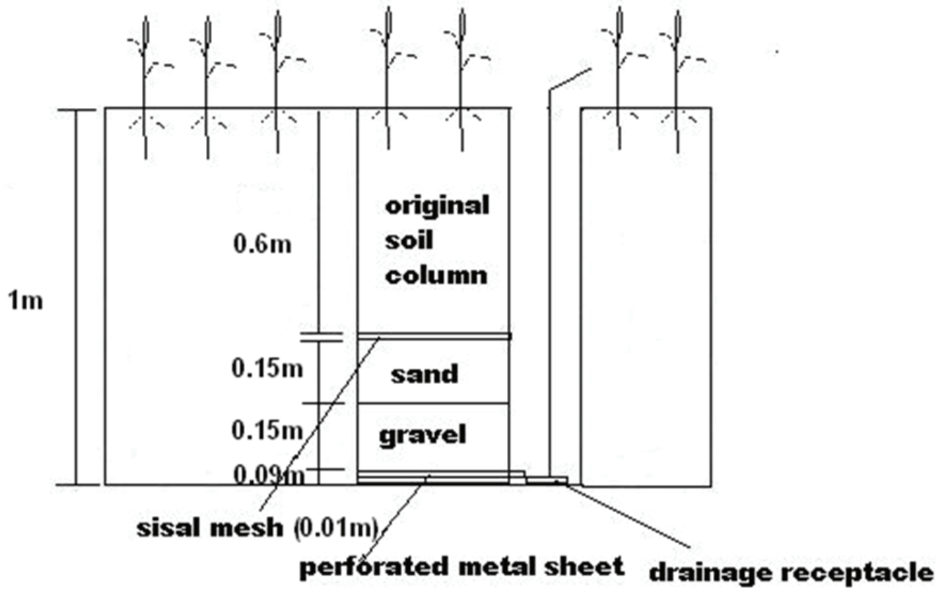

Figure 6.2. Sketch of the locally made lysimter used for measuring barley crop evapotranspiration.

6.2.3 Soil water balance

Time domain reflectometry (TDR) (Eijkelkamp, 1996) was used to measure the soil moisture. Three glass fibre access tubes were installed at each drum to depths of 0.8 to 1 m. TDR reading were observed on alternate days at 0.1 m intervals before and after irrigation. For a proper calibration, gravimetric soil moisture was also measured.

In the drum experiments, a depth of about 15 - 45 mm irrigation water was applied uniformly using a calibrated plastic can every 3 to 4 days depending on the availability of soil water in the root zone. Barley evapotranspiration was computed from the water balance (Equation 6.1) (Allen et al., 1998):

$$ET_c = I + P - D - Ro \pm \Delta S \qquad [6.1]$$

Where:
ΔS is the change in soil moisture storage between soil moisture measurements (mm)
I is irrigation (mm).
P is rainfall (mm).
D is drainage (mm).
Ro is runoff (mm).

There was no runoff because water application was controlled. Groundwater effect was ignored because the water table was deep.

6.2.4 Crop Coefficient

Barley crop coefficient (k_c) values for the initial, mid and late season stages were calculated by dividing the barley evapotranspiration (ET_c) (obtained from the water balance) by the reference evapotranspiration (ET_o) (effect of climate) (Equation 6.2) which is described in Doorenbos and Pruitt (1977); Allen et al. (1998) and Liu et al. (2002) but the difference is that ET_c was derived from the drum.

$$k_c = \frac{ET_c}{ET_o} \qquad [6.2]$$

6.2.5 Irrigation water requirement and crop water productivity

A survey was conducted on 48 household ponds in 2005 to study the economic water productivity and irrigation crop water productivity of the major crops grown under pond irrigation around the study site (at a radius of about 5 to 50 km) (Araya et al., 2006). Data on the pond capacity, the irrigation method, soil type, major crops grown in the area, and the cropping period were gathered (Araya et al., 2006). Taking the major crops grown under irrigation in the area (onion, tomato and barley) as a reference is necessary in the evaluation because comparisons have to be made to demonstrate that the choice of crop and cropping pattern determines the viability of any irrigation project.

The precipitation over the 1960 - 2009 was statistically evaluated. Test of homogeneity was applied and the data was proven to be consistent. The probability of exceedance of decadal rainfall over the record period was analysed and this was used to determine the decadal dependable precipitation and classified in scenarios as: > 20% (very wet), 40 - 20% (wet), 60 - 40% (normal), 80 - 60% (dry) and < 80% (very dry). Grouping of the long-term decadal rainfall into five rainfall scenarios would make it more representative than just taking one long-term mean decadal rainfall value. Hence, it minimizes errors that could occur due to over or under estimation of the long-term rainfall data. In addition, the use of long-term mean values of the short range probability as described above is more accurate and representative than use of wider range. Mean values for these ranges were obtained and each respective probability level was used in the estimation of crop water requirement however about 25% of the rainwater was estimated to be lost as runoff (Araya and Stroosnijder, 2010). Thus, the net irrigation water requirement was computed based on Equation 6.3.

$$NIWR = ET_c - R_p \times (0.75) \qquad [6.3]$$

Where:
NIWR is net irrigation water requirement.
R_p is the respective dependable decadal rainfall for each corresponding scenario.

The 0.25 was deducted due to runoff hence 0.75 was taken as a multiplier. Gross irrigation (GIWR) requirement was estimated from the project efficiency and net irrigation water requirement as shown in Equation 6.4.

$$GIWR = \frac{NIWR}{P_E} \qquad [6.4]$$

Where:
P_E is project efficiency.

The product of conveyance, distribution and field application gives project efficiency (Doorenbos and Pruitt, 1977). As the distance between irrigable area and pond was so short and the type of irrigation method was a direct water application (such as using plastic cans and pump), thus, only field application loss was considered. The major soil textures in the study area were loam and silt loam. Hence, the field application efficiency for medium textured soils was taken as 70% (Doorenbos and Pruitt, 1977). The total irrigable area by the household pond was estimated based on Equation 6.5.

$$TIA = \frac{NPC}{GIWR} \quad [6.5]$$

Where:
TIA is total irrigable area (ha).
NPC is the net pond capacity (m^3).
GIWR is gross irrigation water requirement (m^3 ha^{-1})

Economic water productivity (EWP) is expressed in gross income in USD per gross water supplied in m^3 while the crop water productivity (CWP) is expressed in gross weight of product (kg) per gross water supplied (m^3). EWP was computed from the estimated irrigable area, obtainable yield and from the seasonal price (USD) of the main product and bi-product as shown in Equation 6.6. Local market price was considered because almost all of the products are consumed locally under the present condition. EWP was thus calculated based on Equation 6.6.

$$EWP = \frac{GI}{GIWR} \quad [6.6]$$

Where:
GI is gross income from the sale of grain and straw (USD).
GIWR is gross irrigation water requirement (m^3).

The crop water productivity (CWP) was also computed based on Equation 6.7.

$$CWP = \frac{GY}{GIWR} \quad [6.7]$$

Where:
GY is the main yield (kg ha^{-1}).

6.3 Results and discussion

6.3.1 Crop development stages

The crop growing season has been divided into four based on Doorenbose and Pruitt, (1977). Table 6.1 shows the length of crop development stages of the three crops (onion, tomato and barley) grown under irrigation in the region particularly around the study site. The initial stage refers to crop germination/transplanting. It also refers when the soil surface is not covered by the crop (canopy cover < 10%). The crop development stage denotes the vegetative period of the crop that includes from the end of initial stage to full canopy cover (canopy cover 70 – 80%). The mid-season stage represents the period between full ground cover to the time of start of maturity (leaf yellowing). Late season stage stands for the crop period from end of mid season stage to full maturity.

Table 6.1 The length of growth stages (days) of the crops grown under irrigation near the study site, in Tigray, northern Ethiopia.

Crop	Initial	Vegetative	Mid	Late	Total (days)
Onion	15	25	70	30	140
Tomato	30	30	50	30	140
Barley	18 -20	18 - 20	28 - 30	18 - 20	82 - 90

6.3.2 Reference evapotranspiration and crop evapotranspiration

The relationship between reference evapotranspiration (ET_o) and barley crop evapotranspiration (ET_c) is shown in Figure 6.3. The evapotranspiration of the crop varied across the growing stages. The ET_c at the early stage was lower than the ET_c at the vegetative and mid season stages (Figure 6.3). There was higher ET_c at vegetative than initial stage and mid than vegetative stage mainly caused by change in plant characteristics. The trend is in agreement with reports for various crops documented in the past (Doorenbose and Pruitt, 1977; Allen et al., 1998).

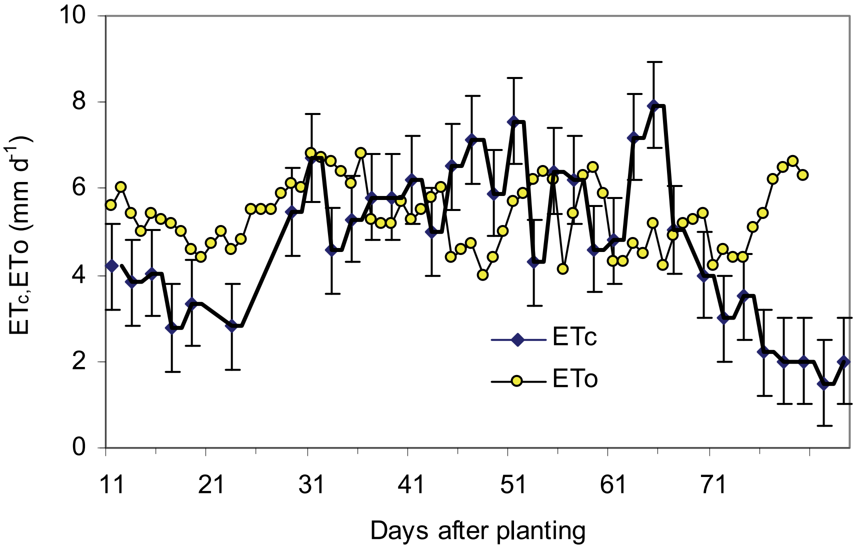

Figure 6.3. The ET_o and the measured ET_c for barley in 2010 at Mekelle, northern Ethiopia.

ET_o was higher than the ET_c during the initial and development stages whereas ET_c was higher than the ET_o during the mid stage of the crop. The ET_c and ET_o at initial stage varied from 3 to 4 mm per day and 4.4 to 5.4 mm per day respectively. The difference could be attributed mainly to low canopy cover of the crop at sowing. The majority of evapotranspiration at sowing come from soil evaporation (Allen et al., 1998), in contrast, reference evapotranspiration refers to a (reference grass) well grown green grass, fully covering the ground (Doorenbose and Pruitt, 1977) and hence the well grown reference grass is assumed to extract and to use more water for its evapotranspiration than a crop just sown before few days. ET_c and ET_o increased during the vegetative stage from 3.3 to 6.7 and 4.6 to 6.8 mm per day respectively. Like the initial stage, the difference could be mainly due to the effect of crop characteristics because ET_c is affected by the nature of the crop (leaf arrangement, stomata and plant height) and crop growth stage. Both ET_c and ET_o reached their equilibrium approximately at 30 days after planting. This implies that the crop has fulfilled at least equivalent to the requirement of the reference (hypothetical) grass as defined in FAO-56. ET_c of barley was slightly higher than the ET_o during the time between 35 and 65 days after planting (Figure 6.3). This difference was mainly attributed to change in plant characteristics. Barley crop at this stage acquires higher canopy cover and relatively deeper roots to extract water from deeper soil profile and hence most of evapotranspiration comes from transpiration while minimizing evaporation. ET_c starts to decline at 65 days after planting and reached its minimum level at 84 days after planting and afterwards.

Nagaz et al. (2008) estimated the seasonal ET_c of barley to be about 340 mm whereas in our experiment the seasonal ET_c was about 375 mm. The difference could be attributed to differences in climate and cultivar characteristics.

Table 6.2. Crop coefficient (k_c) values used for crops grown under irrigation near the study site in Tigray, northern Ethiopia.

Crop	Initial	Vegetative	Mid	Late	Source
Onion	0.6	0.75	1.05	0.75	Doorenbos and Kassam (1979); Allen et al. (1998)
Tomato	0.45	0.75	1.15	0.7	Doorenbos and Kassam (1979); Allen et al. (1998)
Barley	0.35	0.75	1.05 – 1.2	0.15-0.45	Doorenbose & Pruitt (1977); Brouwer & Heibloem (1985); and Allen et al.(1998)
Barley	0.6 –0.8	0.6 – 1.0	1.0 - 1.05	0.3 – 0.4	Local experiment result

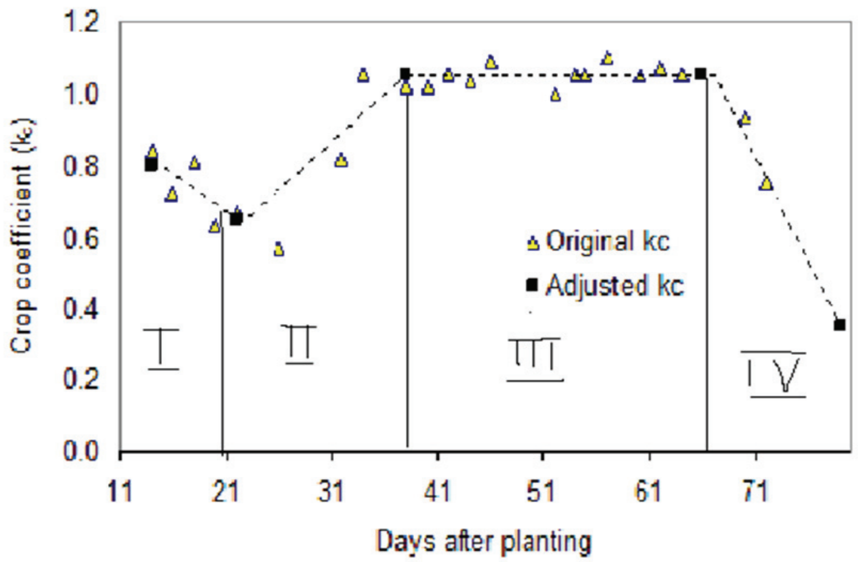

Figure 6.4. The original and adjusted crop coefficient (k_c) values for barley obtained during the experimental season in 2010 at Mekelle, northern Ethiopia. I, initial stage; II, crop development stage; III, mid season stage; IV, late season stage.

6.3.3 Crop coefficient (k_c)

The single crop coefficient values for barley are given in Table 6.2. Accordingly, the k_c values increased from initial stage to mid season stage and decreased during the late season stage (Figure 6.4). Figure 6.4 shows the relationship between the original and adjusted k_c values. In this case, the adjusted k_c values are the single representation of k_c based on crop stage while the original k_c values are the mean of the k_c values for each observation event. The k_c value for vegetative stage can also be obtained by interpolation.

There was also an increasing trend in k_c during the first few days after germination attributed to frequent wetting and soil evaporation. k_c value started to decline at the end of initial stage because of decrease in soil evaporation. Then, the development (vegetative) stage k_c values started to increase up to the mid season stage and form a plateau for about 30 days and later declined during the late season stage

(k_c started to decline at 66 days after planting). The later trend agreed well with previous studies (Doorenbose and Pruitt, 1977; Allen et al., 1998). The k_c value for the initial stage varied widely compared to the other growth stages of the crop. Allen et al. (1998) stated that evapotranspiration during the initial stage is dominated by evaporation component. Thus, the interval between wetting events, the magnitude of the wetting events and evaporative power of the atmosphere determine the values of k_c at initial stage. Generally, the k_c values for crop development, mid and late season stage of barley obtained in our experiment were similar to that of the values documented in FAO publications as shown in Table 6.2. Thus, this research verified that the local barley crop coefficient did not differ much from that of the documented crop coefficient in the past. Hence, the reason for the mismanagement of irrigation water in barley fields was not due to wrong k_c value but could be due to other factors such as lack of awareness, lack of skill, technology and lack of adequate knowledge in applying the documented k_c values into practice.

6.3.4. Crop water productivity (CWP)

The average gross and net pond capacity in the surveyed sites were 180 m^3 and 127 m^3 respectively (Araya et al., 2006). The average obtainable yields of barley, onion and tomato which are the main products under irrigation in the study area were 2000 kg ha^{-1}, 18000 kg ha^{-1} and 25000 kg ha^{-1} respectively. The barley straw (bi-product) was also considered in the analysis (8000 kg ha^{-1}). The average current season price per kg of the product was considered in the analysis. Accordingly, the mean of one season price per kg of barley, onion and tomato was respectively 0.4, 0.8 and 0.75 USD. The average current season of local market price of barley bi-product was estimated to be 0.0615 USD per kg.

Table 6.3. Crop water productivity (CWP, kg m^{-3}) of onion, tomato and barley under the present pond water use in Tigray, northern Ethiopia.

Crop	Very wet	Wet	Normal	Dry	Very dry
Onion	7.0	4.8	4.3	3.7	2.9
Tomato	12.2	7.7	6.9	6.0	4.6
Barley	1.53	1.08	1.0	0.88	0.68

Table 6.3 indicates the crop water productivity in terms of gross produce obtained per gross pond water supplied. In this case, crops have different water productivity due to difference in water requirement and productivity per given area of land. The analysis showed that CWP of tomato was substantially higher than that of the onion and barley and the CWP of onion was considerably higher than that of barley. The crop water productivity for tomato and onion were 85 – 87% and 76 – 78% higher than that of barley, respectively.

The crop area coverage per pond water supplied across the various seasons scenarios were evaluated. The result showed that a very dry season scenario has lower crop area coverage than that of the other seasons. Consequently, the yield obtained per gross pond water was small. Higher yields of tomato per a given drop of water were obtained compared to onion and barley (Araya et al., 2006). Hence, tomato has relatively higher crop water productivity.

Table 6.4. Economic water productivity (EWP, USD m^{-3}) of onion, tomato and barley under the present pond water use in Tigray, northern Ethiopia.

Crop	Very wet	Wet	Normal	Dry	Very dry
Onion	5.6	3.9	3.4	3.0	2.3
Tomato	9.2	5.8	5.2	4.5	3.4
Barley	0.61+(0.38)	0.43+(0.27)	0.4+(0.25)	0.35+(0.22)	0.27+(0.17)

Note: the values in bracket are the gross income gained from the sale of the straw.

6.3.5 Economic crop water productivity (EWP)

Increase in crop production per unit of water does not necessarily result into an increase in the farmer's income because of the non-linearity of crop yield with the price of products. Table 6.4 shows the economic water productivity of barley, onion and tomato. Accordingly, we found out that tomato has the highest irrigation EWP followed by onion. Barely has the lowest irrigation. The economic water productivity for tomato and onion were generally 87 – 89% and 81 – 82% higher than that of barley, respectively. Though, the sale of the bi-products (straw) was also considered for barley, the yield per equivalent unit area and the price of barley was lower than onion and tomato. Tomato is perishable and most producers do not allocate larger area for tomato unless they made a deal in advance with their clients. Experience showed that there have been seasonal price fluctuations. Thus, there need to be assessment on the EWP parameters based on the anticipated prices before planting and it is also good to know client's and other producers interest in order to optimize the EWP. Understanding the interest of the farmer and consumer in advance would help in improving or in optimizing the economic water productivity.

Hence, in evaluating EWP, it is essential to study the economic gross income from each drop of water supplied.

Generally, EWP and CWP declined from very wet to very dry climatic scenario because, in very dry scenario, the pond water was enough only for a relatively smaller cropland compared to the other climatic scenarios. Thus both EWP and CWP increase with increase in rainfall.

6.4 Conclusion

The crop evapotranspiration of barley during the main growing season was approximately 375 mm per season. However, this amount can be slightly affected by intra-seasonal weather variability especially with reference to evapotranspiration. For example, in the normal summer cropping season, the reference evapotranspiration may reach 350 mm whereas during the experimental period it has reached about 485 mm.

The average k_c values for initial, development, mid and late stages of local barley were 0.6 – 0.8, 0.6 – 1.0; 1.0 – 1.05 and 0.3 - 0.4 respectively. These values can be applied in the determination of irrigation water requirement of local barley in the region. With the exception for the initial stage, the crop coefficient value of local barley was found to be similar to that of the documented values in the past. Thus, the assumption that the local barley crop coefficient differs from that of the documented crop coefficient was found to be incorrect. The mismanagement of the irrigation water in barley fields could be due to little follow-up, lack of awareness, lack of adequate knowledge and lack of irrigation skill of the farmers. This problem can be minimized through intensive training.

In this study, growing tomato showed higher EWP and CWP than growing onion and barley. This is because the price and the productivity of tomato per unit of water supplied are higher than that of onion and barley. Evaluation of crops based on their water productivity as presented in this research would improve the productivity of irrigation schemes and ultimately improve food security.

As supply and demand determines the price of products, farmers and extension workers need to understand the cropping pattern of the irrigation sites. The extension workers have to give advice in order to balance the area coverage per each crop from the irrigation projects so as to avoid undesirable extreme price falls and rises. Such measures could improve the water productivity of the pond irrigation system.

Chapter 7

Test of AquaCrop model in simulating biomass and yield of water deficient and irrigated barley (*Hordeum vulgare*)

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Test of AquaCrop model in simulating biomass and yield of water deficient and irrigated barley (*Hordeum vulgare*)

Abstract

With the current water shortage in East Africa improving crop water use is vital especially in the arid and semi-arid regions of Ethiopia. To understand the response of barley to water and to simulate the biomass and grain yield of barley under various water inputs and planting dates, we tested the FAO AquaCrop model versions 3.0 using independent data sets during the cropping seasons of 2006, 2008 and 2009 at Mekelle site in northern Ethiopia. We found that the model is valid to simulate the barley biomass and grain yield under various planting dates in the study site. AquaCrop model can be used in the evaluation of optimal planting time. Out of the tested planting dates, planting on July 4 (early sowing) was found to maximize barley biomass, grain and water use efficiency. The model can also be used in the evaluation of irrigation strategies. Barley showed slightly lower performance under mild water stress condition compared to full irrigation condition. However, the model has indicated the possibility of obtaining more biomass and grain yield from a relatively larger barley field under (deficit irrigation) mild stress condition.

7.1 Introduction

In many countries of the sub-Saharan Africa, food production has been hindered by lack of water for agriculture. With the increase in population pressure in many parts of the world, there has been a call to increase food production (to fill the food shortage) through improved water management.

Agriculture has been the main source of employment and livelihood for the majority of Ethiopians. Ethiopian agriculture is highly dependent on natural rainfall. The rainfall over the majority of the country is erratic and unreliable (Tilahun, 2006; Bewket and Conway, 2007; Araya et al., 2010a). The rainfall is torrential in behaviour (high intensity over short time) (Nyssen et al., 2005), which may cause high runoff and waterlogging over short time. It is also characterized by long dry spells, that may also cause severe crop water stress during the critical period and the rainy season mostly ends early before the crop reaches maturity (Araya et al., 2010b). The situations have been worsened by recent unfavourable weather caused by human interference. An increase in risks of drought would be expected under global warming due to increased evaporative demand of the atmosphere (Rizza et al., 2004). Projections of future climate scenarios indicate that severe water and heat stress could be the most crop limiting factors (Vorosmarty et al., 2000; Rizza et al., 2004).

Barley is one of the major staple food crops in Ethiopia. Barley accounts over 60% of the food of the people in the highlands of Ethiopia and it is the cheapest food source in the local market. Traditionally barley is consumed in many different food types such as *Injera, Kita, Beso, Tihlo, Giat* and also consumed in the form of homemade drinks such as *Siwa (Tella)*. Its straw is also used for animal feed. Despite its importance, the productivity remains poor with a national average yield of 1.14 tons ha^{-1} (FAOSTAT, 2006).

