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WATERPRODUCTIVITEIT VAN GERST EN TEF IN DE TIGRAY HOOGVLAKTE VAN ETHIOPIË

Crop water productivity of Barley and Tef in the Highlands of Tigray (Northern Ethiopia)

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Abstract

The pace at which the world's water supplies are depleting and polluted, urges to develop sustainable water saving techniques and strategies in different areas of competence. The number of completed and ongoing research projects in agriculture, the largest water consuming sector, illustrates the necessity for scientific survey. This study entails the research of the water productivity of two important crops in a semi-arid region in Ethiopia, where rainfall is unreliable and unpredictable. The population relies in essence on hazardous rainfed agriculture for her survival. The survey on crop water productivity examines the capacity of crops to produce a certain amount of yield with a given volume of water. Starting from the acquired knowledge about the water productivity of agricultural crops, the ultimate objective of the research is to estimate crop yield under diverse agroclimatic conditions by means of a water productivity model, and to formulate practical guidelines for farmers.

A field experiment, subdivided in units with distinct water supply, was conducted at Mekelle University (Northern Ethiopia) to study the crop water productivity of barley and tef. Climate, soil and crop parameters were collected during the traditional main growing season to gather necessary information about crop development and performance. Data were analyzed and used to calibrate and validate the crop water productivity model AquaCrop. A frequency analysis of historical rainfall data allowed the determination of dry, normal and wet years. For those different types of years, yields were simulated and predicted with AquaCrop. The predictions are a first step in the formulation of guidelines for farmers in the future. After calibration and validation, simulations in AquaCrop furnished good results for barley and underpin the assumption that the relationship between transpiration (normalized for evapotranspiration) and aboveground biomass is linear. Calibration and validation of AquaCrop for tef did not give the desired results. Several aspects involved in the water productivity performance of tef remained too uncertain to calibrate AquaCrop appropriately. By way of precaution, no yield predictions were made for tef with the non-validated model. There is the scope and need to fill the gap of knowledge about this endemic, but promising crop, and to complete the general study about water productivity with more data, gathered at the field level.*

* *Keywords :* crop water productivity, barley, Hordeum vulgare, tef, Eragrostis tef, AquaCrop, Ethiopia, semi-arid

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List of abbreviations and symbols

A	net carbon dioxide assimilation
ANOVA	analysis of variance
α	coefficient
CC	canopy cover
CEC	cation exchange capacity
CGC	crop growth coefficient
CIA	Central Intelligence Agency
CN	curve number
CSA	Central Statistics Agency of Ethiopia
CWP	crop water productivity
CWP°	normalized crop water productivity
DP	deep percolation
DPPA	Disaster Prevention and Preparedness Agency
Δ	slope of the vapor pressure curve
Δc	difference in CO_2 concentration between atmosphere and crop intercellular space
Δw	difference in water vapor concentration between atmosphere and crop intercellular space
e_a	actual vapor pressure
EF	model efficiency
e_s	saturated vapor pressure deficit
ET_0	reference evapotranspiration
ET_c	crop evapotranspiration
FAO	Food and Agricultural Organization of the United Nations
FC	field capacity
G	soil heat flux density
GDP	gross domestic product
G_e	groundwater contributions to effective rainfall

γ	psychometric constant
$h(t_i)$	water level in the hole at time i (Porchet method)
HCl	Hydrogen Chloride
HI	harvest index
IAR	Institute of Agricultural Research
ICARDA	International Center for Agricultural Research in the Dry Areas
IFPRI	International Food Policy Research Institute
ILRI	International Livestock Research Institute
I_n	net irrigation requirement
IWMI	International Water Management Institute
K_c	crop coefficient
K_{sat}	saturated hydraulic conductivity
LAI	leaf area index
LGP	length of growing period
LSD	least significant difference
NDVI	normalized difference vegetation index
NIR	reflection in near infrared band of spectrum
NRC	National Research Council
p	depletion factor, i.e. fraction of TAW that can be depleted before stress occurs
P	rainfall
PE	probability of exceedence
P_{eff}	effective rainfall
PPP	Purchasing Power Parity
r	radius of the hole in the Porchet method
R^2	proportion of variation
RAW	readily available soil water in root zone
red VIS	reflection in red band of visible spectrum
RMSE	root mean square error
R_n	net radiation at crop surface
RO	runoff
ρ_b	bulk density
S	potential maximum retention after runoff begins
SAT	saturation point
SCS	US Soil Conservation Service

T_a	actual crop transpiration
TAW	total available soil water in root zone
TH	threshold value for soil water content
t_j	elapsed time at moment j
θ	volumetric water content
θ_{FC}	volumetric moisture content at FC
θ_m	mass water content
θ_{SAT}	volumetric moisture content at SAT
θ_{WP}	volumetric moisture content at WP
u_2	wind speed at 2 m
UN	United Nations
UNDP	United Nations Development Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
vol%	volume percentage
W_b	stored soil water
WFP	World Food Program
WP	wilting point
W_r	soil water content in the root zone
WRB	World Reference Base for Soil Resources
WUE	water use efficiency
Z_r	thickness of the root zone

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Chapter 1

Introduction

Water is one of earth's most important resources. During the last decades, it became clear that it unfortunately will also be one of earth's most scarce resources if the world does not change its behavior concerning the unsustainable use and management of water, and if the population keeps increasing (IWMI, 2000; FAO, 2002; IWMI, 2006; Rijsberman and Manning, 2006).

Several causes can be listed for water scarcity. Through the ages, water has been a major source of conflicts and misuse of authority, creating inadequate property rights accompanied by water scarcity in aggrieved regions. Inequitable distribution of water, rather than absolute resource scarcity, is here a cause of water insecurity (Cosgrove, 2003). Another source of water scarcity is the contamination of both surface and ground water. Contamination not only compromises the water quality and threatens the ecology and biodiversity of the ecosystem, it also lowers the available amount of water (Meinzen-Dick and Rosegrant, 2001). Third, the ongoing process of global warming is thought to contribute to the destabilization of the world's weather system, affecting people in drought-prone regions and in areas susceptible to inundations (Vörösmarty *et al.*, 2000). In addition, the growing world population and developing industries are today involved in a competitive struggle with the agricultural sector, the major water consumer, and leave more than once their stamp on the availability of water (IWMI, 2000; IWMI, 2006; Rijsberman and Manning, 2006). An urgent tackling of the problem is necessary to guarantee water and food security for every person in the world and this with a strong scientific base.

This dissertation aims to be a contribution to the broad scientific research on sustainable water use in (semi-)arid regions. It focuses on crop water productivity in agriculture. The irregular and unpredictable character of the rainfall determines the agricultural sector in semi-arid and arid regions. Many families are directly dependent on the variable distribution of rain for their survival. Studying the water productivity of local cultivated crops is of high importance, for improved agricultural water management remains the only option for achieving food security worldwide (FAO, 2003b; FAO, 2003c).

The study of crop water productivity is represented by the slogan «more crop per drop». It tries to reveal the maximum *return of crop* (in terms of yield or biomass) that can be obtained *per drop* (unity of water applied by natural rainfall or irrigation and consumed by the crop), and under which circumstances this maximum crop water productivity manifests itself (Oweis *et al.*, 1998; Pereira *et al.*, 2002; Bessembinder *et al.*, 2005). Limited water availability causes crop water stress, which is responsible for yield decline. Since the degree of yield decline is conditional on the specific crop development stage when water stress occurs, the water management - an answer to the question ‘how much water at what time’ - is a key element in influencing and examining the crop water productivity (Zhang and Oweis, 1999; Zwart and Bastiaanssen, 2004; Oweis and Hachum, 2006; Raes *et al.*, 2006a).

To study crop water productivity and its possibilities to increase and stabilize crop yield in critical regions profoundly, an experiment was conducted at the experimental station of Mekelle University. Field and laboratory work consisted of collecting climatic data, determining relevant soil properties, and assessing plant response to water availability. Research was carried out on two important agricultural crops in the highlands of Ethiopia: barley and tef[1]. Barley is a universally cultivated, and consumed cereal and an important component of the Ethiopian diet (Hailu and Van Leur, 1996). Tef, an endemic grasslike cereal, is the basic staple food of the Ethiopian people, but also an interesting crop because of the added value to world’s biodiversity and the diversification of agriculture. Ketema (1993) indicates in his work that ‘it is of general interest that tef, extensively used in Ethiopia but little known elsewhere, deserves sufficient research attention and will be saved as a human heritage’. In the promotion of the conservation and the use of underutilized and neglected crops, the study of the crop water productivity of tef is useful for the further characterization and evaluation of economically important traits such as tolerance to drought (Ketema, 1997).