Barley performs well in broader altitude range between 1800-3000 meters above sea level (m. a. s. l) (Araya et al., 2010a). Barley resists water stress due to its extensive root system (Fischer and Maurer, 1978). The crop is well adapted to semi-arid environment although its yield has been severely hindered by water deficit and aeration stress (excessive wetness) (Araya and Stroosnijder, 2010; Araya et al., 2010a). The extent of yield reduction may differ depending on the timing, duration, extent and type of stress (aeration stress or water deficit). For example, yield of barley was reported to reduce when it is waterlogged even for few hours during its early stage between 2 and 6 weeks after planting (Setter and Waters, 2003).

The amount and distribution of rainfall has been the major determining factor in barley production in the semi-arid region of northern Ethiopia (Araya and Stroosnijder, 2010). Given that water is scarce for agriculture under the present climate, improved water use has been a challenge to many farmers in Ethiopia. In semi-arid areas where yields are low due to unpredictable rainfall, improving crop water productivity could stabilize yields (Pereira et al., 2002). Mismatches of crop growing period with the seasonal rainy period was reported to cause crop water stress and crop failure (Tesfay and Walker, 2004; Araya et al., 2010a). At present, the rainy seasons in northern Ethiopia are shorter than the length of growing period of the currently available crop varieties in the region. For example, crops adapted to the area require more than 80 days to mature but the rainy period in northern Ethiopia rarely exceeds 65 days. In this region, severe water stress occurs during the grain filling period which corresponds to the cessation of rain in early September. Planting short maturing crop varieties that fit to the growing season has not been fully realized yet, among many others, due to unavailability of improved varieties. Choice of proper planting date of barley could improve the rainwater use. To achieve this, a good understanding of crop response to water stress and tools which simplify the complex crop response to various environmental factors, especially to water, are needed. If we can improve water management systems in barley, it is possible to mitigate the impact of climate change and this will have a positive impact on food security.

The Food and Agricultural Organization (FAO) in its effort to ensure efficient use of water for sufficient food has developed AquaCrop model. The model deals with yield response to water. The model evolved from concepts of yield response to water as presented in Doorenbose and Kassam (1979) to a concept of a normalized crop water productivity (Steduto et al., 2009). Unlike many models, it is simple to understand by none research end users. Besides, the model is accurate, robust and requires fewer data inputs (Hsiao, et al., 2009; Steduto, et al., 2009). Under water constraint environment, like the case of northern Ethiopia where land is not a constraint, there have been needs to evaluate the possibilities of maximizing yield and biomass either through deficit irrigation or optimal irrigation. This can be achieved through the use of a validated water productivity model such as AquaCrop.

In addition, with the projected future climate change, the calibration of the model could be vital for generating yield predictions and for improving water use, the result may be of interest to climatologists, agriculturists, policy makers, planners, practitioners and relief organizations. At present, many interested researchers have established a network to parameterize and calibrate the model for some specific crops (Hsiao et al., 2009). Therefore, taking into account the efforts made by FAO and the overwhelming need of improving water use in the region, we decided to carry out a preliminary calibration of the model using a single location data sets. The objective was to calibrate and validate AquaCrop model version 3.0 for simulating barley yield over three years period with different planting dates and water availability conditions and to evaluate the performance of the model in optimizing planting date and in evaluating water use efficiency under irrigated and rainfed barley conditions at Mekelle study site in northern Ethiopia.

7.2 Materials and methods

7.2.1 Site description

The experiment was conducted at Mekelle site (13^{o} 03’ latitude and 39^{o} 06’ longitude) in 2006, 2008 and 2009. Daily sunshine hours, wind speed, temperature and relative humidity data were obtained from Mekelle University meteorological station which is within 200 m of the experimental site. The mean annual rainfall and reference evapotranspiration for Mekelle site for the period 1960-2009 was approximately 600 mm and 1700 mm respectively. Daily reference evapotranspiration values were calculated using FAO-

Penman-Monteith equation based on full data sets (daily mean wind speed, temperature, relative humidity and reference evapotranspiration) as described in Allen et al. (1998) (Figure 7.1). The maximum and minimum temperatures at the site during the growing periods were 28 and 12 ^{o}C, respectively. The soil at the study site was silt loam, 0.6 m deep overlaid on white calcareous soil fragment. Soil physical characteristics such as bulk density, texture, depth, field capacity, permanent wilting point and water content at saturation of the experimental sites were determined in the laboratory (Table 7.1).

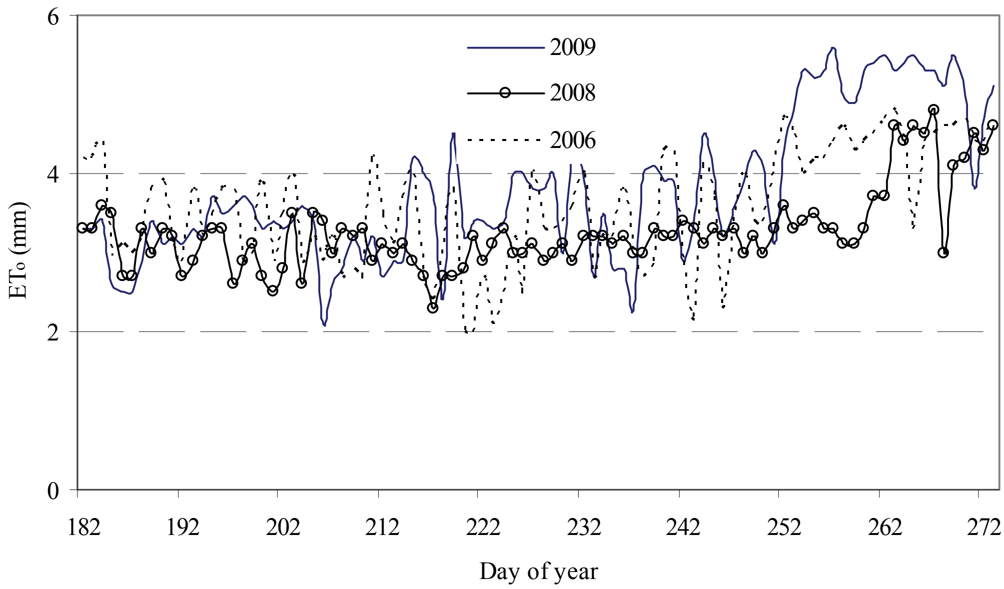


Figure 7.1. Daily reference evapotranspiration for Mekelle area during the cropping period in 2006, 2008 and 2009.

Table 7.1. Soil physical characteristics of the experimental sites.

Site	Depth (m)	Moisture content (vol %)			BD	Ksat	CN
		FC	WP	Sat	(g cm^{-3})	mm day^{-1}	-
Mekelle	0.0-0.2	27	14	50	1.55	250	87
(Barley)	0.2-0.3	42	22	46	1.45	250	
	0.3-0.6	42	22	50	1.45	175	

The total rainfall and irrigation amount during the experimental seasons in 2006, 2008, 2009 for barley are presented in Table 7.2.

Table 7.2. The seasonal rainfall (mm), irrigation (mm) and reference evapotranspiration (mm) and the corresponding barley sowing dates for the cropping season 2006, 2008 and 2009 at Mekelle, Northern Ethiopia.

	Rainfall (mm)				ET_o (mm)			
	Planting date				Planting date			
Year	4-Jul	10-Jul	12-Jul	22-Jul	4-Jul	10-Jul	12-Jul	22-Jul
2006	557	515.3 + (45)	506.3	467.5	314.5	294.5	288.5	254.2
2008	278.1	246.6 + (75)	226.1	212.2	289.8	271.3	265.4	236.1
2009	507.4	490.7 + (95)	469.7	379.7	339.6	322.6	316.3	281.7

Note that the values in the bracket are supplementary irrigation.

7.2.2 Field layout, cultural practice and measurements

Three experimental seasons (2006, 2008 and 2009) were carried out. A locally adapted major barley cultivar (*Birguda*) was grown. The treatments were planting time and water (rainfed and/or rainfed+ irrigation). In 2008 and 2009 four planting dates based on the local farmer's practice were used: July 4 (early planting under rainfed condition), July 10 (normal planting under irrigation condition), July 12 (normal planting under rainfed condition) and July 22 (late planting under rainfed condition). In both 2008 and 2009, planting on July 4, 12 and 22 were under rainfed condition. In 2006 only one planting date (July 10) was used under both irrigated and rainfed condition. In all years planting on July 10 was used under irrigated condition.

All plots in the experimental seasons were arranged in a randomized complete block design. The plot size was 4.0 m x 6.0 m with 1.5 m buffers between all plots. The plots were separated from each other using soil bunds of about 0.25 m high and were positioned uniformly at a 2% slope.

Figure 7.2 shows the daily rainfall and supplementary irrigation during the experimental period. These rainfed and supplementary irrigation treatments were replicated three times. The supplementary irrigation was applied after the cessation of rain. Irrigation amounts of 10 to 15 mm were applied every 3 to 4 days (Figure 7.2). This amount was sufficient to maintain the top soil at field capacity during the growing season. About 3 to 6 irrigations were applied. The irrigation water was supplied from a container of known volume and the water was applied to the field by using a pipe.

All crop management techniques were carried out following regional recommendations. For example, the barley cultivar was sown by broadcasting. For all years the seeding rate was 120 kg ha^{-1}. Assuming 75% germination, the plant population was approximately 155 plants per m^2 and the fertilization rate was 64 kg ha^{-1} of N and 46 kg ha^{-1} of P. The required amount of nitrogen was applied half at planting and the other half a month after planting.

In 2008 and 2009, soil water measurements were carried out every 2 days at a depth of 0.1 m interval using Time Domain Reflectrometry (TDR) (Eijkelkamp, 1996). Occasionally, gravimetric soil water observations were also taken to calibrate the TDR values. Evapotranspiration of barley was computed based on Equation 7.1 (Allen et al., 1998).

$$ET_c = I + P - D - Ro \pm \Delta S \qquad [7.1]$$

Where:
ΔS is the change in soil moisture storage between soil moisture measurements (mm).
I is irrigation (mm).
P is rainfall (mm).
D is drainage (mm).
Ro is runoff (mm).
Groundwater effect was ignored because the water table was deeper than 100 m.

The maximum crop coefficient (k_c) values at maximum crop coverage needed in AquaCrop model was calculated based on single crop coefficient approach as presented in Equation 7.2. (Doorenbos and Pruitt 1977; Allen et al., 1998; Liu et al., 2002).

$$k_c = \frac{ET_c}{ET_o} \qquad [7.2]$$

Runoff was measured during the cropping season using drums. The drums were inserted at the lower side of the plot to collect the surface runoff which was measured using a calibrated can. The surface runoff was measured manually following each rainy day. The runoff coefficient was calculated to adjust the appropriate curve number in the model. Deep percolation (drainage) below the root zone was estimated using TDR measurement.

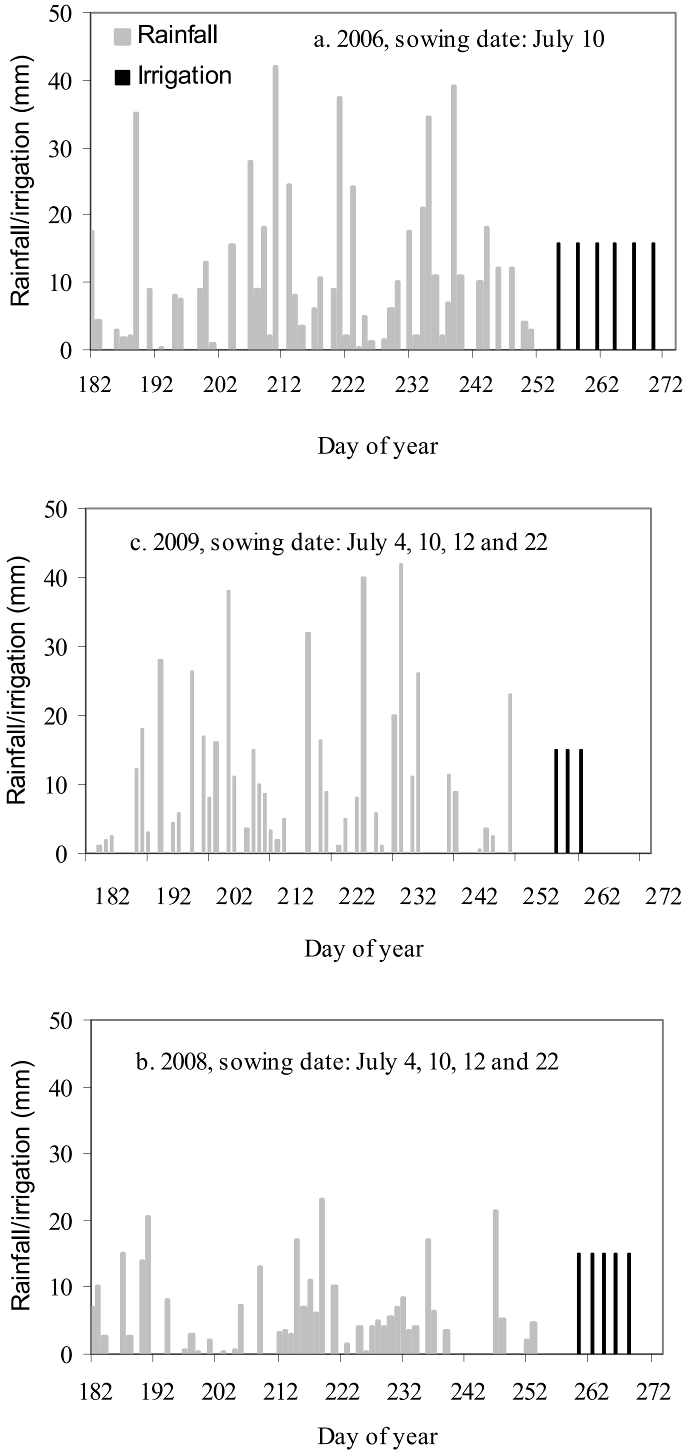


Figure 7.2. Daily rainfall and irrigation for the cropping period 2006, 2008 and 2009 at Mekelle, Ethiopia.

7.2.3 Crop parameters and measurements

The days from sowing to emergence, maximum canopy cover, start of senescence, and physiological maturity, as well as maximum rooting depth were recorded in the field. With the given temperature data sets the model estimated the degree days for each crop development. The base and upper temperatures were assumed to be 7 ^{o}C and 30 ^{o}C respectively. Growing degree days in AquaCrop was calculated based on McMaster and Wilhelm (1997).

Root observation was done in the field at about maximum canopy cover and at maturity from all plots. The conventional destructive technique of root length measurement (washed out of soil samples from roots) was used. In 2006 and 2008 leaf area index was measured from rainfed treatment using LAI-2000 Plant Canopy Analyser (Li-Cor Inc., 1992) once every seven to ten days. Canopy cover was estimated from leaf area index based on Ritchie type of equation (Ritchie, 1972; Ritchie et al. 1985; Belsmans et al., 1983) as applied by Farahani et al., (2009) Equation 7.3.

$$CC = 1 - \exp^{(-K * LAI)} \qquad [7.3]$$

Where:
CC is canopy cover.
K is extinction coefficient.
LAI is leaf area index.

The extinction coefficient was assumed to be 0.65 (unpublished data). In both 2006 and 2008, the sequential aboveground biomass was measured every ten days from an area of 0.5 m^2. Three biomass samples were taken at a time. The biomass was weighed after drying in an oven at 60-70 ^oC for 48 hours.

The final biomass and grain yield were obtained from all plots after maturity from an area of 1 m^2 in 2006 and 6 m^2 in 2008. The 1000 grain weights for the various treatments were also measured.

7.2.4 Description of AquaCrop model

AquaCrop relates its soil-crop-atmosphere components through its soil and its water balance, the atmosphere (rainfall, temperature, evapotranspiration and carbon dioxide concentration) and crop conditions (phenology, crop cover, root depth, biomass production and harvestable yield) and field management (irrigation, fertility and field agronomic practices) components (Raes et al., 2009a; Steduto et al., 2009).

AquaCrop calculates a daily water balance and separates its evapotranspiration into evaporation and transpiration. Transpiration is related to canopy cover which is proportional to the extent of soil cover whereas evaporation is proportional to the area of soil uncovered. The crop responds to water stress through four stress coefficients (leaf expansion, stomata closure, canopy senescence, and change in harvest index). The model reproduces the canopy cover from daily transpiration taking into account leaf area expansion and canopy development, senescence and harvest index (Steduto et al., 2009).

The normalized crop water productivity is considered constant for a given climate and crop (for crops not limited by mineral nutrients) in order to make the model applicable to diverse locations and seasons including future climate change scenarios (Hsiao et al., 2009; Steduto et al., 2009). The normalized crop water productivity for C_3 crops like barley is set between 13 and 18 g m^{-2} (Raes et al., 2009b). Using the normalized crop water productivity, AquaCrop calculates the daily aboveground biomass production (Hsiao et al., 2009; Steduto et al., 2009).

In AquaCrop, yield is obtained by multiplying biomass by harvest index. Harvest index (HI) is simulated by a linear increase with time starting from flowering up to physiological maturity (Steduto et al., 2009). The adjustment of HI in relation to the available water depends on the timing, severity and duration of water stress (Hsiao et al., 2009; Raes et al., 2009a; Steduto et al., 2009). HI is adjusted for five water stress coefficients namely coefficient for inhibition of leaf growth, for inhibition of stomata, for reduction in green canopy duration due to senescence, for reduction in biomass due to parenthesis stress and for pollination failure (Raes et al., 2009a; Steduto et al., 2009). A further detailed conceptual description of AquaCrop is available in Raes et al. (2009a); Raes et al., (2009b) and Steduto et al. (2009).

7.2.5 Methods of model calibration, validation and testing

Soil water data in AquCrop was calibrated using the measured data sets in 2008 whereas it was validated using the 2009 measured data sets.

Canopy cover (CC) was calibrated under nearly optimal growing (irrigated) condition in 2008 (planting on July 10) whereas the validation was done using the data set measured in 2006 (planting on July 10). The main calibration parameters for CC include the canopy growth coefficient (CGC), the canopy decline coefficient (CDC), water stress (P_{upper}, P_{lower} and the shape factor) affecting leaf expansion and early senescence. The measured canopy cover was reproduced by adjusting the stress coefficients. Canopy cover per seedling was estimated based on the general knowledge of the crop characteristics.

After calibrating CC, suitable threshold for stomata closure was chosen to reproduce the periodically observed biomass. In AquaCrop, the biomass growth rate is simulated through Equation 7.4 (Steduto et al., 2009).

$$Bm,_i = W_p \times \left(\frac{Ti}{ETo,i} \right) \qquad [7.4]$$

Where:
$B_{m,i}$ is the daily aboveground biomass production.
W_p is the normalized crop water productivity.
T_i is the daily crop transpiration.
$ET_{o,i}$ is the daily reference evapotranspiration (Heng et al., 2009; Steduto et al., 2009).

Since transpiration was not easily available, we used evapotranspiration as presented in Farahani et al. (2009). Evapotranspiration was obtained based on Equation 7.1.

Normalized water productivity (W_p) was derived from the average linear relationships of the biomass sampled periodically from the crop planted on July 10 with irrigation in 2008 (calibration) and in 2006 (validation) against their corresponding normalized evapotranspiration.

The harvest index obtained from field experiment varies from 9% to 24%. The most common harvest index value under good condition with the given inputs of fertilizer across the experimental years in the site was selected. The stress coefficient for HI was adjusted for increase due to inhibition of leaf growth at flowering; increased due to inhibition of leaf growth before flowering; decreased due to water stress affecting stomata closure during yield formation; and increased due to water stress affecting leaf expansion during yield formation were adjusted through trial and error process.

The validation of the model for biomass and grain yield was done using independent data sets of the cropping seasons of 2006 (rainfed, planted on July 10); 2008 (rainfed, planted on July 4, 12 and 22) and 2009 (rainfed, planted on July 4, 12 and 22; supplementary irrigation, planted on July 10). In validating the model, we compared the observed with the corresponding simulated grain yield or aboveground biomass data. Best fits of the simulated data were evaluated graphically and statistically.

Root mean square of error (RMSE) presented in Equation 7.5 and model efficiency (ME) based on Loague and Green (1991) was applied to evaluate the performance of the model. More detailed information regarding a model calibration and evaluation are available in Todorovic, et al. (2009), Farahani et al. (2009); Heng et al. (2009); Hsiao et al. (2009) and Steduto et al. (2009).

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(S_i - O_i \right)^2} \qquad [7.5]$$

Where:
S_i and O_i are simulated and observed values respectively.
n is the number of observations.

Values of RMSE close to zero indicate the best fit of the model.

Model efficiency (ME) was calculated based on Equation 7.6. ME is a measure of the robustness of the model.

$$ME = \frac{\sum_{i=1}^{n}(O_i - MO)^2 - \sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - MO)^2} \qquad [7.6]$$

Where:
O and S are observed and simulated values, respectively, for each of n study cases, and MO is the mean observed value.
ME ranges from negative infinity to positive 1; the closer to 1, the more robust the model.

Coefficient of determination (R^2) is the magnitude of variance explained by the model compared with the total observed variance. R^2 ranges from 0 to 1. A value closer to 1 shows a better agreement with the observed value.

After calibration and validation of the model, we calculated the grain water use efficiency (Grain-WUE) (Equation 7.7) and biomass water use efficiency (Biomass-WUE) (Equation 7.8) as presented in Araya et al. (2010b).

$$Grain - WUE = \left[\frac{G_Y}{\sum T}\right] \qquad [7.7]$$

$$Biomass - WUE = \left[\frac{B_m}{\sum T}\right] \qquad [7.8]$$

Where:
G_Y is grain yield in kg ha^{-1}.
T is transpiration simulated by AquaCrop model.
B_m is aboveground final biomass in kg ha^{-1}.

7.3 Results

7.3.1 Results of model calibration, validation and testing

The crop parameters used for calibrating the model are presented in Tables 7.3 and 7.4. Table 7.3 shows barley phenological development.

Table 7.3. Phenological observations of the barley cultivar (*Birguda*) at Mekelle, northern Ethiopia.

Cultivar	Sowing to emergence, GDD	Sowing to flowering, GDD	Flowering period, GDD	Sowing to senescence, GDD	Sowing to max canopy cover	Sowing to harvest, GDD	Max. root depth (m)
Birguda	91	676	130	962	702	1105	0.6

GDD is growing degree days. The base and cut off temperatures considered are 7 and 30 ^{o}C respectively.

Table 7.4 shows the different crop parameters and the values used for calibrating the model. Key stress parameters such as canopy expansion and canopy senescence coefficients were adjusted and readjusted to simulate the measured canopy cover. There was good agreement between the simulated and observed canopy cover (Figure 7.3a) with strong linear relationship (r^2 >0.92).

Table 7.4. Crop data inputs used in AquaCrop to simulate barley.