1.1 Structure of the dissertation

The first chapter of this dissertation elaborates the concept *crop water productivity*. Subsequently, the study area Tigray, an Ethiopian province with a semi-arid character where food insecurity is a dire problem, is situated. Because the study of crop water productivity can open new prospects for the country in its entirety, attention is also briefly fixed to the

[1] Tef can be found in literature spelled *teff* or *t’ef.* In this dissertation, preference was given to use *tef*: simple, concise, and a fit marketing name to realize the potential crop expansion worldwide (NRC, 1996).

Ethiopian context. Subchapter 2.3 (barley) and 2.4 (tef) of the literature review, elucidate general features of the examined crops, in common with their position in Ethiopia. The dissertation continues with the presentation of the materials and methods used to collect and process climate, soil and crop data. The corresponding results are presented and discussed in the ensuing subchapter. Chapter 4 represents the outcome of the simulations carried out with the crop water productivity model AquaCrop (Raes *et al.*, 2006b; Steduto *et al.*, 2006), and a comparison of the simulated and empirical data. The model will be calibrated and validated, before grain yield estimations for different types of years will be made.

1.2 Objectives

The objectives of the study are:
In general:

- To determine crop water productivity of barley and tef;
- To estimate yield of barley and tef in years with different rainfall characteristics and under different management practices.

Specifically:

- To collect climate, soil and crop data of the study area;
- To evaluate the soil water balance in the root zone of the barley and the tef field;
- To evaluate crop development by assessing the canopy cover of the barley and the tef field throughout the season;
- To simulate the soil water balance, crop development and grain yield in AquaCrop for barley and tef;
- To assess the production of barley and tef under rainfed conditions in the study area.

1.3 Spin-offs

After validation of the water productivity model AquaCrop, it will be possible to formulate practical guidelines for farmers in this specific semi-arid region to improve the productivity of barley and tef. Guidelines should be easy to interpret and should make it possible to adapt management practices to changing weather characteristics.

Chapter 2

Literature review

2.1 Crop water productivity: development of the concept

2.1.1 Water scarcity

Arid and semi-arid regions all over the world suffer from water scarcity. During the past decades, the phenomenon of desertification has manifested itself increasingly, drought spells have become more severe, property right conflicts have struck several regions and the general water quality has decreased due to diverse pollution sources. The combined action of these events causes water scarcity for millions of people. In addition, a continuously growing world population enlarges the pressure on the existing water resources (UN-Water, 2006).

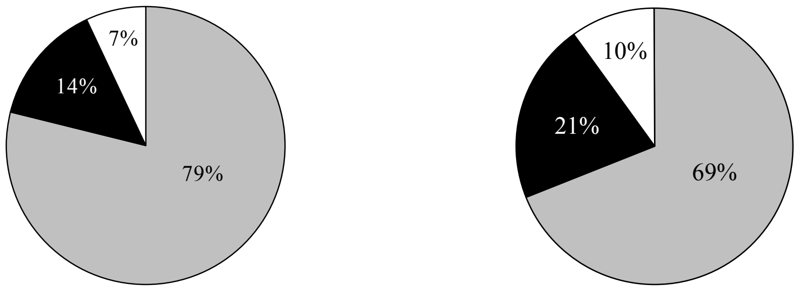
Not at least the African continent faces problems of water scarcity (IWMI, 2006). FAO reports the total amount of renewable water resources for whole Africa less than 9 % of the global renewable resources (AQUASTAT, 2007). Table 2.1 compares Africa and the world with regard to water resources and water use.

Table 2.1: Water resources in Africa and the world (2005) (Source: AQUASTAT, 2007)

	Africa		World	
	[$m^3 \cdot year^{-1}$]	[%]	[$m^3 \cdot year^{-1}$]	[%]
Renewable water resources	$3.931 \cdot 10^{12}$	-	$43.744 \cdot 10^{12}$	-
- per capita	$4.521 \cdot 10^{3}$	-	$6.859 \cdot 10^{3}$	-
Total water withdrawal (% of resources)	$0.215 \cdot 10^{12}$	5.5	$3.818 \cdot 10^{12}$	8.7
- agriculture (% of total withdrawal)	$0.185 \cdot 10^{12}$	86	$2.661 \cdot 10^{12}$	69
- municipalities (% of total withdrawal)	$0.0215 \cdot 10^{12}$	10	$0.380 \cdot 10^{12}$	10
- industry (% of total withdrawal)	$0.0090 \cdot 10^{12}$	4	$0.777 \cdot 10^{12}$	21
- per capita	$0.271 \cdot 10^{3}$	-	$0.599 \cdot 10^{3}$	-

From 1994 to 2004, total water withdrawals have grown by 43 % in Africa, while water use per capita increased by 35 m^3. Both the increase in population and the increase in per-capita consumption are responsible for this growth (AQUASTAT, 2007).