Description	Value	Units	Interpretation
Canopy cover per seedling at 90% emergence (CC_o)	3.56	%	Increase in CC relative to existing CC. (2 .3 cm^2 per plant).
Canopy growth coefficient (CGC)	0.923	%/°C /day	Increase in CC relative to existing CC per GDD
Maximum canopy cover (CC_x)	80	%	Well covered
Maximum crop coefficient	1.05	-	At max canopy
Canopy decline coefficient (CDC) at senescence	1.703	% /°C/ day	Decrease in CC relative to CC_x per GDD
Water productivity	13	g m^{-2}	Biomass per m^2
Upper threshold for canopy expansion	0.3	-	Leaf growth stop completely at this *P* value
Lower threshold for canopy expansion (P_{lower})	0.6	-	Above this leaf growth is inhibited
Leaf expansion stress coefficient curve shape	3.5	-	
Upper threshold for stomatal closure	0.6	-	Moderately tolerant to water stress but above this stomata begins to close
Stomata stress coefficient curve shape	3.5	-	
Canopy senescence stress coefficient (P_{upper})	0.55	-	Above this canopy senescence begins
Senescence stress coefficient curve shape	3.5	-	
Reference harvest index	0.20	-	Common for good condition
Coefficient, HI increased by inhibition of leaf growth at flowering	0.85		Upper threshold for increase in HI due to inhibition of leaf growth
Coefficient, HI increased due to inhibition of leaf growth before flowering	12	%	Maximum HI increased by inhibition of leaf growth before flowering
Coefficient, HI decreased due to water stress affecting stomata closure during yield formation	5	-	moderate
Coefficient, HI increased due to water stress affecting leaf expansion during yield formation	2	-	moderate
Aeration stress when waterlogged	15	Vol.%	Severely affected when waterlogged.

GDD, growing degree days

The simulated aboveground biomass agreed well with the observed biomass (Figure 7.3b). The simulated aboveground biomass was also adjusted using the stress coefficient (such as P_{upper} for stomata) to reproduce the observed biomass. There was strong relationship between the observed and simulated biomass (r^2 >0.8).

Figure 7.4 shows the simulation of the soil water by the model at the top 0.6 m soil depth. The observed soil water in 2008 and 2009 agreed well with their corresponding simulated values. As the crop is extremely sensitive to aeration condition, we set a value that correspond to that in the model (Sat. 15 vol.%) (Table 7.4)

The most common harvest index value obtained from field experiment with the given level of fertilizer and variety under optimal water condition was 20%. Thus 20% was set in the model and adjustment for HI was done for an increase due to inhibition of leaf growth at flowering (0.85); increased due to inhibition of leaf growth before flowering (12%); a decrease due to water stress affecting stomata closure during yield formation (5); and an increase due to water stress affecting leaf expansion during yield formation (2) (Table 7.4).

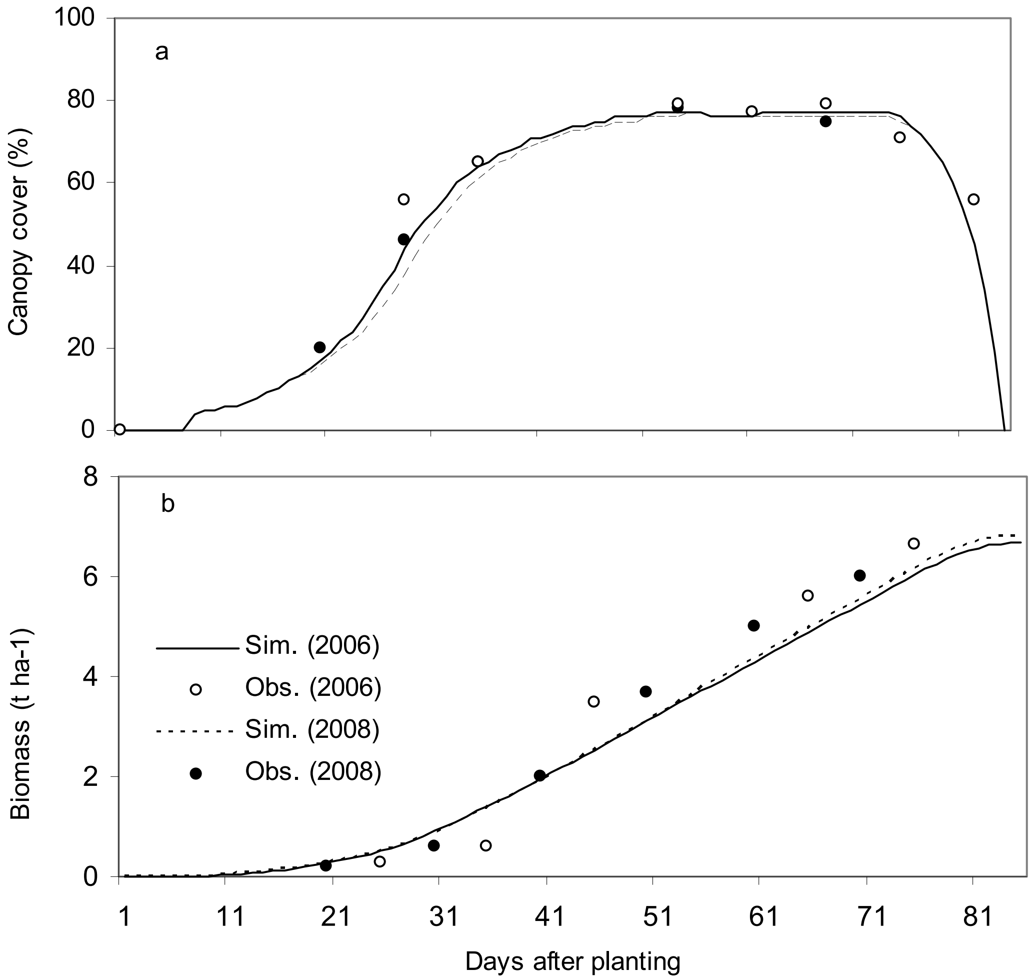


Figure 7.3a and b. Simulated and observed canopy cover (a) and sequential aboveground biomass (b) of barley grown in the cropping season 2006 (validation) and 2008 (calibration).

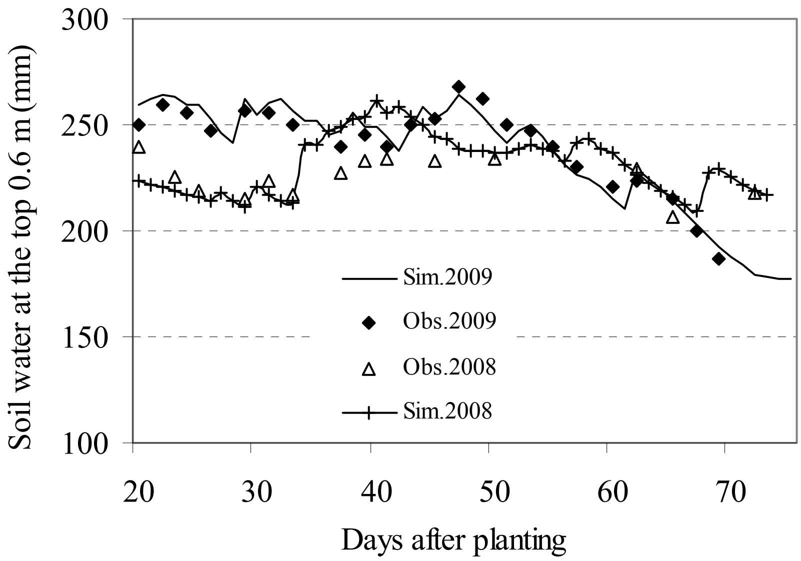


Figure 7.4. Simulated and observed soil water at the top 0.6 m in the cropping season 2008 (calibration) and 2009 (validation) at Mekelle, Ethiopia.

Both grain yield and aboveground biomass were adequately simulated by the model (Figure 7.5). Table 7.5 shows a deviation of the simulated biomass (-4.3% to 14.6%) and grain yield (-13% to 15.1%) from their corresponding observed data. The deviation of the simulated biomass from the observed calibration data set in 2008 was -5.6%. Whereas the deviation of the simulated grain yield from the observed calibration data set was -9.6%. Although not substantially different, the biomass was better simulated by the model when compared with the grain yield. Despite the moderate deviation of the calibration data sets for both biomass and grain yield, the simulations by the model in the validation data sets were reasonably good (i. e. -4.3 to 14.6% for biomass and -13 to 15.1% for grain yield).

Table 7.5. The simulated and observed biomass and grain yield of barley at various planting dates and % of deviations from the observed during the cropping season 2006, 2008 and 2009 at Mekelle, Ethiopia.

		Biomass			Grain		
Year	Planting date	Observed (t ha^{-1})	Simulated (t ha^{-1})	Dev.%	Observed (t ha^{-1})	Simulated (t ha^{-1})	Dev. %
2006	10/07/2006	6.55	6.66	1.7	1.50	1.33	-13.0
2008	04/07/2008	6.75	6.80	0.7	1.28	1.38	7.1
2008	12/07/2008	6.36	6.35	-0.2	1.16	1.30	10.6
2008	22/07/2008	4.97	5.30	6.3	0.79	0.93	15.1
2009	04/07/2009	6.47	6.76	4.4	1.38	1.35	-2.0
2009	12/07/2009	5.37	5.94	9.6	1.03	1.16	11.4
2009	22/07/2009	4.01	4.69	14.6	0.57	0.63	9.1
2006#	10/07/2006	7.13	6.87	-3.8	1.53	1.37	-11.9
2008#*	10/07/2008	7.15	6.77	-5.6	1.54	1.40	-9.6
2009#	10/07/2009	7.20	6.90	-4.3	1.55	1.38	-12.1

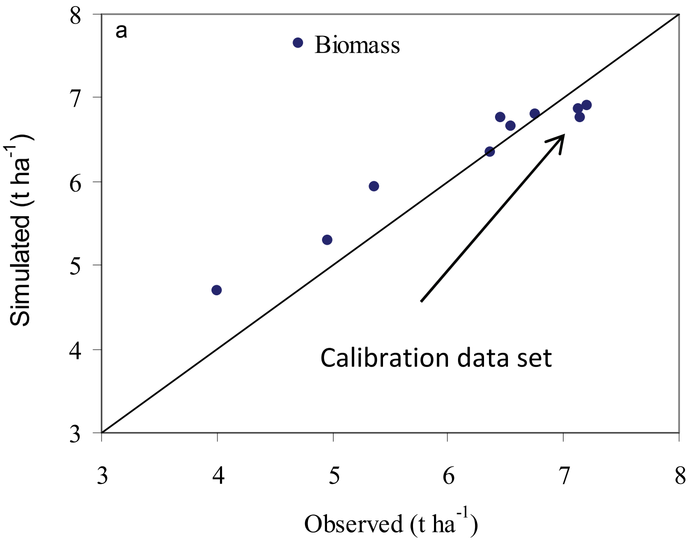
Full irrigation; * Calibration data set; biomass, final biomass at harvest; grain, final grain yield at harvest.

The model efficiency (ME) and root mean square of error (RMSE) also showed moderate performance (Table 7.6) for biomass (ME = 0.53 to 1.00, RMSE = 0.36 to 0.90 t ha^{-1}) and grain yield (ME = 0.50 to 0.95, RMSE = 0.07 to 0.27 t ha^{-1}). Moderate ME values and lower RMSE values indicate the good performance of the model. The ME for the validation data sets fall in the range of 0.5 to 0.95 for grain and 0.53 to 1 for biomass. Whereas, the ME value for the calibration data set was comparatively good (0.84 for biomass and 0.74 for grain yield) (Table 7.6).

Table 7.6. The root mean square of error (RMSE) and the model efficiency (ME) for biomass and grain yield of barley at various planting dates during the cropping season in 2006, 2008 and 2009 at Mekelle, Ethiopia.

		Biomass		Grain yield	
Year	Planting date	ME	RMSE (t ha^{-1})	ME	RMSE (t ha^{-1})
2006	10/07/2006	0.98	0.42	0.82	0.27
2008	04/07/2008	1.00	0.54	0.82	0.15
2008	12/07/2008	1.00	0.36	0.73	0.19
2008	22/07/2008	0.79	0.49	0.50	0.17
2009	04/07/2009	0.75	0.42	0.95	0.07
2009	12/07/2009	0.53	0.70	0.73	0.18
2009	22/07/2009	0.67	0.90	0.84	0.09
2006#	10/07/2006	0.90	0.49	0.83	0.26
2008#*	10/07/2008	0.84	0.60	0.74	0.19
2009#	10/07/2009	0.79	0.44	0.51	0.21

Full irrigation; *Calibration data set; ME, model efficiency; RMSE, root mean square of error; biomass, final biomass at harvest; grain, final grain yield at harvest.



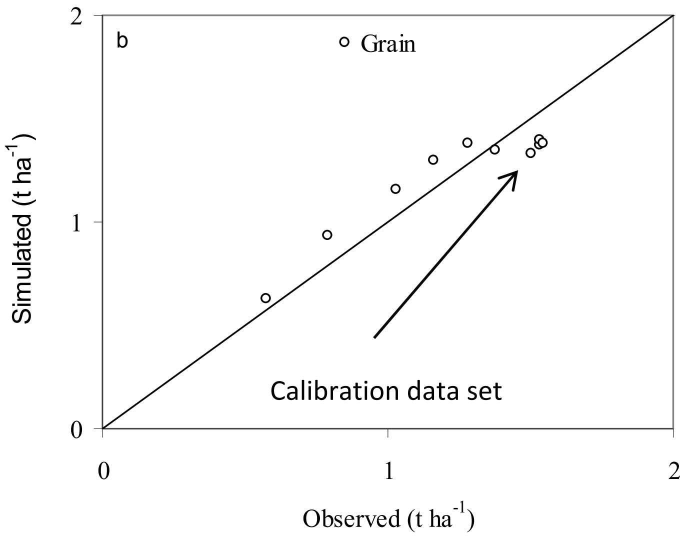


Figure 7.5a and b. Graphical test of the simulated versus observed aboveground biomass and grain yield (R^2 > 0.8) of barley for in the cropping season 2006, 2008 and 2009 at Mekelle, Northern Ethiopia. Note that the data points are for both calibration and validation data sets. The calibration data set is indicated by an arrow.

7.3.2 Biomass, grain yield and water use efficiency

The seasonal reference evapotranspiration as can be seen in Table 7.2 is slightly higher than the seasonal rainfall in 2008 whereas, in 2006 and 2009, the seasonal rainfall was greater than the reference evapotranspiration and the amount of rainfall received per each rainy day was higher (Figure 7.2) than in 2008.

The 1000 seed weight for planting date of July 4 (early sowing), July 12 (normal sowing) and July 22 (late sowing) were 55 - 61, 50 - 56 and 43 - 49 gm respectively. The 1000 seed weight for irrigated and for rainfed with planting date on July 4 was almost equal. This shows that seed weight decrease with a decrease in water availability. This result may have implication on harvest index.

In both 2008 and 2009, planting on July 4 yielded higher biomass and grain than planting on July 12 and July 22 (Table 7.5 and 7.7). There were relatively more transpiration and lower biomass and grain yield in 2009 than in 2008 (Table 7.7). Higher grain and biomass yield per m^3 of water was obtained from the crop planted in 2008 than in 2009. Consequently the biomass and grain water use efficiency was higher in 2008 than in 2009.

Table 7.7. Biomass-WUE and Grain-WUE in response to the seasonal transpiration over the different planting dates across years at Mekelle, Northern Ethiopia

Year	Planting date	Biomass ($kg\ ha^{-1}$)	Grain ($kg\ ha^{-1}$)	T ($m^3\ ha^{-1}$)	Biomass-WUE ($kg\ m^{-3}$)	Grain-WUE ($kg\ m^{-3}$)
2006	10/7/2006	6550.0	1500.0	1845	3.6	0.8
2008	4/7/2008	6750.0	1282.5	1608	4.2	0.8
2008	12/7/2008	6362.5	1162.5	1554	4.1	0.7
2008	22/07/2008	4965.0	790.0	1326	3.7	0.6
2009	4/7/2009	6465.0	1377.5	1917	3.4	0.7
2009	12/7/2009	5370.0	1027.5	1737	3.1	0.6
2009	22/07/2009	4007.5	572.5	1417	2.8	0.4
2006#	10/7/2006	7132.5	1532.5	1859	3.8	0.8
2008#*	10/7/2008	7150.0	1535.0	1668	4.3	0.9
2009#	10/7/2009	7200.0	1547.5	2049	3.5	0.8

Full irrigation slightly improved the biomass and grain yield in all experimental years. But this has not resulted in significantly higher biomass and grain water use efficiency. This indicates barley has shown a tendency to respond positively to a mild water stress condition.

7.4 Discussion

The same sets of conservative parameter values were used to validate the model for the different treatments across years (2006, 2008 and 2009). The estimated normalized crop water productivity (13 $g\ m^{-2}$) was within the range of the default values set for C_3 plants (like barley) in the model (Raes et al., 2009b).

The model simulated the soil water adequately however the observed deviations between 33 and 43 days after planting in 2008 might be due to imprecise measurement of the soil physical characteristics (data inputs) used in the model (Figure 7.4).

The upper threshold for stomata closure in barley is between the ranges of 0.5 to 0.7 (Rizza et al., 2004). The experimental barley cultivar in our study site (0.60) corresponds to the average of the values obtained in the literature (Table 7.4).

The model underestimated and overestimated the biomass under irrigated and rainfed fields by -4.3% and 14.6% respectively. This deviation is most likely due to problems in the calibration. As can be observed in Figure 7.5a and 7.5b the calibration data set was slightly deviated from the 1:1 line. Despite the slight deviation, the RMSE values for biomass (0.36 to 0.90 $t\ ha^{-1}$) were considerably low implying the simulation by the model was satisfactory.

Similarly the predicted grain yield deviated from the observed data with a range of -13% to 15%. The ME (0.50 to 0.95) values for the grain yield were moderate but lower than the ME value for biomass (0.53 to 1). The model has relatively simulated better for the biomass than the grain. This relatively larger deviation in grain yield might be due to the fixed HI value (20%) used in the mode as the HI for the experimental cultivar under good condition during the experimental period varied from 14 to 24%. Despite this deviation, the RMSE values for grain yield were very low (0.07 to 0.27 $t\ ha^{-1}$), implying the model simulated the grain yield reasonably.

Early planting (July 4) and irrigation improved the harvest index when compared to late planting (July 22) (data not shown). Late sown barley was exposed to late season water stress due to early cessation of rain. The water stress during grain filling period in late sown (July 22) barley has resulted in shrivelled and low seed weight consequently reduced harvest index. Nagaz et al. (2008) also obtained a decrease in trend in 1000 barley seed weight with a decrease in water supply levels from fully irrigated field (100% ET_c) to moderately deficit irrigated field (50% ET_c). This decrease in 1000 seed weight was attributed to grain filling failure as a result of reduced water supply. HI may reduce due to shortening of the canopy cover duration resulting in short grain filling period (Hsiao et al., 2009).

The experimental cultivar in our study site seems very exceptional when compared with the yield obtained from the genotypes tested by Rizza et al. (2004). About 89 barley genotypes were tested under rainfed and irrigated condition in a Mediterranean environment. Although not tested in the same environment, most of these genotypes out yielded the cultivar used in our study site. This shows different cultivar of the same crop may have difference in yield (may be due to the difference in length of growing period or other genetically factors). Nagaz et al. (2008) also obtained high grain yield and HI values under full irrigation condition which is almost more than double that of the yield and HI value obtained from our experimental station. Hsiao et al. (2009) also outlined the possibility of variation in HI with cultivars of the same crop. This shows cultivar characteristics may affect the world wide validity of the model; hence, we recommend including more cultivars (genotypes) for this study.

The second possible reason for the difference in yield when compared with the yield obtained in Rizza et al. 2004 and Nagza et al. 2008 could be due to the difference in field drainage conditions. Barley is known to be very sensitive to waterlogging (Setter and Waters, 2003; Pang et al., 2004; Araya and Stroosnijder, 2010). Many farmers also claim that there have been total crop failure seasons even due to short time exposure of the crop to excessive soil wetness conditions. Therefore the barley biomass and grain yield in our study sites was most likely reduced by aeration stress especially in 2009. The sensitivity of the crop to aeration stress depends on rainfall, drainage characteristics of the field (which also depend on soil characteristics and slope of barley fields), crop stage and length of time of exposure to waterlogging). Based on this information, we calibrated the model assuming the crop in our experiment to be extremely sensitive to aeration stress. Despite these conditions, the model was able to simulate the yield and biomass yield of the cultivar used in the experimental site with relatively moderate accuracy.

Generally, the results of this experiment showed that the model adequately simulated the biomass and grain yield of barley under various planting dates and water availability conditions across the experimental seasons. However, the model showed slight deviation hence we recommend verifying and refining the HI across crop cultivars. Hsiao et al. (2009) also advised that further calibrations by including more characteristics of the crop under diverse climate and soil conditions may improve the worldwide validity of the model.

The simulation result showed that planting on July 4 (early planting) improved the biomass and grain yield more than planting on July 12 and July 22. Comparatively, there was high biomass and grain water use efficiency when planting on July 4 followed by July 12 and least is when planting on July 22. This indicates that early sowing of the crop enabled to gain greater opportunity for most of the crop growing period to be with in the rainy season. Hence July 4 seems close to the optimal planting time when compared with July 12 and July 22. Early sowing has advantage in escaping water stress that may occur during the grain filling period. In line with this, Araya et al. (2010a) verified that early cessation (short growing period) causes severe yield reduction in northern Ethiopia.

Full irrigation has not significantly improved the grain and biomass yield when compared with their corresponding rainfed treatment. In line with this, Nagaz et al. (2008) obtained the highest yield and biomass at full irrigation (100% $ET_{c,}$) but was not significantly higher than the treatment with mild water stress (85% ETc). Rizza, et al. (2004) also indicated that low yielding varieties perform well under rainfed than full irrigated conditions. Hence it is possible to generalize that the barley cultivar in our study site has showed positive response to mild water stress condition.

In addition to the biomass and grain yield, the water use efficiency also responds positively for mild water stress (rainfed or deficit irrigation) when compared to full irrigation. Similarly, Nagaz et al. (2008) obtained higher water use efficiency in water stressed barley (50% ET_c) than in fully irrigated barley (100% ET_c). The implication is that in semi-arid environment and with no restriction of arable land like the case of northern Ethiopia, deficit irrigation may save water and improve barley water use efficiency.

The overall result showed that AquaCrop model can be used in the evaluation of optimal planting time and deficit irrigation strategy for barley. By running the model under different planting dates, it is possible to optimize the barley planting date. The essence of optimal planting may differ from place to place but in our case optimal planting is the planting date which allows the crop to use maximum natural rainwater leading to a relatively proper growing period for relatively maximum biomass, grain yield and water use efficiencies.

Furthermore, the model can be used in the evaluation of irrigation strategy in barley. By using the model it is possible to explore for better irrigation options that would give maximum grain and biomass yield per unit of water supplied/used. In this experiment, barley under mild water stress condition showed slightly lower performance compared to fully irrigated condition (Table 7.7). Assuming that water is scarce and land is not limited, the model indicated the possibilities of obtaining relatively higher biomass and grain yield if less irrigation could be applied to a larger barley area than more irrigation in a relatively smaller barley area. In line with this, Hsiao et al, (2009), highlighted that the model can be used in improving irrigation management strategies if it is well calibrated and validated for the crop species.

7.5 Conclusion

AquaCrop version 3.0 has adequately simulated the soil water in the root zone, as well as the biomass and grain yield of barley under various planting dates and water availability conditions. However, revision of HI and the crop water stress coefficients by including more crop cultivars under different soil, climate conditions may be important to improve the worldwide validity of the model. AquaCrop model can be used to optimize planting time under water constraint environment for barley. In addition, the model can be used in the evaluation of crop irrigation strategies. Assuming that water is scarce and land is not scarce, the model has indicated the possibility of obtaining more grain and biomass from relatively larger barley field by applying less water. This result may contribute to food security improvement through increasing crop yields especially in water stressed areas similar to the case of northern Ethiopia.