The agricultural sector is still the largest consumer of water, but FAO (2002) reports a change in the partition of water to the three main water-consuming sectors. Figure 2.1 shows the decline in relative water availability worldwide for the agricultural sector in favor of industries and municipalities. The downward tendency is continuing whereas the agricultural sector has to produce more food to secure the growing world population (FAO, 2003a).



1950 **(a)**   **1995** **(b)**

Figure 2.1: Partition of water to different sectors in the world (2005) (Source: AQUASTAT, 2007)
□ Agriculture □ Municipalities ■ Industry

The sustainable use of water has become a challenge of vital importance for the agricultural sector of water scarce regions. There is need for the adoption or improvement of efficient water technologies, integrated in the complex of water and land resources, and for the awakening to wise water allocation policies. Water use efficiency and crop water productivity are key issues in this debate (FAO, 2003c).

2.1.2 Water use efficiency and crop water productivity

Water use efficiency (WUE), as formally defined by Oweis *et al.* (1998), is the ratio of crop biomass per unit area (production) over water consumed by the crop (seasonal transpiration). However, in terms of plant performance, crop physiologists like Steduto (1996) define it as the ratio between crop carbon assimilation (total biomass) and transpiration. In any case, the term WUE should not be confused with irrigation efficiency, which evaluates the performance of irrigation infrastructure (Pereira *et al.*, 2002).

Pereira *et al.* (2002) prefer to use the term *crop water productivity* (CWP), instead of WUE, to give an idea of the water input performance relative to crop yield response. CWP has been defined as the output produced by the plant per unit water input for this production, expressed in kg·m^{-3}. CWP represents the value added to water under given circumstances (Bessembinder *et al.*, 2005) and is often referred to as the search for «more crop per drop». Bessembinder *et al.* (2005), point out the importance of the consideration *which crop* and *which drop* the scientific debate is about. The CWP ratio differs accordingly to the interpretation of its numerator (biomass produced) and its denominator (water used) (table 2.2).

Table 2.2: Possible interpretations of crop water productivity (Source: Bessembinder *et al.*, 2005)

Nominator - Biomass produced [kg]	**Denominator** - Water used [m^3]
- Dry above-ground biomass	- Transpiration
- Fresh above-ground biomass	- Evapotranspiration
- Dry grain yield	- Amount of rainfall and/or irrigation water
- Fresh grain yield	- Effective amount of rainfall and/or irrigation water

In this dissertation CWP is defined as given in equation 2.1:

$$\textbf{CWP} = \frac{\textbf{Total dry biomass of marketable product produced}}{\textbf{All water of different sources taken up by the crop}} \qquad \text{(eq. 2.1)}$$

where CWP = crop water productivity [kg·m^{-3}]

Higher levels of CWP go together with increased grain production without increasing the water supply, or with a stable production when less water is supplied. Both illuminate the water saving potential of increased CWP (Pereira, 2002).

Yet, water productivity is no magic concept to alleviate water scarcity. Care must be taken not to lose track of the fact that yield is a result of the combined action of water, nutrients, labor input, weed incidence, agricultural practices and weather patterns. Increase in crop production per unit water does not necessarily increase the farmer's profit because of the non-linearity of crop yield with production inputs, particularly with water and its interactions with other input factors (Doorenbos and Kassam, 1979). Moreover, if the opportunity costs of saving water are high, a suitable economic evaluation of alternative solutions is necessary (Ortega *et al.*, 2004). However, in semi-arid regions like Ethiopia, where yields are low and unpredictable, increased CWP can contribute to temper the water scarcity problem and meanwhile stabilize yield production (Pereira *et al.*, 2002).