Chapter 8

Risk assessment by sowing date for barley (*Hordeum vulgare*) in northern Ethiopia

This paper is under review as:

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Risk assessment by sowing date for barley (*Hordeum vulgare*) in northern Ethiopia

Abstract

Risks of dry and wet sowing methods of rainfed barley were evaluated in the northern Ethiopia. The evaluation was based on yield simulation using a validated AquaCrop model. Risks of failure were assessed by taking two yield threshold levels (0 t ha^{-1} and 0.1 to 0.3 t ha^{-1}) from defined early, normal and late sowing by farmer's and depth criterion over the long-term (21 to 41 years) climate observation. The study verified that false start significantly increased over the study area by stations in the order from west to southeast and northeast. The risk level representing false start (yield = 0 t ha^{-1}) by farmer's criterion ranged from 27 to 54%, 18 to 46%, and 9 to 31% for early, normal and late sowing, respectively, whereas the corresponding false start by depth criterion ranged from 22 to 33%, 14 to 29% and 5 to 24%. The average yield for early, normal and late sowing ranged from 0.7 to 1.3, 0.8 to 1.5, and 0.8 to 1.7 t ha^{-1} when farmer's criterion was applied whereas the corresponding average yield ranged from 0.8 to 1.4, 0.5 to 1.6, and 0.4 to 1.7 t ha^{-1} when depth criterion was applied. The result suggested that risks of false start and crop failure acceptably reduced and yield reasonably improved when early or normal sowing and late sowing are applied based on depth criterion and farmer' criterion, respectively. Generally, stations situated west of the catchment are characterized by early start and late cessation (longer length of growing period) whereas stations situated towards the east are characterized by relatively late start and early cessation and hence short growing period. Assuming all factors are available constantly, yield reduced from west to east mainly due to effect of time of start and cessation of rain.

8.1 Introduction

Barley is one of the major staple food crops in the northern Ethiopia. Barley is well adapted to mid - highland (alt. 1800 – 3000 m. a. s. l.) of the northern region of Ethiopia. The crop grows under rainfed condition by peasant farmers who survive with mixed crop and livestock farming system. The crop is grown primarily for preparing traditional food in form of '*Enjera'*, '*Giat' 'Kita'* and many other food types. The crop is the most important food source in the day to day life of the people of northern Ethiopia. Rainfall is the most important yield determinant factor for barley in the northern semi-arid area of Ethiopia.

The rainfall characteristics in the northern Ethiopia that includes the study area is by majority bimodal. The short rainy season is locally known as *'Belg'*. The *Belg* season occurs between the months of February and May. It has little agricultural importance because of its low amount and variability of the rainfall. The only season for crop growing which is the period between June and September is known as '*kiremt*. The *Kiremt* season rainfall is poor in distribution and there has been high inter and intra-annual rainfall variability in the region (Araya et al., 2010a). Usually, the crop faces severe rain onset uncertainties resulting in crop failure and replanting. In addition, the crop also suffers from too short growing season (Araya et al., 2010a). In some of the years, rain starts in late June to early July and may be followed by dry spell of about 10 days. Such circumstances are important causes of crop failure. The yearly variation of the onset together with the variation in the cessation of rain makes it difficult to have a well-defined sowing time. In order to have well defined onset, we need to determine a dependable onset and cessation date.

Sowing in the northern Ethiopia, particularly, in the Giba catchment is based on past experience (Araya et al., 2010a). Most farmers prefer to practice dry sowing particularly for barley. Most farmers are interested to sow early for the following reasons: i. to prolong the growing season, ii. to reduce work burden, and iii. to sell oxen and labour power. Late sowing for barley is not normally intended for but could be due to absence of enough labour or oxen or due to occurrence of false start. Success of early sowing in dry soil depends on the rainfall distribution. There have been many occasions of early rain storms which are followed by long dry spell (Araya et al., 2010a). These events result in germination but the seedling won't be able to succeed because it dies due to the dry period after germination. Under such conditions, farmers maintain the crop by replanting. Replanting is normally done soon after the crop is known to fail which is about 3 weeks after sowing. This condition affects the farmers cropping schedule and cost is high to the poor farmer. In addition, replanting shortens the growing period and the crop may face severe water stress especially during the grain filling period leading to reduction in yield. Hence, knowledge of long-term characteristics of the start and end of a growing season and risks involved are vital for food security and for planning agricultural activities in the region. Despite the importance of the problem little has been done to evaluate the risks of crop failure and to identify less risky sowing date.

Previous sowing date risk evaluations by Raes et al. (2004) and Kipikorir et al. (2007) have employed mean relative transpiration and relative evapotranspiration over 30 days following sowing, respectively. In this study, we employed a different approach where two different sowing date criteria are used to study the risk of sowing in barley with the help of a yield simulation FAO model. Yield assessment with the help of a model based on long-term climate data is useful to evaluate the risks of sowing date especially for late (wet) planting. Late planting may favour seedling establishment but the final fate of late planting can be known if the final yield could be estimated. Araya et al., (2010c) validated the FAO AquaCrop model for the common barley grown in the northern Ethiopia. The model depends on the concept of water productivity as described in Steduto et al. (2009) and Raes et al. (2009a and b). This model was used to quantify and identify risks of sowing date for barley in the study area.

The objective of this study is thus to evaluate the early, normal and late sowing practice based on farmer's criterion and pre-determined depth criteria (Raes et al., 2004) and to quantify the false start risk and identify less risky planting date for barley crop in the study area.

8.2 Materials and methods

8.2.1 Site description

The study area (Giba catchment) is located in northern Ethiopia (lat. 13^{o} 15' N to 14^{o} 16' N and long. 39^{o} 0' E to 39^{o} 44 $E^{'}$) (Figure 8.1). The mean annual maximum and minimum temperature range from 21 to 31 ^{o}C and 3.3 to 16 ^{o}C, respectively. The mean annual rainfall and reference evapotranspiration range from 550 to 920 mm and 1495 to 1950 mm, respectively.

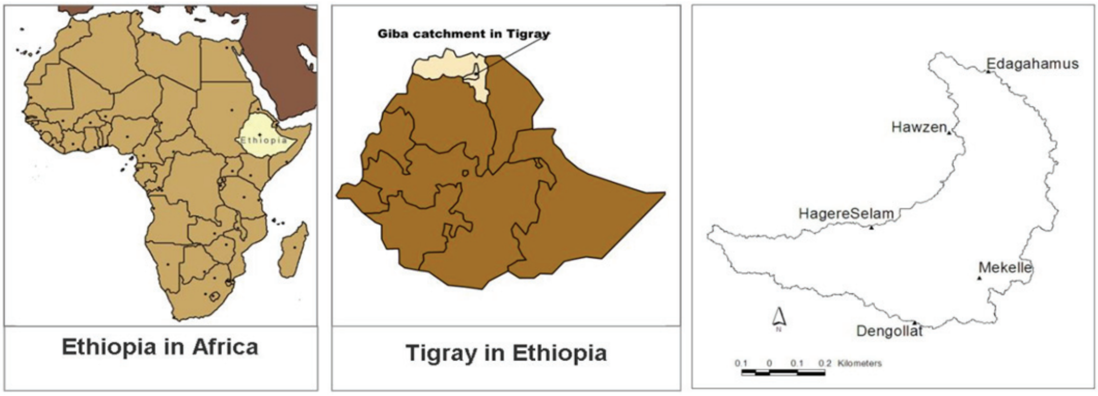

Figure 8.1. Map of Ethiopia and the study area located in Tigray region.

The soils in the Giba catchment are shallow in depth; land degradation is typical characteristics of this area. Various soil types exist out of which loam and sandy loam soils are the most common soil types in the study area. In this study, the characteristics for commonly observed loam and sandy loam soils were obtained based on pedotransfer function (Saxton, 1986) (Table 8.1). The average soil depth for the study area was assumed to be 0.5 m. This estimate was based on field observation over the Giba catchment.

Table 8.1. Soil characteristics of the study area based on Saxton (1986).

Soil type	PWP (Vol.%)	FC (Vol.%)	TAW (mm/m)
Sandy loam	10	22	120
Loam	14	27	130

FC, field capacity; PWP, permanent wilting point; TAW, total available water

8.2.2 Climate data and analysis

Daily climate data from four stations which are situated in the southwest, (Hagereselam (HS)); northeast, (Edagahamus (EH)); southeast, (Mekelle (MK)) and northwest (Hawzen (HW)) of the study area over a period of 21 to 41 years were used. Daily rainfall and temperature data were commonly available in all of the stations in the study area (Table 8.2).

Table 8.2. Characteristics of the meteorological stations in the study area.

Station	Latitude	Longitude	Altitude	Record	Data type
MK	13^{o}.29N	39^{o}.32'E	2212	41	T, R, W, SS
HS	13^{o}.39'N	39^{o}.1'E	2600	24	T, R
EH	14^{o}.12'N	39^{o}.33'E	2650	23	T, R
HW	14^{o}.01'N	39^{o}.27'E	2280	28	T, R

MK, Mekelle; HS, HagereSelam; EH, Edagahamuse; HW, Hawzen
T, temperature; R, rainfall; W, wind speed; SS, sunshine hours

In addition, daily relative humidity, sunshine hours, and wind speed data were available at Mekelle station. Reference evapotranspiration (ET_o) for Mekelle station was determined based on full datasets using the FAO Penman Monteith method whereas the ET_o of the other stations was determined based on limited datasets. The ET_o determined using the limited dataset was calibrated as described in Allen et al. (1998). Homogeneity test of the seasonal and annual rainfall data was carried out based on Buishand (1982). After confirmation of the consistency of the data the rainfall means were analysed.

8.2.3 Estimation of onset and cessation and length of growing period (LGP)

Onset was determined using the two criteria namely the depth criterion (40 mm in 4 days) (Raes et al., 2004), and the 'farmer's' criterion. In depth criterion, the 4 days cumulative rainfall is assumed to bring the top 0.25 m of the soil to field capacity (Raes et al., 2004; Kipkorir, et al., 2007). The dry sowing by farmers in the northern Ethiopia corresponds to the rainfall-reference evapotranspiration relationship used for sowing as presented in Araya et al. (2010a). The daily rainfall should meet about 50% of the evapotranspiration followed by greater rainfall afterwards (Araya et al., 2010a). We called this criteria as 'farmer's' because it fully coincides with the farmer's common barley planting time (in which case sowing is carried out after few showers of rain). Dry seeding criterion is used for barley, which grows in the highlands of northern Ethiopia including the study area. The dry seeding date at each station is fixed but varies from station to station.

Experience shows that *kiremt* (June to September) rain begins after June 15 hence in generating the onset for each criteria, the search date after June 15 was chosen. To determine the first date on which the criteria are satisfied was generated using the climate criteria option in AquaCrop model as well as by drawing a graph of rainfall against time using an excel spread sheet. This technique eliminates problems of early showers that are followed by longer dry spells.

Similarly, cessation was assumed to be the end of the growing period, a week after the rainfall meets the 50% of the ET_o and rainfall declines afterwards (Araya et al., 2010a). This was easily obtained by drawing the graph of daily rainfall against daily evapotranspiration for each season and station. At the end of the season one week was considered for the crop to use the soil water reserve before it reached the wilting point.

The length of growing period was assumed to be the period between the onset and cessation. The LGP was analysed for all stations and years by two different criteria.

A characteristic of the start and end of growing season for each station was evaluated by depth and farmer's criteria. Probability of occurrence of early, normal and late start and cessation for each station over its long period of observation was evaluated. In addition, characteristics of each station relative to catchment level start and end of rain have been evaluated by depth criterion. Such evaluation is essential to understand relationship between the start and end of the growing season among the stations in the study area because it has direct relationship with the cropping possibilities and in planning various agricultural activities across the study area.

8.2.4 Mapping

Mapping was carried out with the available digitized map of the Giba catchment using the ArcGIS 9.2. The isohyets for three rain onset dates (25% (late), 50% (normal) and 75% (early)) were drawn. The isohyets for three LGP categories (long (25%), normal (50%) and short (75%)) were also drawn.

8.2.5 Assessment of crop failure and false start

Previous false start (failure) studies in Zimbabwe and Kenya have used the mean relative transpiration and relative evapotranspiration over 30 days following sowing. Failure or false start was assumed when the relative transpiration is less than 35% and hence, that crop (maize) can not produce any yield or needs to be re-sown (Raes et al., 2004; Kipkorir, et al., 2007). Unlike the previous study, a validated AquaCrop model was used to simulate the yield and biomass directly for early, normal and late sowing of barley based on the two criteria. Often less risk of crop failure is expected when using late planting because of the high water requirement satisfaction. However, the growing season over this region is too short, hence, the crop that has successfully established may suffer from severe water stress at flowering and grain filling stage. This method eliminates uncertainty such that final fate of late (wet) planting is clearly known. In addition, since the initial crop establishment threshold conditions described for maize in Raes et al. (2004) can not be directly used for barley, uncertainties that could be caused by the use of arbitrarily (crop water satisfaction) threshold limit for the occurrence of false start is avoided. The model is able to simulate the biomass and yield of barley with a given data inputs such as climate, soil and crop information (Araya et al., 2010c). Yield and biomass threshold levels were used to understand and identify the crop failure that occurred due to false start. Theoretically, false start is said to be occurred when the biomass and yield are equal or very close to zero (0 to 0.099) t ha^{-1}. Normally biomass and yield can not be zero unless the crop has failed at seedling stage. This threshold is used to estimate the probability of false start which is comparable to the previous work made by Raes et al. (2004) which assumes that crop can hardly produce any yield.

8.2.6 Statistical analysis

The fact that barley cultivars are more diverse, their sowing time varies. For example, the commonly grown cultivars '*Birguda'* is normally sown in dry soil or after few showers of rain whereas sowing for some of the quick maturing barley cultivars such as *'Saesea'* is carried out when soil is wet. Thus, it is essential to carry out frequency analysis in order to execute a reliable indicator of the rain onsets and cessations (Raes et al., 2004; Kipikorir, et al., 2007; Mugalavai et al., 2008). Julian rain onset and cessation dates were used to calculate the probabilities of exceedance using the RAINBOW software (Raes et al., 1996). After selecting the type of distribution, dates that represent the 75% (early), 50% (normal) and 25% (late) probability of exceedance levels were selected for both onset and cessation. The corresponding LGP probabilities of exceedance levels were also selected in similar fashion to indicate long, medium and short season, respectively. Finally, the frequency of failure was counted for each criterion and their probabilities of occurrence were computed for early, normal and late planting dates by criterion and by station.

8.3 Result and discussion

8.3.1 Characteristics of the start and end of growing season

Onsets determined by farmer's and depth criteria are presented in Table 8.3. Rain onset progressively covers from southwest to north and southeastern part of the study area. On average the difference between the early and late sowing dates by the farmer's criterion is 13 days whereas the average difference between the early and late sowing dates by depth criterion is 21.5 days (Table 8.3). The reason for the earlier and narrower onset range with the farmer's criterion is because of the criteria for dry planting is met during the first few shower of rain than the wet planting which is described in the depth criterion (Raes et al., 2004).

Table 8.3. Onset and cessation for the stations over the Giba catchment. Probability of exceedance 75% (early), 50% (normal) and 25% (late).

	Onset						Cessation		
	Farmer's criterion			Depth criterion					
Stations	Early	Normal	Late	Early	Normal	Late	Early	Normal	Late
MK	3/7	7/7	14/7	7/7	18/7	27/7	6/9	11/9	16/9
HS	20/6	26/6	1/7	29/6	4/7	20/7	16/9	20/9	23/9
EH	27/6	3/7	14/7	5/7	13/7	27/7	2/9	12/9	18/9
HW	19/6	27/6	2/7	10/7	16/7	3/8	12/9	16/9	20/9

Note that the onset is presented by farmer's and depth criteria while only one cessation criterion was used.

Figure 8.2a and 8.2b show characteristics of the start and end of the growing season by depth (8.2a) and by farmer's (8.2b) criterion for each station in the study area. The difference in characteristics of the start and end of the growing season among the stations was attributed to medium and micro scale climate controllers.

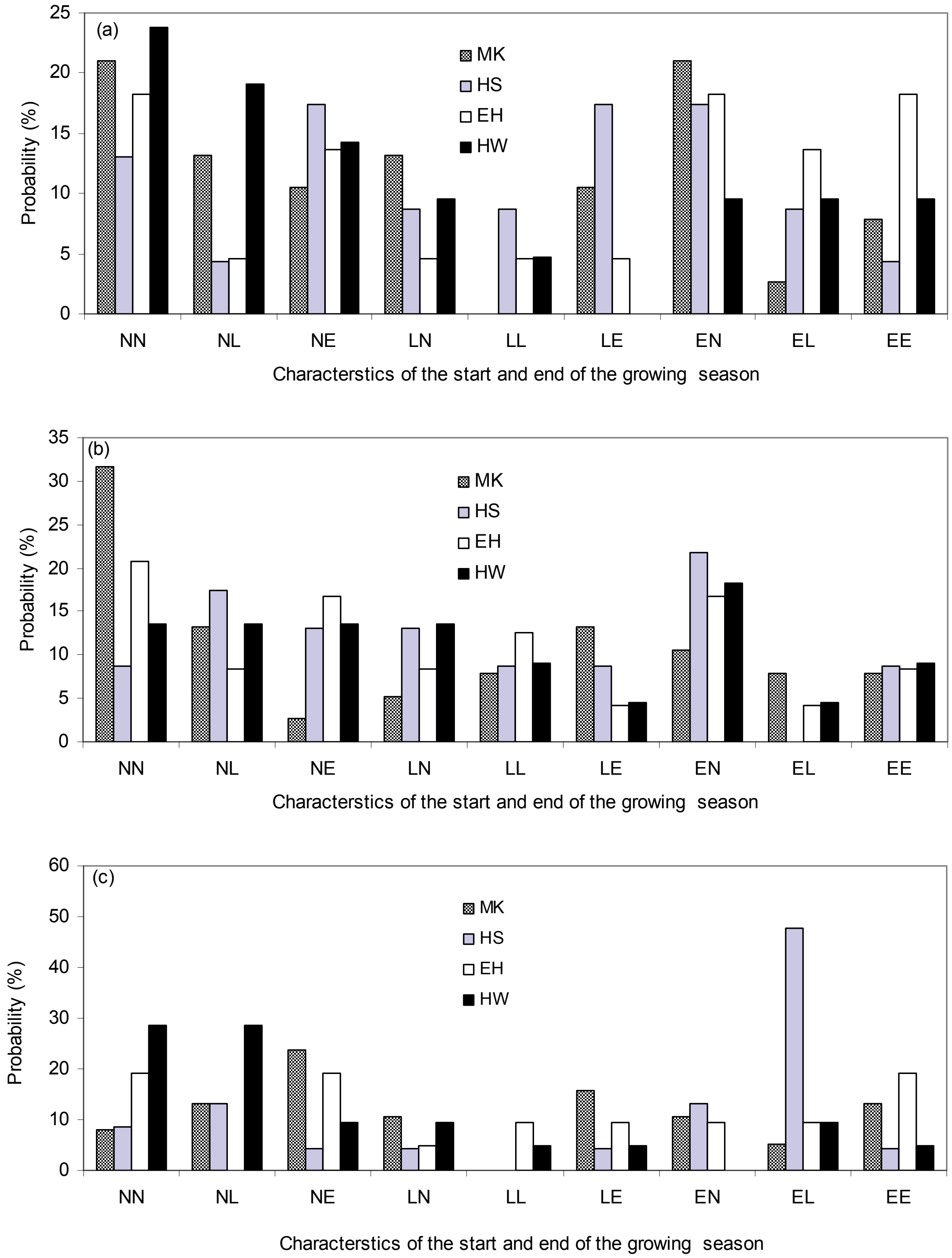

Figure 8.2a-c. Characterization of the start and end of the growing season considering the long-term growing season for each specific station by depth criterion (a), and by farmer's criterion (b). Characteristic of the start and end of the long-term growing season at catchment scale by depth criterion (c).

The various combinations of start and cessation characteristics of the growing season in the study area were evaluated these are: NN, normal start and normal cessation; NE, normal start and early cessation; NL, normal start and late cessation; LE, late start and early cessation; LN, late start and normal cessation; LL, late start and late cessation; EE, early start and early cessation; EN, early start and normal cessation and EL, early start and late cessation.

Figure 8.2c shows the characteristics of the start and end of growing season when applying the depth criterion at a catchment level. Unlike other stations in the study area, HS is characterized by early start and late cessation (EL) (Figure 8.2c). This characteristic has direct relationship with the cropping possibilities in the area. In line with this statement, Araya et al. (2010a) grouped medium maturing crops to this part of the catchment. LE, NE, and EE are those rains that start late or normally or early, respectively, but end early. Seasons with these type of characteristics were most common in MK and EH areas (Figure 8.2c). This shows that MK and EH areas have relatively shorter growing periods when compared to the other stations in the study area. In agreement with this statement, Araya et al. (2010a) categorized short maturing crops to this part of the catchment. This shows that the growing season is affected by the start and end of a growing season. At HW station, rain starts normal and ends normal or late (NN, or NL) (Figure 8.2a and 8.2c). However, there have been higher risks of false start over the station. This might be attributed to relatively uncertain onset and cessation and the intra-seasonal dry spells that occurred over the station in addition to the low water holding capacity of the soil (sandy loam). There was no strong relationship between the start and end of the growing season among the stations in the Giba catchment. This might be due to variable topographical feature and other micro scale factors of the catchment. The spatial presentation of the early, normal and late planting for both depth and farmer's criteria are presented in Figure 8.3a-c and Figure 8.4a-c, respectively. The special variation is reasonably larger between the eastern and western part of the catchment. Rain onset progressively covers from southwest to north and southeastern part of the study area. On average, the difference between the early and late sowing dates by the farmer's and depth criteria are 10 to 20 days, respectively. The reason for the earlier and narrower onset range with the farmer's criterion is because of the criteria for dry planting is met during the first few shower of rain than the wet planting which is described in the depth criterion (Raes et al., 2004).

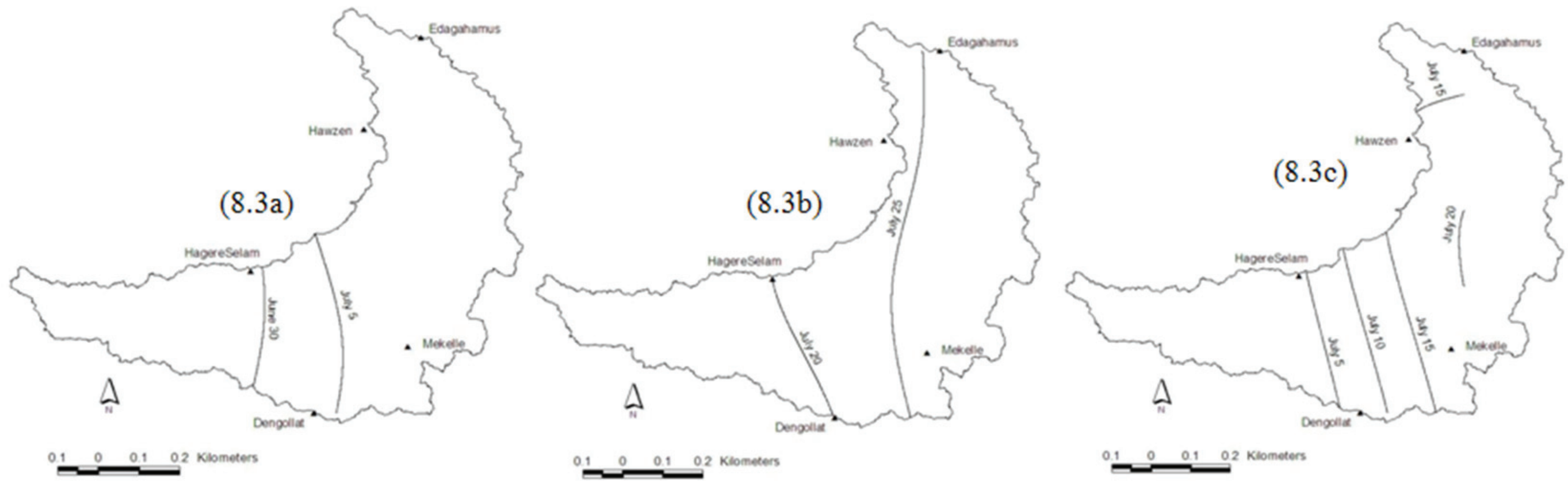

Figure 8.3a-c. Onset date determined by depth criterion (a) early (75%); (b) late (25%); (c) normal (50%).

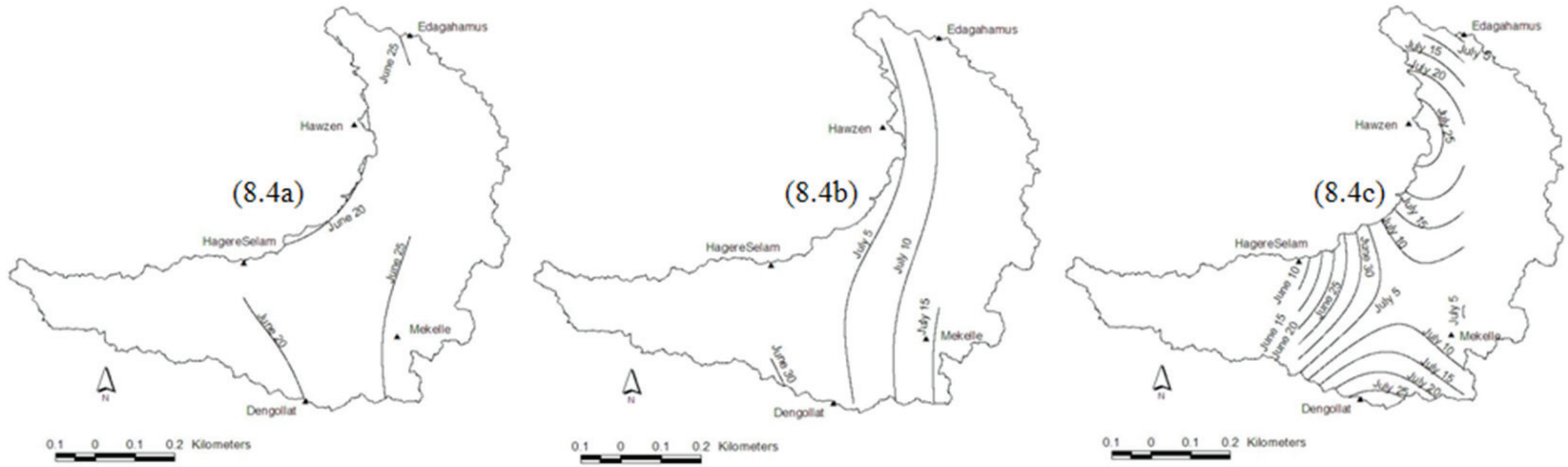

Figure 8.4a-c. Onset date determined by farmer’s criterion (a) early (75%); (b) late (25%); (c) normal (50%).

Although not significantly different, the onset over the northeastern is more uncertain and variable than the southwestern part of the catchment. This indicates the uncertainty of the onset date over the northeastern part of the catchment has been one of the major causes of crop failure. In fact the indistinctiveness of rain expectation has seriously challenged the rain-fed based agriculture in the northern semi-arid Ethiopia.

Considering the Giba catchment as a whole, the seasonal average length of crop growing period is too short (85-90 days) especially in the north and south eastern part where the length of growing period falls below 80 days. Figure 8.5a-c and Figure 8.6a-c show the spatial representation of LGP over the Giba catchment. The ranges between the short and long LGP based on depth and farmer's criterion were 44 and 85 days and 58 and 98 days, respectively (Table 8.4).

Table 8.4. The length of growing period over the Giba catchment both by farmer's and depth criterion. Probability of exceedance 25% (long), 50% (medium) and 75% (short).

	Farmer's criterion			Depth criterion		
Stations	Long	Medium	Short	Long	Medium	Short
MK	76	68	62	69	56	44
HS	98	91	83	85	80	64
EH	79	75	58	70	61	53
HW	96	87	82	74	65	55

LGP increased from the eastern towards the western part of the study area. Crops grown in the eastern part of the study area would suffer from short growing period at least in one out of four years. Assuming early planting, the average growing period over the Giba catchment reached more than 85 days in the southwestern and declined to less than 75 days in the north and southeastern part of the catchment. The LGP over the western part has better certainty when compared with the eastern part of the study area. In agreement with this statement Araya et al. (2010a) categorized medium maturing cultivars of barley to the western part while quick maturing to the eastern part of the study area.

The onset over the northeastern is more uncertain and variable than the southwestern part of the catchment. This indicates the uncertainty of the onset date over the northeastern part of the catchment has been one of the major causes of crop failure (Table 8.5). In fact the indistinctiveness of rain expectation has seriously challenged the rain-fed based agriculture in the northern semi-arid Ethiopia.

The earliest and latest cessation over the study area ranged from 2nd to 20th of September. Considering normal cessation the latest onset is to the southwestern while the earliest is to the eastern part of the catchment. The cessation over the study area is as variable as the onset which makes the growing season more uncertain and hence, challenging the food security in the region.

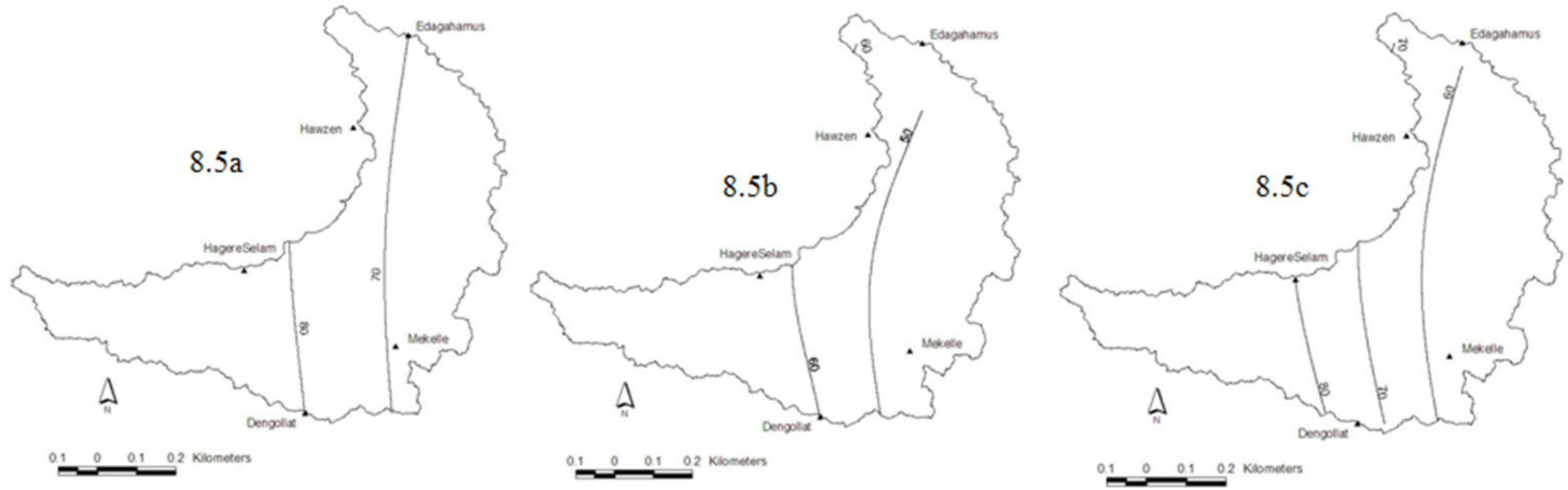

Figure 8.5a-c. LGP determined by depth criterion (a) long (75%); (b) short (25%); (c) normal (50%).

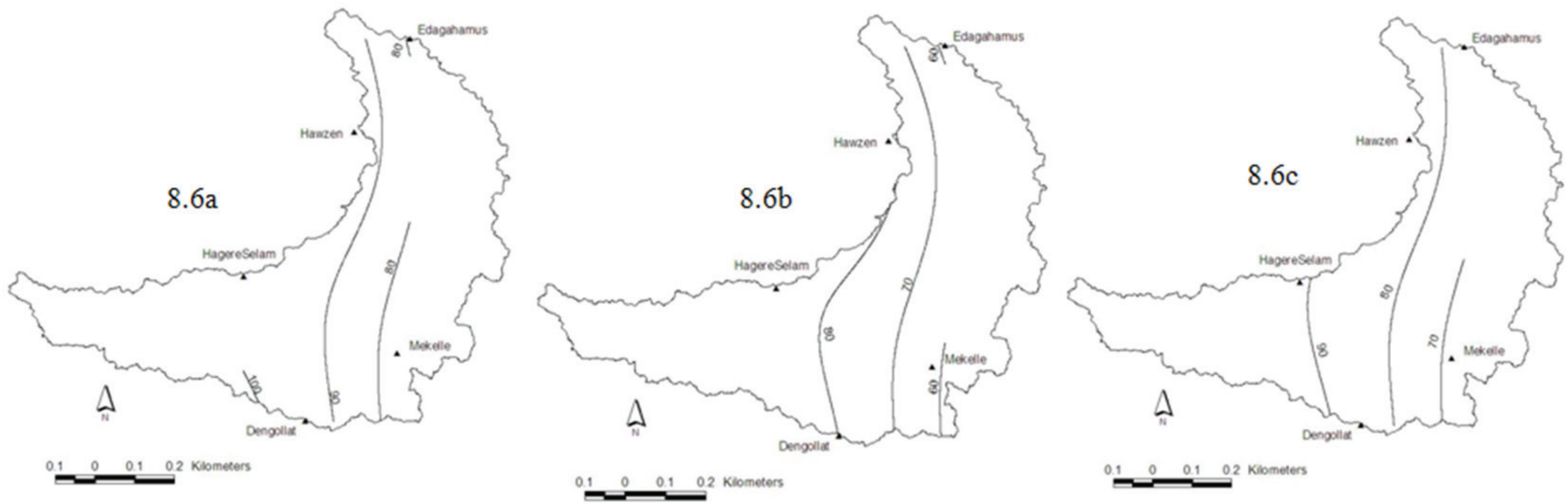

Figure8.6a-c. LGP determined by farmer’s criterion (a) long (75%); (b) short (25%); (c) normal (50%).

Table 8.5. The frequency and probability of crop failure over the stations long-term growing period estimated using AquaCrop model by applying early, normal and late planting based on onset determined by farmer's and depth criteria (yield threshold level was assumed to be 0 t ha^{-1}).

	Farmer's criterion						Depth criterion					
	Early		Normal		Late		Early		Normal		Late	
Station	Freq.	P (%)	Freq.	P (%)	Freq.	P (%)	Freq.	P (%)	Freq.	P (%)	Freq.	P (%)
Mk	11	27	10	24	7	17	9	22	7	17	10	24
HS	6	27	4	18	2	9	5	23	3	14	1	5
EH	8	38	6	29	5	24	7	33	6	29	4	19
HW	14	54	12	46	8	31	7	27	5	19	6	23

Freq., Frequency; P, is probability of failure

Note that the failure rate here is assumed mostly due to false start. The numbers of observation years used for this analysis are: Mekelle (MK), 41 years; Hagereselam (HS), 22 years; Edagahamus (EH), 21 years and Hawzen (HW), 26 years.

Table 8.6. The average biomass and yield of barley over the stations for the long-term total growing period as estimated using AquaCrop model by applying early, normal and late planting based on onset determined by farmer's and depth criteria.

	Farmer's criterion						Depth criterion					
	Early		Normal		Late		Early		Normal		Late	
Station	BM	Y	BM	Y	BM	Y	BM	Y	BM	Y	BM	Y
MK	4.7±3.0	1.2±0.8	4.9±2.8	1.3±0.8	4.9±2.3	1.2±0.6	4.9±2.8	1.3±0.8	4.5±2.2	1.1±0.6	3.9±1.5	0.6±0.4
HS	5.3±2.2	1.3±0.7	5.5±2.0	1.5±0.6	6.4±2.1	1.7±0.6	5.4±3.0	1.4±0.7	6.1±2.5	1.6±0,7	6.4±1.5	1.7±0.4
EH	4.0±2.4	0.8±0.6	4.2+2.7	1.0±0.7	3.9±2.3	0.8±0.7	3.6±2.9	0.9±0.8	3.7+2.5	0.8±0.7	3.1±1.9	0.4±0.5
HW	2.8±2.6	0.7±0.8	3.1±3.2	0.8±0.9	4.3±3.0	1.1±0.8	3.9±2.2	0.8±0.6	3.3±2.0	0.5±0.6	4.0±2.6	0.7±0.6

The numbers of observation years used for this analysis are: Mekelle (MK), 41 years; Hagereselam (HS), 22 years; Edagahamus (EH), 21 years and Hawzen (HW), 26 years.

8.3.2 Yield assessment and crop failure

The evaluation of the failure and success based on total growing season was carried out by exploring the biomass and yield as simulated by AquaCrop model based on two threshold levels. The onset by farmer's criterion assuming a threshold of absolute zero yield for a failure season showed relatively lower failure possibilities when late planting was used. There was significant difference among the resulting crop failures due to the different planting time across the stations. Crop failure significantly increased by stations in the order HS, MK, EH and HW. Crop failure probabilities reduced from early planting to late planting. However lower failure does not necessarily mean higher yield and *vice versa* so it is important to compromise for reasonable yield increment and acceptable crop failure due to false start. There have been some irregularities on the optimal sowing time among the stations. Late planting by farmer's criteria seems to give reasonable yield and acceptable risk of false start or crop failure for most of the stations with exception for HS station. In the case of HS station where the LGP is relatively longer than 80 days, the late planting by farmer's criterion gives relatively lower false start and comparatively higher yield.

Unlike the farmer's criterion, the onset determined by depth criterion showed a reasonably acceptable crop failure or false start and reasonably good yield when early or normal planting was used. Generally, HW (31-54%) and EH (24-38%) showed substantially higher failure probabilities when compared with MK (17-27%) and HS (9-27%) (Table 8.5) may be mainly due to the low water holding capacity of the soils in the area.

Taking into account the depth criterion, there was substantial difference in risk of failure over the stations by planting time for example, normal planting by depth criterion showed less failure than early and late planting. EH (38-57%) and HW (23-50 %) showed appreciably higher failure compared to MK (17-27%) and HS (5-23%). Out of all stations, HS showed the lowest failure when late planting was used (Table 8.5).

The study, generally, showed that the risk level representing false start when dry sowing (farmer's criterion) was applied ranged from 27 to 54%, 18 to 46%, and 9 to 31% for early, normal and late sowing, respectively, while the corresponding values when wet sowing method (depth criterion) was applied ranged from 22 to 33%, 14 to 29%, and 5 to 24%, respectively.

All stations showed higher false start with farmer's criterion when compared to the depth criterion. The result suggested that the use of normal onset by depth criterion or late onset by farmer's criterion would reduce false start substantially.

Yield and biomass performance of barley was also evaluated by onset criterion, by planting time and by station. The assessment based on farmer's onset resulted in relatively higher yield when normal or late plating time was used compared to the crop planted earlier (Table 8.6). The average yield in early, normal and late planting ranged from 0.7 to 1.3, 0.8 to 1.5, and 0.8 to 1.7 t ha^{-1} when dry sowing was applied whereas the corresponding average yield ranged from 0.8 to 1.4, 0.5 to 1.6, and 0.4 to 1.7 t ha^{-1} when wet sowing was applied, respectively (Table 8.6). The result has also indicated that there is greater yield and biomass variability when early planting is applied compared to normal and late planting regardless of the planting criteria used.

All stations showed higher false start with farmer's criterion when compared to the depth criterion. The result suggested that the use of normal onset by depth criterion or late onset by farmer's criterion would reduce false start significantly.

8.4 Conclusion

The result showed that the success of the growing season over the stations was affected by the start (onset) and cessation characteristics. When considering the whole study area some of the stations were characterized by early start-late cessation (EL) of rain while other stations were on the contrary characterized by late start-early cessation (LE) of rain (HS was characterized by early start and late cessation (EL) of rain on the contrary MK and EH stations were characterized by late start and early cessation (LE) of rain). Those stations with EL characteristics obviously have long growing period while those stations with LE characteristics have short growing period. However, what makes it unique was stations have no strong relationship for the start and end of the growing season, which may be due to various regional and small scale climate controlling factors. Such characterization will have significant contribution for food security such as in planning irrigation and other food security strategies. However, there was no strong relationship between the start and end of the growing season among the stations in the Giba catchment, which may be due to various regional and catchment scale climate controlling factors.

The LGP over the south western (HS) station was significantly higher than those of the stations found in the southeastern (MK) and northeastern (EH) part of the catchment. HS and MK stations gave substantially higher yield when compared with EH and HW stations. On the contrary, EH and HW showed significantly higher probability of failures when compared with MK and HS.

Generally the result suggested that risks of false start and crop failure acceptably reduced and yield reasonably improved when late and normal sowing are applied based on farmer's and depth criterion, respectively.

The use of model simulations for sowing enhances our understanding of the crop growing period for improved crop rainwater use and crop production with a minimum cost. Identification of less risky planting like the one presented in this study could have significant contribution for ensuring food security in the drought prone semi-arid regions of Ethiopia.

Chapter 9

Effects of tied ridges and mulch on barley (*Hordeum vulgare*) rainwater use efficiency and production in northern Ethiopia

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Effects of tied ridges and mulch on barley (*Hordeum vulgare*) rainwater use efficiency and production in northern Ethiopia.

Abstract

Two alternative in-situ area rainwater conservation practices (tied ridging and mulching) were evaluated for four seasons (2004, 2007, 2008 & 2009) at an experimental station in Mekelle, Ethiopia. The objectives were to evaluate the performance of barley as influenced by mulch and tied ridge and to understand the relationships of rainfall and runoff on barley fields. About 16 to 30% of the seasonal rainfall resulted in runoff when barley was grown without water conservation, whereas the in-situ conservation practices resulted in significantly low runoff. Tied ridging and mulching increased the soil water in the root zone by more than 13% when compared with the control. Consequently, grain yield and rainwater use efficiency increased significantly with tied-ridging but not with mulching. Tied ridging increased the grain yield over the control at least by 44% during below average rainfall years. Neither mulching nor tied ridging were significantly different from the control when the seasonal rainfall was above average. Since rainfall is often unreliable, we recommend tied ridging as a water conservation technique for loams in the study area in order to mitigate the effect of drought stress in barley. However, tied ridges could be carefully opened when excess water is expected to cause waterlogging.

9.1 Introduction

Eastern Africa is prone to extreme climate events and in the late seventies and eighties, droughts caused widespread famine and economic hardship, particularly to Ethiopia, where agriculture is mainly rain-fed. Studies in many drought-prone environments have shown that meteorological dry spells are important causes of low yield (Rockstrom et al., 2002; Barron et al., 2003; McHugh et al., 2007). Even during periods of high seasonal rainfall, if the interval between consecutive rain events is too long it may cause total pasture and crop failure (Tilahun, 2006; Araya, 2005). The risk of drought in sub-Saharan Africa is also linked to a lack of available water as a result of deteriorated soil physical characteristics (Stroosnijder and Slegers, 2008).

The impact of drought stress on crop productivity is particularly severe when the drought coincides with the moisture-sensitive stage of the crop and if farmers have no management alternatives to overcome the problem (FAO, 2002). In Ethiopia, the problem is aggravated by the traditional tillage system, which has reduced the use of rainwater because a plough pan has formed, resulting in poor rainfall partitioning and ultimately to land degradation (Temesgen et al., 2009). According to the Food and Agriculture Organization (FAO, 2002), crop yield can be significantly increased if cost-effective field water-harvesting technologies are used. Various forms of improving rainwater use can help to retain water in situ by minimizing runoff and bringing more water to crops by maximizing infiltration (Rockstrom et al., 2002; FAO 2003; McHugh et al., 2007; Stroosnijder, 2009; Temesgen et al., 2009).

Since rainfall is the only source of water for agriculture in most of Tigray, rainwater should be managed properly in order to minimize crop water stress. There are many physical soil and water conservation structures for retaining surface runoff in the field and thereby altering the soil water status within the root zone (Hulugalle, 1990; Wiyo et al., 2000; Li et al., 2001; Nuti et al., 2009; Temesgen et al., 2009). They include so-called line structures or areal structures (Stroosnijder, 2009). Since the mid 1970s, line structures – specifically stone bunds and terraces – have been implemented on a large scale in Tigray. One of their drawbacks is that yields usually only improve close to them (where the most water is retained) and sometimes may even be lower because topsoil was removed to create the terraces (Gebremichael et al., 2005; Vancampenhout et al., 2006).

Although water infiltrates behind the line structure, sometimes overtopping may aggravate the risk of soil erosion when there is much runoff. Areal measures overcome these drawbacks. They may be physical (contour furrowing, contour ridging) or agronomic (such as contour ploughing and sowing). Gebreegziabher et al. (2009) report good results with contour furrowing. A drawback of furrows is that if they are not perfectly level, they are ideal waterways and may cause erosion. This can be overcome by connecting the ridges every 2-3 m so that small basins are formed; this system is known as tied-ridging, furrow diking, basin tillage, furrow blocking, soil pitting, micro-basin, or reservoir tillage (Wiyo et al. 2000; Nuti et al., 2009; Temesgen et al., 2009). Mulching, an agronomic method, prevents soil crusting and enhances infiltration. Mulching and tied ridging have been widely used in many different areas in other countries (Papendick and Parr, 1987; Hulugalle, 1989; Li et al., 2001; Chakraborty et al., 2008). However, before these practices can be recommended to smallholders growing barley in Tigray specifically in the Mekelle area of the Giba catchment, they have to be tested. In this paper we therefore report on a study that set out to investigate the relationship between rainfall and runoff on barley fields and to evaluate the performance of barley as influenced by mulching and tied ridging.

9.2 Materials and methods

9.2.1 Study area

The Mekelle area is found in the Giba catchment of the Tigray highlands (2212 m. a. s. l, 13^{o} 30’ N and 39^{o} 29’ E) (Figure 9.1) in the Northern Ethiopia. The main growing season is from June/July to September, which is the period of the *Kiremt* rains (main rainy season) (NEDECO, 1998; Mersha, 2001). In this part of Ethiopia the spatial and temporal variability of the rainfall is particularly pronounced (NMSA, 1996; Nyssen et al., 2005). The availability of moisture is limited not only by the rainfall variability but also by low water-holding capacity of the soil, which is the consequence of the severe soil erosion (NEDECO, 1998).

Agriculture consists exclusively of small-scale family farms. The land reform introduced in the 1980s has led to land holdings that are roughly equal in size (Hendrie, 1999). On average, families in the study area farm two or three parcels of cropland, with a combined area of 0.5 - 1 ha. Grassland, rangeland and forest are communally owned (Nyssen et al., 2007). Cultivated crops include cereals like barley (*Hordeum vulgare*) and wheat (*Triticum* sp.), as well as tef (*Eragrostis tef)*, a cereal with very fine grains, endemic to Ethiopia. Horse beans (*Vicia faba*) are also important (Ruthenberg, 1980). Barley is a major crop grown in the Mekelle area. It is grown mainly for its food and malting (for beer) value and its straw is used as fodder (Maaza and Lakech, 1996).