2.1.3 Conservative behavior of crop water productivity

Steduto *et al.* (2007) define in their work the (photosynthetic) CWP as the ratio of net carbon dioxide assimilation (A) to actual transpiration (T_a). When this relation is more thoroughly worked out, it can be proven that CWP is proportional to the gradient of two gases, namely the CO_2 gradient between the atmosphere and the crop intercellular air space, and the water vapor gradient between the atmosphere and the intercellular air space (equation 2.2):

$$\mathbf{CWP} = \frac{\mathbf{A}}{\mathbf{T_a}} = \boldsymbol{\alpha} \cdot \frac{\boldsymbol{\Delta c}}{\boldsymbol{\Delta w}} \qquad \text{(eq 2.2)}$$

where CWP = crop water productivity [mol·mol^{-1}]
A = net carbon dioxide assimilation [mol·m^{-2}·s^{-1}]
T_a = actual amount of water transpired by crop [mol·m^{-2}·s^{-1}]
α = coefficient [-]
Δc = difference in CO_2 concentration between atmosphere and crop intercellular air space [mol·m^{-2}·s^{-1}]
Δw = difference in water vapor concentration between atmosphere and crop intercellular air space [mol·m^{-2}·s^{-1}]

Equation 2.2 underlines the dependence of CWP on both the atmospheric CO_2 concentration and the evaporative demand of the atmosphere which is strongly characteristic of the climate.

After scaling up the net carbon dioxide assimilation to seasonal biomass, Steduto *et al.* (2007) state that CWP can be visualized as the slope of the curve that gives the relation between dry above-ground biomass and the cumulative canopy transpiration (equation 2.3):

$$\mathbf{CWP} = \frac{\textbf{Above-ground biomass}}{\mathbf{\Sigma T_a}} \qquad \text{(eq 2.3)}$$

where CWP = crop water productivity [$g{\cdot}m^{-2}{\cdot}mm^{-1}$]

ΣT_a = cumulative canopy transpiration [mm]

In addition, Steduto *et al*. (2007) indicate the conservative nature of CWP in different environments if the CWP is normalized for Δc and Δw. The former is interesting to evaluate old data and to accommodate data to the future rise in atmospheric CO_2; the latter is useful to extrapolate CWP values between climatic zones, and can be realized by dividing T_a by ET_0 (equation 2.4):

$$\mathbf{CWP^{\circ}} = \frac{\textbf{Above-ground biomass}}{\mathbf{\Sigma(T_a{\cdot}ET_0^{-1})}} \qquad \text{(eq 2.4)}$$

where CWP° = normalized crop water productivity [$g{\cdot}m^{-2}$]

$\Sigma(T_a{\cdot}ET_0^{-1})$ = cumulative ratio between transpiration (T_a) and evaporation (ET_0) [$mm{\cdot}mm^{-1}$]

In equation 2.4 the change of units, brought about by the normalization of CWP, should be noticed.

The study of Steduto *et al.* (2007) is not only confined to the elaboration of the conservative behavior of CWP° of one particular crop throughout the growing season, but also proves the constancy of CWP° for crops that use the same photosynthetic pathway (C_3 vs. C_4 crops). For C_3 crops (like barley) CWP° should range from 13.0 to 15.0 $g{\cdot}m^{-2}$, while for C_4 crops (like tef) CWP° should be situated between 26.0 and 30.0 $g{\cdot}m^{-2}$ (figure 2.2).

Given the conservative nature of CWP°, Steduto *et al.* (2007) mention the limited possibilities for improving the productivity of the water consumed by crops. However, the exchange of transpirational water for biomass production is obviously merely one link in the chain starting from the water supplied leading to the final crop yield. The partition of biomass between vegetative mass and grain yield, visualized in the harvest index (HI) of the crop, the relative contribution of crop development in different phenological stages to final biomass and the soil evaporation are some few other links in the overall concept of water productivity (Steduto *et al.*, 2007). All can be influenced by a well-considered management practice, taking into account the different levels of crop sensitivity to water stress in particular development stages.