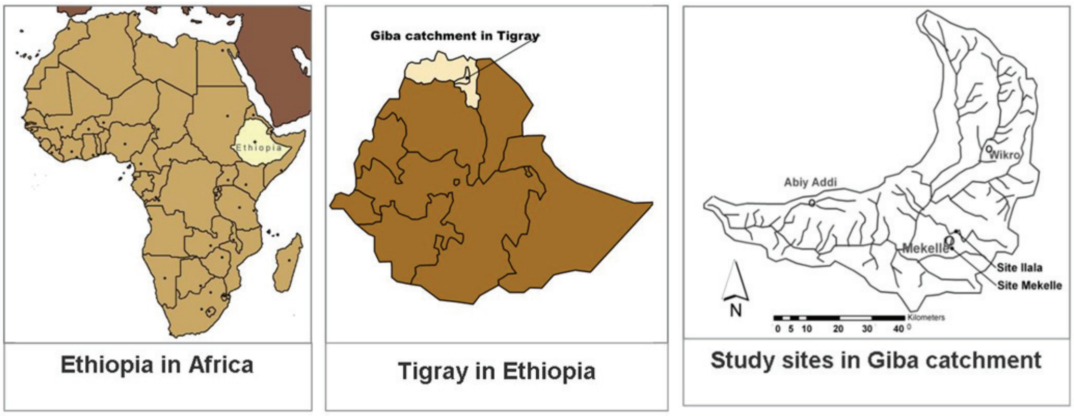

Figure 9.1. Location map of the Mekelle experimental site in the Giba catchment in Tigray, Ethiopia.

9.2.3 Site description and measurement

Soils

The soil at the experimental site (Mekelle) is a Cambisol (Habtegebriel and Singh, 2006) with a silt loam texture in the 0.2 m topsoil. Soil depth is approximately 1 m, with white calcareous rocks (limestone) below this depth. The slope is uniformly 2.5%. Soil organic matter content is 1.85%, total N is 0.21%, available P is 3.12 mg kg^{-1} and available K is 242 mg kg^{-1} (Habtegebriel and Singh, 2006). The field capacity, wilting point and bulk density were analysed in the laboratory in 2004 and 2008 (Table 9.1). Several pits were dug within and around the experimental site from which four replicate samples per pit were taken for each types of soil analysis.

Table 9.1. Soil physical characteristics at the research site (n = 4) in Mekelle site, (in the Giba catchment) Northern Ethiopia.

Depth (m)	Moisture content (vol. %)		Bulk density ($g\ cm^{-3}$)
	FC	WP	
0.0-1.0	30	12	1.55
0.1-0.2	34	14	1.55
0.2-0.6	45	22	1.45
0.6-0.7	34	14	1.37

FC, field capacity; WP, wilting point

Climate

Daily rainfall, temperature (T_{max} and T_{min}), evaporation, wind run, relative humidity and sunshine hours for the growing seasons were obtained from the Mekelle University meteorological station, which is about 200 m from the experimental site. The climate of the area is semi-arid, with mean annual rainfall of about 600 mm. The rainfall distribution is bimodal, with 30% of the annual rainfall received in the short rainy season (February–April). The short rainy season has little agricultural importance. The main rainy season (with 70% of annual rainfall) normally starts in June/July and ends in early September. The long-term average rainfall from July to Sep is about 450 mm. July and August contributed more than 80% of the rainfall in the main rainy season.

Decadal rainfall and reference evapotranspiration (ET_o) (planting to harvest) for the experimental seasons is presented in Table 2. The reference evapotranspiration was calculated using the FAO Penman-Monteith method based on full data sets as described in Allen et al. (1998). The decadal rainfall for 2004 and 2008 was not sufficient to counterbalance for the losses occurred due to evapotranspiration. In 2004 most of rainfall (>70%) was received in the month of August. In the cropping season 2004 and 2008, dry spells with durations of five to seven days were observed in July and September. Whereas in 2007 and 2009, the rainfall was relatively well distributed and was adequate to compensate the evapotranspiration losses except in the end of the growing season (Table 9.2). In addition, relatively fewer and shorter duration of dry spells were observed. Long dry spells are most often observed before mid July and after early September. Figure 9.2 shows the long-term dry and wet spell over Mekelle areas. In this case, the wet spells refers to the probability of occurrence of at least 14 mm rainfall per pentad while the dry spells denotes the probability of occurrence of a pentad with less than 1mm. The 14 mm rainfall per pentad was assumed the minimum rainfall sufficient for seedling establishment in the study area (Araya, 2005). In most of the above average rainfall seasons, waterlogging in barley occurs in the pentads with high probability of wet spells.

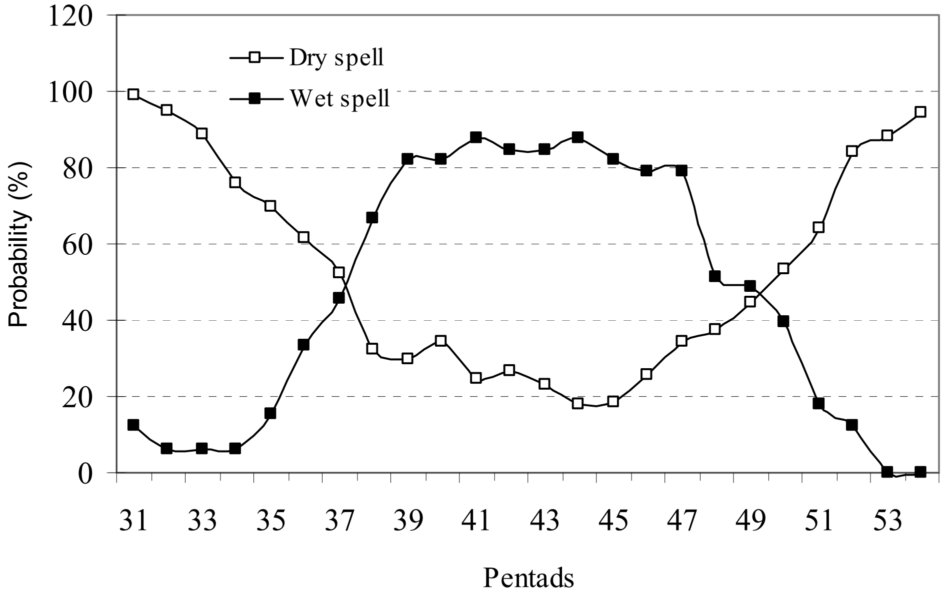

Figure 9.2. Long-term dry and wet spell probability during the main growing season for Mekelle. Wet spell was assumed when the pentad rainfall fulfilled 14 mm rainfall.

9.2.4 Description of water conservation treatments

Land was prepared by using oxen driven plough '*Maresha*' a month and a week before planting. Clods were broken and plots were prepared by hand with the slope of about 2% before sowing. Plough pans were not observed in the site in all seasons.

Two water conservation treatments were examined: mulching and tied ridging. Each treatment was replicated three times in a randomized complete block design (RCBD) of plots sized 4 x 5 m in 2004 and 2007 while 6 x 4 m in 2008 and 2009 spaced 1.5 m apart. All the plots were hydrologically isolated from each other by bunds about 0.2-0.3 m high. Soil and other resources were assumed homogenous.

The ties and ridges were prepared by hand before sowing perpendicular to the slope. The ridges were 0.15 m high and 0.25 m wide and spaced 0.8 to 1 m apart. Ridges were linked at intervals of 2 m, by ties about 0.1 to 0.12 m high. The practice was similar to the currently introduced oxen drawn ridger presented in Temesgen (2000) and McHugh et al. (2007). A dominant local barley landrace variety was grown during the main seasons of the experimental period. Seeds were broadcasted on the surface of the bed and carefully coved by hoeing.

Table 9.2 Decadal rainfall and reference evapotranspiration (ET_o) from planting to maturity during the experimental seasons (2004, 2007, 2008 and 2009) at Mekelle, Ethiopia.

	2004			2007			2008			2009		
Decade	ETo (mm)	Rainfall (mm)	Difference (mm)	ETo (mm)	Rainfall (mm)	Difference (mm)	ETo (mm)	Rainfall (mm)	Difference (mm)	ETo (mm)	Rainfall (mm)	Difference (mm)
1	39.1	35.9	-3.2	33.5	94.0	60.5	30.5	60.0	29.5	29.8	65.8	36.0
2	38.7	17.6	-21.1	33.9	78.5	44.6	29.3	6.3	-23.0	35.1	78.0	42.9
3	32.6	94.5	61.9	32.8	100.0	67.2	31.8	60.8	29.0	32.4	96.3	63.9
4	31.6	119.5	87.9	26.3	51.5	25.2	28.6	58.5	29.9	35.5	63.5	28.0
5	38.7	38.8	0.1	33.2	51.0	17.8	30.6	45.8	15.2	37.0	116.8	79.8
6	37.0	5.0	-32.0	33.9	22.0	-11.9	31.9	27.0	-4.9	34.7	57.5	22.8
7	40.0	30.0	-10.0	38.0	67.0	29.0	38.0	33.3	-4.7	40.6	29.5	-11.1
8	41.0	0.0	-41.0	43.6	22.0	-21.6	36.0	0.0	-36.0	52.9	0.0	-52.9
Sum	298.7	341.3		275.2	486		256.7	291.65		298	507.4	

Mulching was performed by scattering barley straw on the ground every season to a depth of about 0.01 m (approximately 3 Mg ha^{-1}) over the flat surface seven days after crop germination. Approximately 70% of the surface was covered by the mulch. The treatment mulch was not tested in 2009.

The control plots were without soil and water conservation but with all other management practices similar to those of the in-situ water conservation treatments. For example, land preparation was according to the traditional practice using oxen driven plough. Ploughing is performed twice before sowing and seeding is conducted by broadcasting. Weeding is carried out by hand twice. Fertilization is according to the regional recommendation etc.

There is no hoeing in barley after planting. After harvest, land remained fallow till the next season and most of the crop residues were grazed by animal in all years as practiced by the local farmers.

9.2.5 Soil water and runoff

Soil water was measured using the gravimetric method. Measurements were taken at depth intervals of 0.15 m once in ten days from vegetative to late stage, to a depth of 0.6 m. Soil sampling was conducted by taking three samples per plot at the same date.

All the field plots were positioned uniformly on a 2% slope; at the bottom end of each plot the runoff was collected in a barrel (Figure 9.3). Surface runoff from each experimental plot was entered directly into the barrels by gravity. The barrels have a capacity of about 250 litres. The runoff collected was emptied manually when measuring every rainy day. The runoff volume was measured using a calibrated container. Most of the runoff was generated in August. In 2009 very high runoff was generated in one of the rainy days. The runoff spilled out of the plots hence the measurement was not carried out. Some of the ridges were maintained after the rainy event. Runoff and soil water was not measured for the cropping season 2007. In all seasons, sediment losses were also not measured.

Figure 9.3. Overview of the runoff collectors used in Tigray.

9.3.6 Crop management and crop parameters

In all treatments a barley land race, '*birguda*' was sown at a seeding rate of 120 kg ha^{-1}. Di-ammonium phosphate (DAP) and urea were applied by broadcasting, each at a rate of 100 kg ha^{-1} which is equivalent to 64 kg N and 46 kg P. The nitrogen fertilizer was applied half at planting and the other half a month after planting. These practices correspond to the recommended seeding and fertilizer rates for the area. Weeding was carried out by hand three and six weeks after planting. Dates of emergence, heading and maturity were recorded. Yield was harvested from the central 2 x 2 m area. The main yield parameters used for evaluating the different water conservation techniques were dry grain weight and aboveground dry weight at harvest.

9.2.7 Data analysis

ANOVA was used to evaluate the effect of water conservation techniques on the grain yield, biomass yield, and water use efficiency and on runoff yield with the help of the GMP5 statistical software.

Percent deviation (d in %) from the control (C) was calculated using (Equation 9.1). Y and C represent the measured data (grain or aboveground biomass or soil water data) obtained in the soil water conservation (tied ridge or mulch) and its corresponding value in the control treatments respectively. This type of equations was used in maize and lentil yield assessment by Odendo et al. (2003) and Hossain et al. (2006) respectively.

$$d = ((Y - C) / Y) * 100 \qquad [9.1]$$

Rainwater use efficiency (RWUE in kg ha^{-1} mm^{-1}) was calculated by dividing the total grain yield (GY in kg ha^{-1}) by the amount of rain received from planting to harvest (R in mm) (Equation 9.2).

$$RWUE = GY/ R \qquad [9.2]$$

Harvest index (HI) was calculated by dividing the total dry grain weight (GY in kg ha^{-1}) by the total aboveground dry biomass at harvest (BM in kg ha^{-1}) (Equation 9.3).

$$HI = GY/BM \qquad [9.3]$$

Both RWUE and HI were used to evaluate the effectiveness of the water conservation techniques in barley production.

9.3 Results and discussion

9.3.1. Runoff

The seasonal average runoff was between 5-9% in the plots with water conservation and 16 to 30% in the plots without water conservation. Similar studies in semi-arid Ethiopia have indicated that tied ridging on slopes less than 3% reduced the runoff by more than 75% compared with control practice (McHugh et al., 2007). There was very small difference among the measured runoff of the same treatment. Figure 9.4a-c shows the measured runoff and the corresponding rainfall. The runoff in the mulch and tied ridges were by far lower than the runoff in the flat land (control). The runoff reduced by mulch and tried ridging was significantly different ($p < 0.01$) from the control but there was no significant difference between the mulch and tied ridge (Table 9.3). The runoff coefficient for the control practice (arable land without water conservation) agrees with the values reported by Rockstrom et al. (2002); McHugh et al. (2007) and Nuti et al. (2009). Reduced runoff means an improvement in the soil water status in the root zone and a reduction in soil loss, which in turn leads to reduced land degradation and reduced crop water stress (Rockstrom et al., 2002; Stroosnijder, 2009; Temesgen et al., 2009).

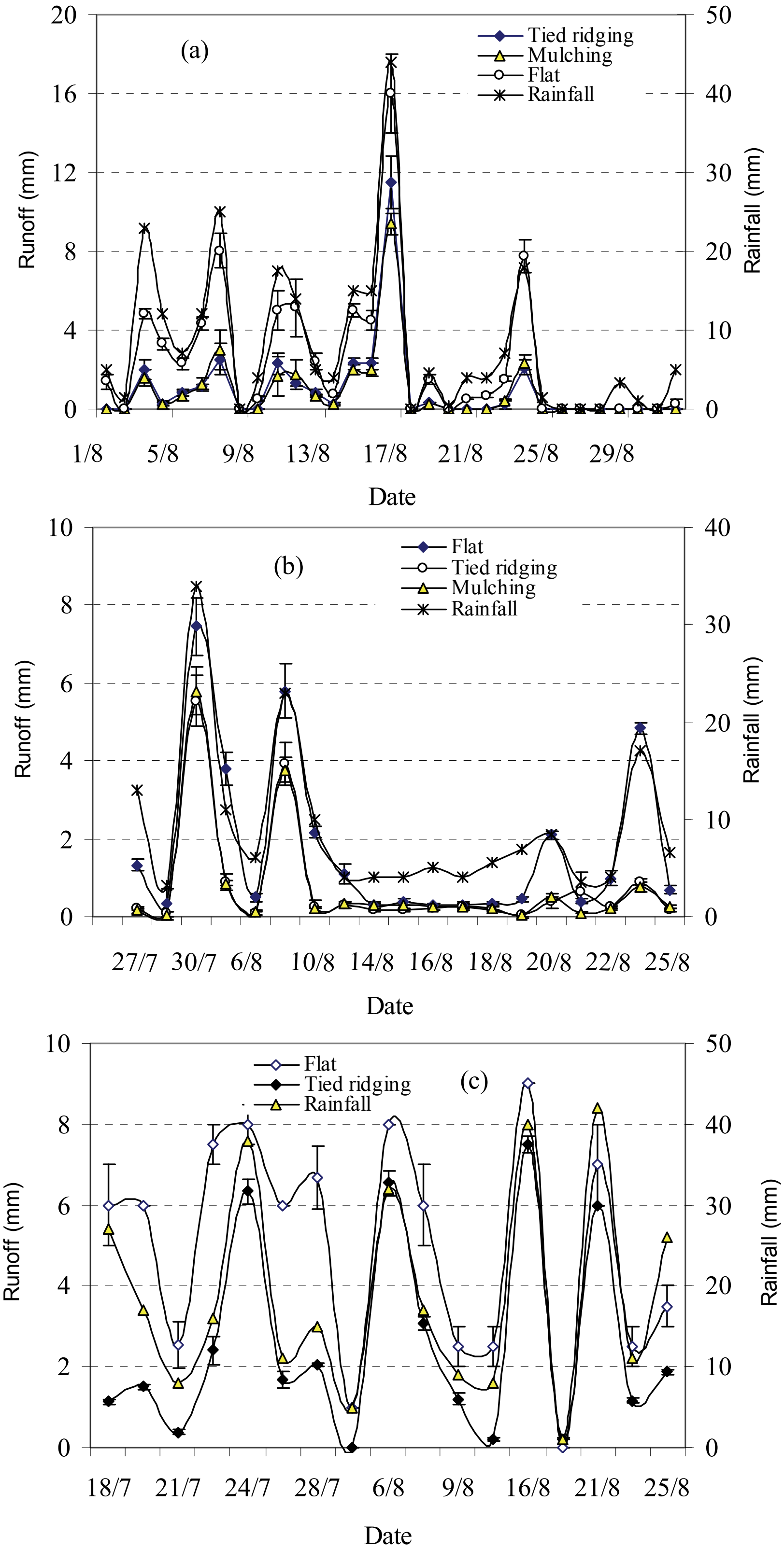

Figure 9.4. Daily rainfall and runoff under treatments with (tied ridges and mulch) and without in-situ water conservation (control) during the cropping seasons of 2004 (a), 2008 (b) and 2009 (c) on a silt loam soil, Mekelle, Ethiopia. Most of the runoff was generated in August. Vertical bars are standard deviation. There was small variation of runoff among the plots with the same treatment particularly in the mulch and tied ridges. Flat represents the control.

9.3.2 Available water

The soil water content was affected by both water conservation measures (Table 9.3) but the variability in measured moisture between plots of same treatment was very small (Figure 9.5a-c). During the summer of 2004, 2008 and 2009, the available water in the root zone of treatments with tied ridging increased by more than 13%, 16% and 27% compared with the control respectively (Table 9.3). A 15 – 24% improvement in soil water was reported in McHugh et al. (2007). Especially at the of end of growing period the soil water in tied ridges was by far higher (above threshold limit) when compared with the control (at permanent wilting point) (Figure 9.5b & c). In cereals like barley, threshold is said to be reached when the actual crop evapotranspiration approaches half of the potential crop evapotranspiration. This value is equivalent to the mid point between the 100% field capacity and wilting point for the soils under consideration. Cereals like barley start to suffer from moisture stress when the soil water reaches below the threshold (Doorenbos et al., 1979). The tied ridge hence lengthens the moisture availability period for the crops. Hence, crops in tied ridges are unlikely to suffer from short duration dry spells (dry spells 7-10 days). In 2004 and 2008, barley was exposed to late water stress in the control treatment earlier than the crops in the tied ridges (Figure 9.5a & b).

The soil water observation indicated that most of the runoff which was captured has infiltrated. Various authors have reported that tied ridging improves positive partitioning of rainwater for better utilization by crops (McHugh et al., 2007; Nuti et al., 2009, Temesgen et al., 2009) and enhances the crop response to rainfall and nutrient (Jensen et al., 2003). Tied ridging and mulching improved the soil water in most seasons of the experimental period. There was no significant difference in availability of soil water between the mulching and tied ridging treatments. Mulching improved rainwater capture (Figure 9.5a & b). The increased storage of water in the root zone due to mulching confirms the findings of Papendick and Parr (1987) and Chakraborty et al. (2008).

9.3.3 Barley yield

Tied ridging improved the barley yield significantly ($p < 0.01$ in 2004) and ($p < 0.05$ in 2008) by comparison with the control practice (Table 9.3). As a result of water conservation, in 2004 the grain yield and aboveground dry biomass increased by 60% and 39% respectively (Table 9.3). In 2004 and 2008, most of the yield advantage with tied ridges as compared to the control should be attributed to the soil water conserved in the early and late stage (Figure 9.5a) and in the vegetative stage of the crop (Figure 9.5b) respectively. According to Jensen et al (2003) maize yield with tied ridging in years with dry to near normal rainfall was improved by 42% even without any nutrient inputs.

In 2009, the soil water was increased by 27% with tied ridges when compare with the control. However, the crop stand with tied ridges was poor due to the aeration stress and the yield did not result in significant improvement when compared with the control (Table 9.3). The aerations stress symptoms were noticed regardless of the treatments in the barley field especially in 2007 and 2009. The resulting aeration stress, (i.e. inadequate oxygen in the root zone) could have depressed yield, because crop plants require oxygen for proper water and nutrient uptake (Russell, 1973; Setter and Waters, 2003) and the presence of excess water in the root zone might have disrupted the normal functioning of the roots. As reviewed by Setter and Waters (2003), soils with less than 10% air porosity are associated with waterlogged conditions. In wheat every 1% reduction below this threshold air porosity was estimated to cause a yield reduction of 0.29 t ha^{-1} (Setter and Waters, 2003). The rainfall in 2007 and 2009 was very intense from sowing to start of flowering (6 weeks after planting). Grain yield of barley was reported to reduce when the crop is waterlogged at early growth of the crop (2 to 6 weeks after planting) and at mid or late stage (after 10-14 weeks) (Setter and Waters, 2003).

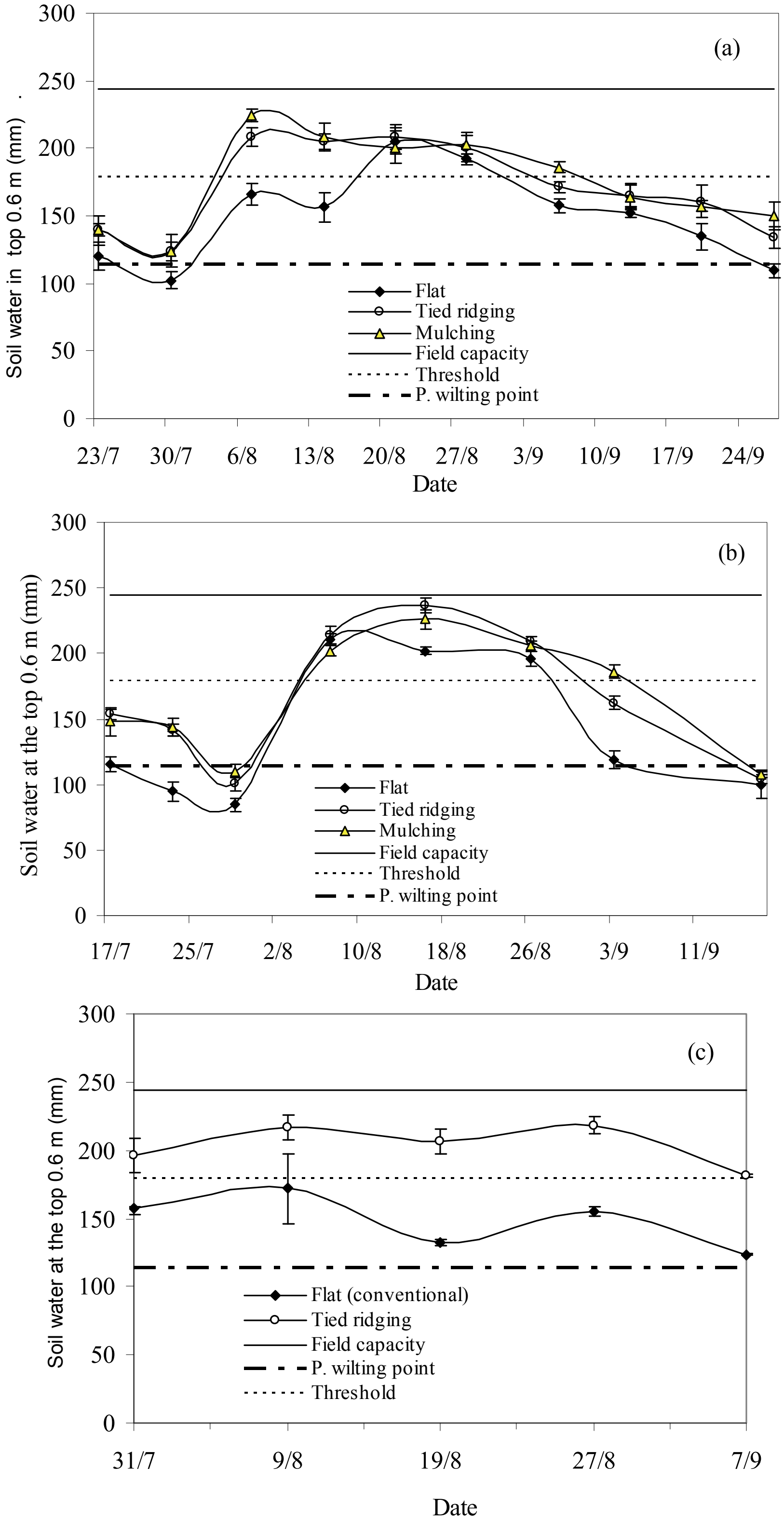

Figure 9.5. Soil water measured in the root zone (top 0.6 m) (mm) with the treatment control (flat), mulch and tied ridge practices during the 2004 (a), 2008 (b) and 2009 (c) cropping season. Maximum available soil water at field capacity is 244 mm. Moisture stress is assumed to begin for crops like barley when it reaches below threshold, indicated by the threshold line. Soil water was not measured for 2007. In 2009, mulch was not tested. Vertical bars are standard deviation.

Table 9.3. Barley biomass and grain yield; the runoff and RWUE for with and without in-situ water conservation and their deviation from the control during the cropping season in 2004, 2007, 2008 & 2009 on silt loam soils at Mekelle, Ethiopia.

Year	Treatment	Rainfall	Soil	Runoff		Grain yield			Aboveground biomass			HI	RWUE	
		(mm)	water improved (d %)	Mean (mm)	SD (mm)	Mean (kg ha^{-1})	SD (kg ha^{-1})	d (%)	Mean (kg ha^{-1})	SD (kg ha^{-1})	d (%)	( )	Mean (kg ha^{-1} mm^{-1})	SD (kg ha^{-1} mm^{-1})
2004	Tied ridge	341	+13.0	30.3b	4.7	2667a**	145.0	+60.0	6237a**	320	+38.7	0.43a	7.8a**	0.5
	Straw mulch		+15.0	27.6b	3.7	1057b	50.0	+1.1	3996b	205	+4.3	0.26a	3.1b	0.2
	Control		-	76.0a**	1.3	1045b	51.0	-	3823b	92	-	0.27a	3.0b	0.2
2007	Tied ridge	486				2321a	91.1	-6.7	7602a	770	-5.0	0.31a	4.8a*	0.2
	Straw mulch					1694b*	76.7	-46.9	6571a	166.7	-17.7	0.26a	3.5b	0.2
	Control					2489a	65.7	-	7980a	818	-	0.31a	5.1a	0.2
2008	Tied ridge	292	+16.0	14.6b	1.0	1373a*	251.0	+44.4	8000a*	890	+28.8	0.20a	4.7a*	1.1
	Straw mulch		+17.0	14.6b	0.6	1063ab	136.0	+28.2	5046b	356	+1.3	0.21a	3.6ab	0.6
	Control		-	47a**	0.7	763b	61.0	-	4980b	597	-	0.15a	2.6b	0.3
2009	Tied ridge	507	+27.0	43.6b	7.1	777a	25.0	+3.2	4267a	50	-12.8	0.18a	1.5a	0.0
	Control		-	84.6a**	1.5	752a	296.0	-	4814a	1545	-	0.16a	1.5a	0.6

* $p < 0.05$; ** $p < 0.01$; letters not with same letter are significantly different. RWUE, rainwater use efficiency; HI, harvest index; SD, standard deviation; d is percent of increase in the treatments with soil water conservation over the control; hyphens (-) indicate not applicable. Note that runoff and soil water was not measured for 2007. All values are means of three replicates. Control represents flat or with out soil water conservation.

The potential water requirement of barley is about 340 mm (Nagazi et al., 2008). Considering 25% runoff, the supplied water in 2007 and 2009 was beyond the gross water requirement of the crop. The result may suggest that water conservation may be unnecessary when the seasonal rainfall is above 480 mm. For example, Wiyo et al. (2000) and Jensen et al., (2003) reached a similar conclusion for maize during above-normal rainfall conditions. Wiyo et al. (2000) out lined that the negative effect dominates when the annual rainfall is above 900 mm. Similarly, Jensen et al. (2003) identified a rainfall limit of approximately 700 and 900 mm at zero nutrient input levels in two different locations respectively. Although yield may not be significantly improved in years with high rainfall, various reports have indicated that tied ridging continues to have important benefits: reducing erosion, improve water availability and water use efficiency and improving nutrient status (Patil and Sheelavatar, 2004; Nuti et al., 2009). In the Tigray case, further investigations might be worthwhile to ascertain to what extent tied ridging reduces erosion and improves the nutrient status under above-normal rainfall conditions with barley.

There was no increase in yield due to mulching as compared to the control in 2004. Although the reason is not fully understood, it seems possible that termites attracted by the presence of mulch might have contributed to this phenomenon. In 2007, mulching even reduced yield by 47% when compared with the control (Table 9.3): the yield reduction during the 2007 wet season was significant ($p < 0.05$). Although soil water and runoff were not measured, the low yield in 2007 is linked with the aeration stress. But further investigation is needed on this. In 2008, however, mulch increased the grain yield by 28% compared with the control, presumably because of the soil water conserved at the vegetative stage of the crop. However, this increase was not significant. It is uncertain whether mulching has other side-effects on barley, so further investigation to assess the effect of mulch on barley performance is desirable.

Except in 2009, slightly higher harvest index values were obtained in the treatment with tied ridge when compared with the treatment mulch and the control (Table 9.3) but they were not significantly different from the control. In 2009, harvest index was very low even when compared with all treatments across the years. One of the main reasons for this result could be aeration stress.

9.3.4. Rainwater use efficiency

In 2004, 2007 and 2008 the rainwater use efficiency (RWUE in kg ha^{-1} mm^{-1}) was significantly higher in the tied ridges than in the mulch and control treatments (Tables 9.3). This demonstrates the effectiveness of tied ridges in capturing rainwater and improving yield. In 2009, tied ridge was not significantly different when compared with the control. The main reasons could be: i. due to low yield resulted from excess wetness. ii. High rainfall beyond the water requirement of the crop resulted in low yield per water supplied. Mulch did not result in increase in RWUE in the test seasons.

Barley yield response to rainfall in below average years (2004 and 2008) was higher when compared to years with above average rainfall (2007 and 2009). Yield response to the relatively high rainfall in 2009 was very low. Jensen et al. (2003) reported that the response of maize yield to rainfall was significantly improved when tied ridging combined with fertilizer inputs. Even though we have not tested if high nutrient inputs in barley could alleviate the negative effect of excessive wetness, the crop is generally well known for its sensitivity to waterlogging (Pang et al., 2004; Setter and Waters, 2003).

9.4 Conclusion

Barley yield under the current practices in Tigray is limited by water stress. To avoid the negative effect of dry spells, management alternatives should be geared towards better use of rainwater, as rain is the main source of water for the subsistence farmers. A significant amount of the rainfall in the semi-arid region of northern Ethiopia is lost as runoff. Tied ridging reduced the runoff and improved the grain yield and rainwater use efficiency significantly in below average rainfall conditions. The increase of the soil water in the root zone by at least 13% has resulted in a significant improvement in yield. This finding can contribute a lot to improve food security in the semi-arid region of the northern Ethiopia where rainfall is often erratic.

Though mulching also increased the soil water it did not result in increased yields, probably because of an aeration problem. A further disadvantage of mulching as a water conservation technique is that it uses straw, which is a fodder.

Considering the runoff, the gross seasonal water requirement of barley is approximately below 480 mm. Hence, tied ridging and mulching in barley may not be useful when the seasonal rainfall is above average. In addition, results suggested that the negative effects may dominate during above rainfall years when tied ridges or mulches are used in barley. But since it is impossible to reliably forecast these conditions at the start of the growing season, and the rainfall is often unreliable, for the semiarid regions of northern Ethiopia we recommend tied ridging as water conservation technique for loams in the study area in order to mitigate the effect of drought stress in barley. The tied ridges could be opened to allow excess water to drain away in order to avoid waterlogging in cases of abundant rainfall.

The benefits from tied ridges as compared with the cost of constructing the ridges and ties need further study. A further investigation is also required on the effect of tied ridging in combination with different planting dates on barley yield.

Chapter 10

Conclusions and synthesis

Conclusions and synthesis

10.1 Problem, main aim and research questions

For decades, drought, crop failure and food insecurity have been familiar to the Tigray region of Ethiopia. These problems have worsened due to climate change and land degradation. Efforts have been made by the government to minimize the problems through the use of drought mitigation and other SWC strategies. Despite these efforts, farmers are still vulnerable to the vagaries of weather.

Rainfall in semi-arid northern Ethiopia is high in intensity and short in duration, which often results in high runoff. In addition, rainfall is highly variable in time and space, and the length of the rainy period is often shorter than the length of the growing period for the predominant crops in the area, i.e teff and barley. Uncertainties in the start and cessation of rain as well as intra seasonal dry spells are very common and make determination of the best sowing period difficult. Furthermore, land degradation processes such as water erosion lead to soil loss and reduced water storage capacity which further exacerbates the situation, and increases the already high risk of crop failure.

The intention of this thesis was to assess, understand and evaluate characteristics of climate in relation to crop failure in northern Ethiopia and then come-up with agro-meteorological and soil and water conservation technologies that enable people to cope with drought. The aim of this PhD-study is to combine agro-climatic information with soil water and crop modelling to determine the potential for improved soil and water management to reduce the risk of crop failure. This would help farmers and policy makers progress toward greater food security in northern Ethiopia. In this chapter, results of the previous chapters are used to address the research questions of this thesis, and present the implications of the findings. The research questions are:

- How suitable is northern Ethiopia for barley and teff and have changes in rainfall affected this suitability?
- How does seasonal rainfall variability and distribution influence the occurrence of soil water drought in semi-arid northern Ethiopia?
- How useful is FAO's AquaCrop model to explore soil water conservation interventions?
- What is the effect of optimal planting?
- Can soil and water conservation measures like tied ridges or straw mulches mitigate dry spells?
- What is the potential for supplementary irrigation?

Section 10.2 discusses the first two questions, sections 10.3 to 10.6 address the rest of the questions, and the major implications are presented in sections 10.7 and 10.8.

10.2 Suitability and cropping risk of northern Ethiopia for barley and teff

In the first two papers (Chapter 2 and 3) of this thesis, agro-climatic and farmer data were collected and analysed. The study showed that most teff and barley cultivars in the study area grow in a range of altitudes from 1550 to 2500 (15 – 24 ^{o}C) and 2000 to 2600 (15 – 22 ^{o}C) m. a. s. l, respectively. The period when low temperatures occur in the study area corresponds to the time of crop's physiological maturity and therefore it can be concluded that temperature has little negative effect on crop production and is therefore not a limiting factor for cropping. This confirms findings by Tilahun (2006) who reported that in the semi-arid tropics the temperature and reference evapotranspiration do not vary a lot and therefore the mayor governing climate parameter is the most variable element - rainfall. This study shows that the three major agro-metrological variables causing crop failure, in the study area were "short growing period", "dry spell” and “total failure of rain”. However, in some seasons waterlogging also contributes to crop failure especially in barley fields.

The period from mid June to mid July corresponds to the time of sowing and early crop establishment of barley. The success of this part of the growing season depends on the onset of rain. Often crops fail during early establishment due to insufficient rain locally known as ‘Aramts’ or ‘Afakus’. This occurs because farmers in the study area sow their barley crop in dry soil or after only a few showers of rain. They use early planting techniques in order to catch the early rains so that they benefit from a prolonged growing season. However, dry planting is only successful if the rains come early, while a severe dry spell at the start of the growing season leads to crop failure. This research indicates that the chances of a false start in the Tigray region can exceed 20 %. This study confirms earlier findings of high frequencies of false starts in northern Ethiopia (Araya, 2005) as compared to Kenya, where the risk of a false start was reported to be only about 9.9 % (Kipkorir et al., 2007). False starts can be avoided if farmers have access to irrigation water, however most do not. Re-sowing is an option if short maturing and drought resistant crops are available, but this shortens the growing period. Through experience, farmers have developed two risk-avoidance mechanisms: (i) replanting with a quickly maturing crop; (ii) delayed sowing (using different short maturing crops) until rainfall wets the top 0.1 to 0.2 m of the soil.

The period between mid July to the end of August represents the peak period of the Kiremt rainy season and coincides with the crop vegetative stage in the case of barley, and the time for sowing and vegetative stage in the case of teff. Teff is normally planted in the peak rainy period in order to ensure successful seed germination and establishment. If during its vegetative growth, teff encounters high humidity, low temperatures, and/or waterlogging, this usually results in slowed growth. But unlike barley, teff tolerates waterlogging. In barley fields, problems with aeration associated with excess water in poorly drained low-lying soils are common observed during this period, resulting in stunted growth and sometimes total crop failure. To better manage water during this time, some farmers make soil bunds (dykes) at the borders of their plot(s) to limit the amount of water entering or open small furrows to let excess water drain away.

The cessation of rains is also highly variable over the study area. Shortening of the growing period as a result of early cessation is a major cause of yield reduction and crop failure in the study area. This conclusion is backed up by the farmers who rank the shortening of the growing period as the main factor limiting crop production. In early September, the weather system is characterized by weakening of the eastern Atlantic and western Indian Ocean monsoon system and the cessation of rains due to the southward retreat of the moist and unstable air mass, Inter-tropical convergence zone (ITCZ). The dominance of the dry northeasterly winds increases after early September. Segele and Lamb (2005) have stated that most of the long dry spells in northeastern Ethiopia occur towards the end of the growing period, particularly in September. A shorter growing period exposes the critical flowering and yield formation stage of crops to long dry spells, resulting in substantial yield losses. On average the contribution of short growing season to crop failure according to this study (Chapter 3) is approximately 40 %. To reduce this problem most farmers use early planting, others use ‘short maturing cultivars’ while only a few them use supplementary irrigation.

Intra-season dry spells that occur between the onset and cessation of rain are also a common cause of crop failure in the study area. This study showed that the average contribution of dry spells to crop failure over the study sites in the northern Ethiopia is about 20 % (Chapter 3). Results showed that a dry dekade[1] is less likely to occur in August than in July and September. Longer dry spells may be related to large-scale or small-scale anomalies in the weather system. Segele and Lamb (2005) indicate that long and

[1] Dekade is defined as a period of 10 days

consecutive dry spells are strongly related to major downturns in dew point, abnormally high temperatures, and easterly winds throughout the troposphere beneath a weak tropical easterly jet.

In addition to the rainy season often being too short, there are some years when rainfall is totally absent (total rain failure). We found that 'total failures' of rain were responsible for, on average, about 40% of the droughts that occurred in northern Ethiopia. For example, the devastating 1984/85 Ethiopian drought was the result of a total absence of rain over multiple years. Note that, the term rain failure is based on our criteria given in chapter 3 section 3.2.5.

The innovative approach of this research is that we developed a simple drought assessing model that depends on drought indices and on the number of wet dekades in relation to the length of growing period. With the use of this simple model we are able to more adequately understand how rainfall distribution contributed to crop failure. The model was also instrumental in identifying the agro-meteorological factors contributing to crop failure and evaluating the frequency of drought relative to normal and wet years. Once the causal factors of crop failure are identified, it is possible to formulate site specific mitigation strategies.

A new comprehensive climate classification technique was developed which links rainfall with evapotranspiration to produce the concept of growing period and merge it with the (temperature/altitude) heat unit requirement of the crops. Previous agro-climatic classification such as the Ethiopian traditional climate classification and Koppen's classification mainly depend on temperature and altitude which are not constraining crop growing conditions in the study area. Similarly, the UNESCO system of climate classification does not consider the length of crop growing period, which makes it inadequate for crop suitability zoning in the semi-arid northern Ethiopia. This new agro-climatic suitability zoning system can be used even on a small scale in the semi-arid areas of Ethiopia.

Considering the frequent occurrence of drought caused by rainfall variability, the study area is climatologically slightly to moderately suitable for short maturing drought resistant cultivars of teff and barley, but not suitable for drought sensitive teff and barley cultivars. The suitability classification can be altered to 'suitable' if effective drought mitigation strategies are employed.

10.3 Experience with FAO's AquaCrop model

Climate data and data from field experiments were used to calibrate and validate FAO's AquaCrop model (version 3.0) which was subsequently used to explore the influence of soil water availability on crop performance (Chapter 5 and 7). Our results show that the model can adequately simulate the soil water, biomass and grain yields of teff and barley under various water availability conditions.

Following the validation of the model, irrigation strategies for barley and teff were evaluated. The model predicts that fully irrigated barley would not significantly improve the grain and biomass yield nor the water use efficiency when compared with the corresponding rainfed (mild water stress) treatment. This statement is in line with the study made by Nagaz et al. (2008). Similarly, Rizza, et al. (2004) also found that low yielding varieties perform as good as under rainfed than under fully irrigated conditions. This implies that in semi-arid environments, with unlimited arable land as is the case in northern Ethiopia, deficit irrigation may save water and improve barley water use efficiency. Therefore, assuming that water is scarce and land is not scarce, the model suggests that more grain and biomass can be obtained from a relatively larger barley area if less water is applied.

In contrast, teff grain yield and above ground biomass were significantly higher in treatments with nearly optimal irrigation, when compared with other rainfed and deficit irrigation treatments. In addition, the nearly optimal irrigation treatments show higher grain water use efficiencies and moderate biomass-water use efficiencies. This implies that in water-stressed conditions with no limitations on arable land, where the main aim is to produce teff fodder, biomass yield can be improved by applying less water to a larger area. However when the main aim is to produce teff grain, a nearly optimum irrigation application would be the best choice. We conclude that the AquaCrop model can be used to explore the best options for improving irrigation water productivity in water scarce environment.

10.4 The role of optimum sowing dates

Considering the importance and uncertainty of rainfall and occurrence of frequent occurrence of false start, improved determination of optimal sowing dates may be an important strategy for successful early crop development and better crop yield. Three years of field experiments with three different sowing dates in northern Ethiopia showed that early sowing (July 4) improved the biomass, grain and water use efficiencies of barley compared with normal and late sowing (Chapter 7). This result was also predicted by the AquaCrop model. Since the climate of northern Ethiopia is highly variable, the use of long-term climatic data is more reliable than depending on just three seasons of experimental data. Hence, the validated AquaCrop model and long-term climate data were used in the evaluation of sowing dates (Chapter 8). The two criteria used in the evaluation, the depth criterion (Raes et al., 2004) and a farmers' criterion, generated quite different result. Results show that the onset of the growing season determined by the depth criterion falls on average 14 days later than the onset according to the farmers' criterion (Chapter 8). Due to this difference, early or normal sowing (depending on the station) based on depth criterion results in acceptable levels of risk of false start or crop failure, and relatively improved yields. By contrast, with the farmers' criterion only late sowing shows acceptable levels of crop failure and yield. The optimum sowing dates correspond to the points at which the top 0.1 to 0.2 m of the soil is moist. This research verifies that use of agro-climatic information and crop models to determine optimal sowing dates can allow exploring options for lower possibilities of false start and enabling crops to exploit the maximum possible rainwater for a relatively better yield and water use efficiency in a growing season.

In addition to evaluating the role of sowing dates, this study suggests improved sowing data analysis technique. In this study, we assume crop failure due to false start to have occurred when there is hardly any yield based on yield simulation model. The advantage of using this technique is that it avoids errors that could occur from using arbitrarily selected early stage water satisfaction values for barley. In addition, the fate of any crop sown at any time is clearly known when a yield simulation model like AquaCrop is used. The use of AquaCrop as employed in this study is a cost effective way to enhance understanding of the crop growing period for improved crop production. Thus, this research also shows that the AquaCrop model can also be used for the evaluation of optimal sowing dates for crops.

10.5 Reduction of crop failure with tied ridges or mulches

Chapter 9 of this thesis reports on the effects of tied ridges and straw mulches in mitigating dry spells and in improving barley yield based on field experimental data. A significant amount of the rainfall in the semi-arid region of northern Ethiopia is lost as runoff. The seasonal average runoff reaches 30% in plots without water conservation compared to a maximum of 9% in the plots with tied ridges or mulch. The available water in the root zone of treatments with tied ridging increased up to 27 % compared with the control. These results are in line with similar studies in other parts of semi-arid Ethiopia which indicated that tied ridges reduced the runoff by more than 75 % compared with the control practice and improve soil water up to 24 % (McHugh et al., 2007). Improving soil moisture availability lengthens the moisture availability period for the crops. Hence, crops in tied ridges are less likely to suffer from short duration dry spells (dry spells of about 7 days). Various other authors have also reported that tied ridging has the potential to improve positive partitioning of rainwater for better utilization by crops (Nuti et al., 2009, Temesgen et al., 2009) and enhances the crop response to rainfall and nutrients (Jensen et al., 2003). The research reported in this thesis show that such strategies can be beneficially employed in the Tigray region.

While this research shows that tied ridging improved the grain and biomass yield of barley significantly compared to the control in below average rainfall years, this is not the case in above average rainfall seasons, probably due to aeration stress. Grain yield of barley has been reported to decrease when the crop is waterlogged during the early growth stage (2 to 6 weeks after planting) and at mid or late stages (after 10 - 14 weeks) (Setter and Waters, 2003). The implication is that increasing soil water storage is undesirable when the seasonal rainfall is above 480 mm.

Mulching did not improve the grain and biomass yield of barley although the soil water in the root zone was significantly improved compared to the control. The reason is not clearly understood yet but it could be aeration stress due to wet soil (waterlogging) as well as mulch induced termite attacks. This research suggests that the use of straw mulch is undesirable for improving soil water availability in barley fields not only due to its lack of effect on barley water use efficiency and grain yield, but also because there are other uses for the straw that have more important benefits for the farmers.

10.6 The potential of supplementary irrigation

Household ponds are the common source of irrigation water in northern Ethiopia. However, the capacity of these household ponds is very small compared to the available irrigable area. Hence, to improve the efficient use of the scarce irrigation water, we quantified the crop coefficient and yield response factor to water stress and subsequently computed water use efficiencies for the major crops. The crop coefficient (k_c) value for teff, the staple food crop in Ethiopia, has never before been documented. The k_c values for teff were developed based on field experimental data (Chapter 4). Similarly, the k_c for the local barley variety was also obtained (Chapter 6). The local barley k_c finding confirms the previously documented k_c values for barley and refutes the agronomists' perception that the local barley crop coefficient differs from that of the documented crop coefficient for barley.

Quantifying yield response factors of crops has significance in water management. For example, in this research, the seasonal yield response to water stress of teff was found to be about 1.04 (Chapter 4). Assuming that water deficit is equally spread over the total growing season, teff responds almost linearly to water stress. Thus, as previously noted, a significantly higher grain yield for teff can be expected when a nearly optimal water supply is provided. Hence, if maximum total grain production is an objective, the best use of available water supply would be to supply the optimal water requirements for teff as much as possible. In barley the highest water use efficiency was also obtained from a fully irrigated crop, however in this case it was not significantly different from a crop grown under a mild stressed condition (Chapter 6). This implies that more barley yield can be obtained by spreading the irrigation water over a relatively larger area. This again shows that use of crop modelling information can generate practical information that can be used to increase crop productivity.

In semi-arid environment where water is scarce like the case of northern Ethiopia, knowledge of the economic water productivity (EWP) and crop water productivity (CWP) is vital for prioritization of crops under supplementary irrigation. We find that the EWP of crops grown under pond irrigation varies with climate, market, crop type, skill and technology conditions (Chapter 4 and 6). For example, EWP and CWP declined from wet to dry climatic scenarios because, in the dry scenario, the pond water is enough only for a relatively small area. Growing tomato shows higher EWP than growing onion, barley or teff. This is because the price and the productivity of tomato per unit of water supplied is higher than that of onion, barley or teff. For example, Chapter 6 reports CWP for tomato and onion as being 85 – 87% and 76 – 78% higher than the CWP of barley, respectively, (due to their higher yield per unit of water applied) and EWP values for tomato and onion are 87 – 89% and 81 – 82% higher than that of barley, respectively, (due to their higher yield and higher price per unit of water applied). This study confirms the findings of earlier studies by Araya et al. (2006), and verifies that growing teff or barley under pond supplementary irrigation is less attractive compared to common vegetable in the region. However, since teff and barley are the main food crops in the region, they have to be irrigated for food security using other source of water e.g. streams.

10.7 The need for further scientific study

This study is limited to two major crops, teff and barley. Most of the analysis was done in reference to a limited scope of the agro-climatic constraints and alternative measures to improve the soil water availability for growing teff and barley in a drought prone semi-arid part of the northern Ethiopia. In future research, we recommend a nationwide characterization of the climate and crop soil water management alternatives using the new approaches developed in this thesis. Furthermore, crop varietal difference both in teff and barley may have an effect on water use efficiency and water productivities; hence further research is also recommended in this area.

Use of the validated AquaCrop model has the advantages of simplicity, low cost and low data requirement, and its application is water driven which is important for exploring yield under various water availability conditions in water scarce environments. However, the model have to be refined for different agronomic conditions such as plant population, cultivar difference, and soil and nutrient conditions as described in chapter 5 and 7 of this thesis.

Tied ridging was found to be effective in mitigating short dry spells in barley fields with loam soils under below average rainfall conditions, however when in above average rainfall conditions there is an adverse effect. Since it is not possible to predict rainfall ahead of time, it would be best if tied ridges are constructed but are able to be opened depending on the rainfall conditions. The construction of such tied-ridging could help minimize the effect of intra-seasonal short dry spells during the rainy period. However analysis of costs and benefit under the local farmers' smallholder conditions is needed before these tied ridges are recommended.

10.8 Recommendation for extension and policy

Often rainfall ceases when crops reach their critical flowering and grain filling stages. On average about 40 % of the drought that occurred in the study area results from water stress in this critical period of the crop, early in September. The application of supplementary irrigation in early September is an option (chapter 3, 5 and 6) even for the main food crops. Sufficient runoff can be harvested in July and August to be stored in farm ponds. It is recommended that irrigation priorities generally be given for crops according to their water productivity as presented in this research. However the main food crops should be irrigated even if their water productivities are low using other water sources such as river diversions, streams, etc.

Under current conditions ponds are the most common water storage structures in the region. These ponds have several problems. Most problems are due to a lack of adequate water management skills at the farmer level (Araya et al., 2006; Tesfay, 2007). It is recommended that the responsible government body prepare demonstration sites and train the agricultural extension workers and farmers. Furthermore, training or informing agricultural extension workers in market dynamics of perishable products can help them better advice farmers regarding production area for various crops in order to avoid extreme price fluctuations. For example, growing only vegetable crops has dangers unless farmers are made aware of the supply and the demand of their products under the predicted market condition because, sometimes bulky perishable products may deteriorate in few days which may force the producers to sell his products at lower prices or causes complete failure. Thus, assessment has to be carried out based on the anticipated prices before planting.

It is also recommended that seepage losses, and sedimentation be recognized as major problems which require governmental attention (Araya et al., 2006; Tesfay, 2007). Furthermore, pond irrigation sites have been found to be favorable breeding grounds for mosquitoes which transmit malaria. Hence, it is recommended that the government give due consideration to appropriate malaria control strategies especially for ponds located near homesteads (Araya et al., 2006; Yohannes and Mitiku, 2010).

Improved irrigation technologies that save irrigation water such as drip technology would improve the water productivities of household ponds. Hence it is recommended that such technologies would help famers to improve their productivity.

Proper agro-climatic classification promotes effective utilization of the available natural resources. In the semi-arid environment rainfall is a greater constraint to crop production than temperature. Thus, the Ethiopian traditional climate classification system (ETCCS) which depends on temperature and altitude is less relevant to crop suitability zoning in semi-arid Ethiopia. Therefore it is recommended that the ETCCS no longer be used unless the length of growing period and the rainfall condition of the areas under consideration are similar to the conditions in that system.

The use of optimal sowing dates is one of the most important drought mitigation strategies. It is vital that farmers be encouraged to sow their crops only after the top 0.1 to 0.2 m of the soil has become moist. This is approximately equivalent to late planting by farmers' criterion and early/normal sowing by depth criterion as described in this thesis (Chapter 8). A strong recommendation from this thesis is that climate information and the crop models be used to determine improved irrigation water productivities, and optimum sowing dates and that these become a key part of extension advice.

Finally, there is the option of growing quickly-maturing crops such as chickpeas in years when rain is insufficient or when the growing season is too short. This may help to avoid complete crop failure because these crops normally grow at the end of growing period, utilizing unused soil water reserves. It is recommended that farmers be encouraged to grow such crops when the seasonal rain starts too late and when there is little possibility for irrigating the crops.

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Summary

Rainfall in Northern Ethiopia has been highly variable in time and space: shorter rainy period compared to the length of the crop growth period; uncertainties in the start and cessation of growing period; intra-seasonal dry spells are very common; in some seasons rainfall is not sufficient for agriculture. Moreover, rainfall is high in intensity over short duration which often results in high runoff. This is exacerbated by land degradation which resulted from improper use of land resources. This thesis tries to assess, understand and evaluate characteristics of climate in relation to crop failure in northern Ethiopia and come-up with alternative agro-meteorological and conservation technologies that enable farmers to cope with drought.

In chapter 2 the suitability of the study area in terms of climate was evaluated. We evaluated the meteorological variables and found that rainfall was the most important factor governing crop growing condition in the semi-arid areas of Ethiopia. To properly classify crops according to their climate suitability, the previous system of crop climate suitability classification systems were found to be mostly irrelevant. Hence, in this study a new comprehensive climate classification technique was developed. The new system links rainfall with evapotranspiration to produce growing period zones and this was merged with traditional thermal zones (heat unit requirement of the crops). The new classification has advantages of its relevance and its applicability at small scale even below the catchment level.

In chapter 3 we studied how seasonal rainfall variability and distribution influence the occurrence of soil water drought in semi-arid northern Ethiopia. Detailed climate analyses were carried out and a simple model was developed taking in to account the crop, soil and climate of the area. Data was also gathered from farmers and documented material which we designated as ‘observed’. The result of the model (‘analysed’) was compared with the ‘observed’ data and we found strong relationships between the two parameters. The newly developed simple model can be used to assess past crop conditions based on climate data and can be used to adequately understand how the rainfall distribution contributed to crop failure. The model also serves as a tool to understand the main agro-metrological factors causing crop failure and in evaluating the frequency of drought affected crop failure in normal to wet years. Based on this information, we were able to formulate a site specific mitigation strategy.

In Chapter 4 and 6 we presented strategies for efficient use of the scarce pond irrigation water. In these chapters, first the crop coefficient for teff and barley and the yield response factor to water stress of teff was quantified and subsequently the water use efficiencies, economic water productivity (EWP) and crop water productivity (CWP) were computed. We find that the EWP of crops grown under pond irrigation vary with climate, market, crop type, skills and the technology used. For example, EWP and CWP declined from wet to dry climatic scenarios because, in the dry scenario, the pond water is enough only for a relatively small area. In that case growing tomatoes shows higher EWP than growing onions, barley or teff. This research confirmed that growing teff or barley under pond supplementary irrigation is less attractive in terms of income compared to other common vegetable in the region. However, since teff and barley are the main food crops in the region, they should be irrigated using other water sources (e.g. streams) in order to warrant sufficient food security.

It was also found experimentally that teff responds almost linearly to water stress (chapter 4). Teff is thus likely to give significantly higher grain yield when a nearly optimal water supply is attained. In barley the highest water use efficiency was also obtained from a fully irrigated crop, but in this case it was not significantly different from a crop grown under a mild stressed condition (Chapter 6). These results imply that more barley yield can is obtained by spreading the saved water over a larger area. Similar result was also obtained using a calibrated and validated model (Chapter 5 and 7). In chapter 5 and 7, climate data and data from field experiments were used to calibrate and validate FAO’s AquaCrop model (version 3.0) which was subsequently used to explore the influence of soil water availability on crop performance. Following the validation of the model, irrigation and optimal sowing strategies for barley and teff were evaluated. The

model predicts that fully irrigated barley have not significant improved the grain and biomass yield or the water use efficiency when compared with rainfed (mild water stress) conditions. This implies that in semi-arid environments and with no restriction of arable land, like is the case in northern Ethiopia, deficit irrigation may save water and improve barley water use efficiency. In contrast, teff grain yield was significantly higher in treatments with nearly optimal irrigation, when compared with other rainfed and deficit irrigation treatments. The nearly optimal irrigation treatments showed higher grain water use efficiencies and moderate biomass-water use efficiencies.

The simulated result based on three years field experimentation on sowing dates in northern Ethiopia also strongly agreed with the observed yield and biomass. Early sowing (July 4) improves the AquaCrop biomass, grain and water use efficiencies of barley (Chapter 7). Following this experimental result, the model was used in the evaluation of sowing dates with the use of long-term climate data (Chapter 8). Two criteria were used in the evaluation: the depth criterion (40 mm in 4 days (Raes, et al., 2004)) and a farmers' criterion (Chapter 2). Results show that the onset of the growing season determined by the depth criterion falls 14 days later than that by the farmers' criterion. However, both sowing dates agreed that the optimal sowing date is at the moments when the top 0.1 to 0.2 m of the soil is moist. This optimal sowing date allows quick crop establishment (lower possibilities of false start) and enables the crops to exploit the maximum possible rainwater for a relatively better yield and water use efficiency in a growing season. Finally, this research showed that the AquaCrop model can also be used for the evaluation of optimal sowing dates and to explore the best option to improve irrigation water productivity in water scarce environments.

In Chapter 9 of this thesis, field experimental data was collected and analysed to study the effects of tied ridges and straw mulches in mitigating dry spells and in improving barley yield. We found that a significant amount of the rainfall (30%) in the semi-arid region of northern Ethiopia is lost as runoff which could be minimized to 9% when tied ridges or mulch were used. Also the available water in the root zone of treatments could be increased up to 27 % using the same techniques. However, when focussing on the crop yield, this research showed that tied ridging improved the grain and biomass yield of barley only significantly in below average rainfall years. Yield was decreased in above average rainfall seasons probably due to aeration stress.

The effect of mulching did not improve the grain and biomass yield of barley although the soil water in the root zone was significantly improved compared to the control. Most likely, this is caused by aeration stress due to water logging as well as mulch induced termite attacks.

Samenvatting

Langdurige droogtes zijn de grootste bedreiging voor voedselzekerheid in semi-aride gebieden zoals Noord Ethiopië. Om de primaire leefomstandigheden en economie van de mensen in de regio te verbeteren, zijn ontwikkelingsplannen gericht op landbouwproductie essentieel, en moeten de droogteproblemen worden opgelost. Door de zeer variabele regenval in zowel tijd als ruimte in het noorden van Ethiopië is het regenseizoen er vaak korter dan nodig is voor de teelt van akkerbouwgewassen. Zowel de aanvang als het einde van de regenperiode zijn onzeker; droge periodes (aaneengesloten dagen zonder neerslag) komen tijdens het groeiseizoen vaak voor en in sommige seizoenen is de totale hoeveelheid regenval niet voldoende om de gewassen tot wasdom te laten komen. Een bijkomend probleem is de hoge regenintensiteit, die resulteert in een hoge oppervlakkige afvoer (runoff), dat verschillende negatieve gevolgen heeft. Ten eerste vermindert het de infiltratie en daarmee de beschikbare hoeveelheid water voor de landbouw; ten tweede wordt door het oppervlakkig afstromende water de bovenste bodem laag geërodeerd. Deze verliezen worden nog verergerd door landdegradatie als gevolg van het oneigenlijk gebruik van de natuurlijke hulpbronnen.

In dit proefschrift worden de kenmerken van het klimaat in het noorden van Ethiopië geanalyseerd en geëvalueerd in relatie tot het risico van het mislukken van de oogst. Het doel van deze studie is om tot alternatieve agro-meteorologische en waterconserveringstechnologieën te komen die het voor boeren mogelijk maken beter om te gaan met droogte.

In hoofdstuk 2 wordt de geschiktheid van het studiegebied voor landbouw geëvalueerd op basis van het lokale klimaat. Uit de evaluatie blijkt dat van de meteorologische variabelen de regenval de belangrijkste factor is voor de gewasteelt in de semi-aride gebieden van Ethiopië. Daarom is het gangbare classificatie systeem voor gewas-klimaat geschiktheid, dat gebaseerd is op het standaard Köppen systeem, weinig relevant gebleken. Daarom werd in deze studie een nieuw classificatiesysteem ontwikkeld, dat de neerslag aan evapotranspiratie koppelt om de lengte van het groeiseizoen te bepalen. Deze informatie wordt daarna gecombineerd met de traditionele indeling in thermische zones (de cumulatieve warmte eis van de gewassen). De nieuwe indeling heeft verschillende voordelen: het is relevanter en kan worden toegepast op een schaal kleiner dan die van een stroomgebied.

Hoofdstuk 3 beschrijft hoe neerslagvariabiliteit en -distributie per seizoen variëren en hoe deze van invloed zijn op het gebrek aan voldoende bodemwater in het semi-aride noorden van Ethiopië. Met behulp van gedetailleerde regenval analyses werd een eenvoudig model ontwikkeld, waarin rekening gehouden wordt met het type gewas en de lokale bodem- en klimaatvariabelen. Deze gegevens werden verkregen van boeren en documenten en worden in deze studie aangeduid met 'waargenomen'. Wanneer we onze model resultaten ('geanalyseerd') vergelijken met de 'waargenomen' data vinden we een sterke correlatie. Dit nieuwe, eenvoudige, model kan worden gebruikt om historische oogstdata op basis van klimaat gegevens te beoordelen en laat zien hoe de relatie is tussen regenvaldistributie en misoogsten. Het model verbetert zo het inzicht in de belangrijkste agro-metrologische factoren die misoogsten veroorzaken en is nuttig voor de evaluatie van de frequentie van de door droogte veroorzaakte misoogsten in 'droge', 'normale' en 'natte' jaren. Op basis van deze informatie zijn we in staat om een site-specifieke conserveringsstrategie te formuleren.

In de hoofdstukken 4 en 6 presenteren we strategieën voor het efficiënt gebruik van schaars beschikbaar irrigatiewater zoals opgeslagen in vijvers op boerenbedrijven (farm ponds). In deze hoofdstukken, worden eerst de gewascoëfficiënten voor teff en gerst en de opbrengst responsfactor voor water stress van teff gekwantificeerd. Vervolgens worden de economische water productiviteit (EWP) en de gewas water productiviteit (CWP) berekend. Hieruit blijkt dat de EWP van teelten met irrigatie varieert als gevolg van het klimaat, de afzetmarkt, gewastype, de vaardigheden van boeren en de gebruikte technologie. Bijvoorbeeld, EWP en CWP dalen als we van een nat naar een droger klimaat gaan omdat in

het droge scenario het irrigatiewater slechts toereikend is voor een relatief klein gebied. In dat geval geeft bijvoorbeeld het telen van tomaten een hogere EWP dan de teelt van uien, gerst of teff. In dit onderzoek wordt dan ook bevestigd dat de potentiële inkomsten van het verbouwen van teff of gerst onder aanvullende irrigatie kleiner zijn dan bij gangbare groenten in de regio. Echter, aangezien teff en gerst de belangrijkste voedselgewassen in de regio zijn, moeten zij worden geïrrigeerd met behulp van andere bronnen van irrigatie water om voldoende voedselveiligheid te waarborgen.

Ook werd geconstateerd dat teff vrijwel lineair reageert op water stress (hoofdstuk 4). Teff geeft dus waarschijnlijk een aanzienlijk hogere korrelopbrengst wanneer een nagenoeg optimale watervoorziening kan worden bereikt. Voor gerst werd de hoogste watergebruik-efficiëntie ook verkregen met volledige irrigatie, maar de efficiëntie was niet significant verschillend van gerst dat geteeld was onder moeilijkere omstandigheden m.b.t. de watervoorziening (hoofdstuk 6). Deze resultaten impliceren dat een hogere opbrengst voor gerst kan worden verkregen door verspreiding van het beschikbare opgeslagen water over een groter gebied. Een soortgelijk resultaat werd ook verkregen met behulp van het gekalibreerde en gevalideerde model zoals gepresenteerd in de hoofdstukken 5 en 7. In de hoofdstukken 5 en 7 werden klimaatgegevens en gegevens uit veldexperimenten gebruikt om FAO AquaCrop model (versie 3.0) te kalibreren. Vervolgens werd dit gekalibreerde model gebruikt om de invloed van de beschikbaarheid van bodemwater op gewas prestaties te verkennen. Nadat het model was gevalideerd, werden irrigatie- en optimale zaaistrategieën voor gerst en teff getest. Hieruit bleek dat het model voorspelt dat volledig geïrrigeerde gerst niet significant meer graan en biomassa opbrengt dan gerst onder regenafhankelijke (milde water stress) omstandigheden. Ook verhoogt de water efficiëntie niet. Dit houdt in dat in semi-aride gebieden waar geen beperkingen zijn van de hoeveelheid bouwland, zoals het geval is in het noorden van Ethiopië, het beperkte irrigatie water beter kan verspreiden over een groter gebied waar gerst op wordt verbouwd, derhalve de watergebruik-efficiëntie te verbeteren. In tegenstelling hiermee worden de teff graanopbrengsten met een vrijwel optimale irrigatie significant hoger dan die onder regenafhankelijke omstandigheden en onder beperkte irrigatie. De bijna-optimale irrigatie behandelingen voor teff vertoonden een hoog graan watergebruik efficiëntie en een matige biomassa watergebruik efficiëntie.

In een drie jarig veld experiment zijn de invloed van zaaitijden op de opbrengsten van biomassa, graan en op de efficiency van het watergebruik bestudeert. Deze zijn vervolgens vergeleken met gesimuleerde resultaten welke goed overeen kwamen met de waargenomen opbrengsten en biomassa's. Vroeg zaaien (4 juli) geeft een verbetering van de biomassa, graan-en watergebruik-efficiëntie van gerst (hoofdstuk 7). Na deze experimentele resultaten, werd het model gebruikt om zaaitijden te evalueren met gebruikmaking van lange-termijn neerslaggegevens (hoofdstuk 8). Twee criteria zijn gebruikt bij deze evaluatie; een 'neerslag criterium' (40 mm regenval in 4 dagen; Raes et al., 2004) en een 'boeren criterium' (Hoofdstuk 2) dat gebaseerd is op de vochtigheid van de bovenste bodemlaag. Het blijkt dat het begin van het groeiseizoen zoals bepaald door het neerslag criterium gemiddeld 14 dagen later valt dan het begin zoals bepaald door het boeren criterium. Echter, voor beide criteria geldt dat het optimale zaai-moment is wanneer de bovenste 0,1 tot 0,2 m van de bodem vochtig is. Een optimale zaaidatum zorgt voor een snelle gewasontwikkeling (minder kans op valse start) en maakt het mogelijk dat de gewassen het regenwater maximaal benutten. Dit resulteert in een betere opbrengst en watergebruik-efficiëntie in het groeiseizoen. Tot slot, heeft dit onderzoek vastgesteld dat het AquaCrop model kan worden gebruikt om de optimale zaaitijd te evalueren en om de beste optie voor het verbeteren van irrigatiewater productiviteit in een waterarme omgeving te verkennen.

Hoofdstuk 9 beschrijft een veldexperiment waarbij gegevens werden verzameld en geanalyseerd m.b.t. de effecten van 'tied-ridges' en stro mulch op het verminderen van het effect van droge periodes en op het verbeteren van de gerst opbrengst. Het onderzoek toont aan dat een aanzienlijke hoeveelheid neersalg (30%) in de semi-aride regio in het noorden van Ethiopië verloren gaat in de vorm van oppervlakkige afvoer (runoff). Dit percentage kan worden teruggebracht tot 9% door gebruik van 'tied-ridges' en stro mulch. Ook kan het beschikbare water in de wortelzone met 27% worden verhoogd met behulp van dezelfde conserveringstechnieken. Echter, wanneer we uitsluitend naar de gewasopbrengst kijken, toont ons onderzoek aan dat 'tied-ridges' de graan en biomassa opbrengst van gerst alleen verhogen in jaren met minder dan gemiddelde regenval. In jaren met meer dan gemiddelde neerslag was de opbrengst was zelfs lager, waarschijnlijk als gevolg van gebrek aan zuurstof in de wortelzone.

Het effect van stro mulch geeft geen verbetering in de graan en biomassa opbrengst van gerst, hoewel de hoeveelheid bodemwater in de wortelzone wel significant verbeterde in vergelijking met de controlegroep. Dit is waarschijnlijk ook het gevolg van een gebrek aan zuurstof ten gevolge van teveel water in de wortelzone en mogelijk ook door aantasting door termieten die op het stro afkomen.

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)
- Copping with droughts for food security in Tigray, Ethiopia

Writing of project proposal (4 ECTS)
- Copping with droughts for food security in Tigray, Ethiopia

Post-graduate courses (6 ECTS)
- Mathematical modelling biology; WIAS (2008)
- ENP-Research methodology: from topic to proposal; MGS, SENSE (2008)

Laboratory training and working visits (0.9 ECTS)
- Dry land agricultural research relevant to cereal research; Debrezeit Agri. And Melkassa Research Center (2008)

Deficiency, refresh, brush-up courses (2 ECTS)
- Ecological methods I
- GIS Tool (2011)

Competence strengthening / skills courses (3.5 ECTS)
- Techniques for writing and presenting a scientific paper; WGS (2008)
- Communication in interdisciplinary research; WGS (2008)
- Writing grant proposal; WGS (2008)

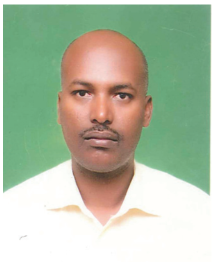
PE&RC Annual meetings, seminars and the PE&RC weekend (2.1 ECTS)
- PE&RC Weekend (2008)
- PE&RC Day (2008, 2010)

Discussion groups / local seminars / other scientific meetings (1.8 ECTS)
- Annual research seminars at Mekelle University (2008, 2009)
- Group discussion on writing proposals for RUFORUM project (2008, 2009)

International symposia, workshops and conferences (6.4 ECTS)
- The 2nd Workshop: lysimeters for global change (2008)
- EGU Conference on climate in the past, present and future (2011)
- Second RUFORUM biennial conference (2010)

Supervision of MSc students: 10 days (3 ECTS)
- Advanced agro-climatology and model application (2009)

Curriculum vitae and author's publication



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