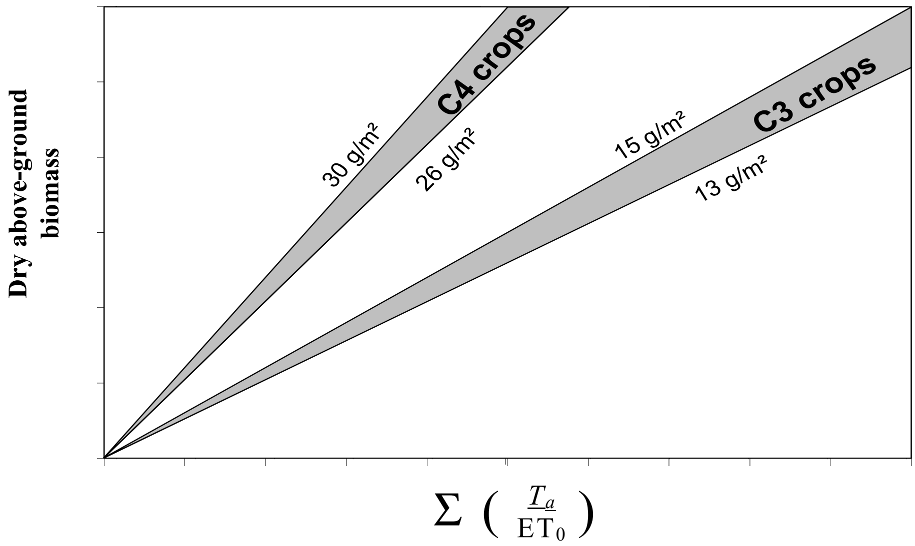


Figure 2.2: Visualization of the conservative nature of normalized CWP for C_3 and C_4 crops

2.1.4 Crop water stress

Crops experience water stress when water deficit occurs and the water supply is not sufficient to keep the actual crop transpiration equal to the potential transpiration (Bessembinder *et al.*, 2005). The stomata of the leaves close partially and create an increased stomatal resistance, reducing the crop transpiration noticeably.

Crops can tolerate a certain degree of water stress. Dependent on the specific complex of several crop characteristics, each individual species exhibits a particular water stress tolerance. However, in this diversity all plants show more or less the same pattern of increasing and decreasing stress tolerance along the growing cycle. Fragile phenological stages, like flowering and grainfilling phase, are characterized by a higher sensitivity to confined water supply (Oweis and Hachum, 2006). Crops can thus be subjected to mild water stress, as embedded in larger management schemes, provided that the water stress occurs in a controlled manner as to impede stress during the most sensitive stages. Knowledge on the crop water requirement, actual water deficit and yield response to water are indispensable to assess crop water use (Doorenbos and Kassam, 1979).

Research (Zhang and Oweis, 1999; Pereira, 2002; Zwart and Bastiaanssen, 2004; Oweis and Hachum, 2006) revealed that crops liable to moderate water stress show significant higher values of CWP. When full crop water requirements are not met, crop growth and yield decrease as a logic result. According to Doorenbos and Kassam (1979), furnishing crops with limited amounts of water can result in a profitable improvement in CWP, provided that the water deficit results in a yield reduction that is less than the concomitant reduction in transpiration.

2.1.5 Crop water productivity and water supply strategies

The majority of the rainfall in Tigray coincides with the beginning of the main growing season from July to early September. Crops can thus outgrow with an extensive amount of stored water. Usually little or no moisture stress occurs during this period, unless the rain fails after an early onset of the rainy season. However, when rain stops abruptly in September, plants transpire strongly and the root zone might be quickly depleted of soil water (Hagos, 2005). The ensuing shortage of moisture often happens during the most sensitive crop development stages - flowering stage and early grainfilling stage - resulting in lower biomass and grain yield production.

To verify the CWP of a particular crop under different patterns of water availability throughout the growing season and the impact of water shortage in sensitive crop development stages on total yield and yield stability through years, supplemental amounts of water can be given to the studied crops to ensure a minimum amount of water available during diverse growth stages when rainfall fails to provide sufficient moisture. In the particular case of Tigray, irrigation can be given in field experiments after the rainy season in critical growth stadia - flowering and/or grainfilling stage - or during the whole season in order to simulate rainfall patterns in different years and their impact on CWP and crop development.

2.2 Study area: The Tigray Highlands in Northern Ethiopia

2.2.1 State and Nation

Ethiopia

The Federal Democratic Republic of Ethiopia is situated in the Horn of Africa, East-Africa. The country shares borders with Somalia, Kenya, Sudan, Djibouti and Eritrea (figure 2.3). Since the declaration of independence of Eritrea in 1993, Ethiopia appears as a landlocked country (CIA, 2007).

Figure 2.3: Ethiopia's location in East-Africa (Source: CIA, 2007)

Ethiopia is one of the oldest countries on the African continent, with more than 2,000 years of history. Its population is estimated to reach 75 million people in 2007 and still grows at an annual rate of 2.3 % (CIA, 2007). The border war with Eritrea and the recent conflict with Somalia mark the country with social unrest.

Agriculture is the buttress of the country's economy, accounting for almost half of the gross domestic product (GDP) (CIA, 2007). Recurrent drought spells, barren soils and poor technical development of agricultural practices cause the sector difficulties. Serious droughts in the successive growing seasons of 1983-1984 and 1984-1985 hit the agricultural sector and the national economy as a whole; nearly one million people starved to death (Tollens, 2004). Today, food insecurity and famine characterize the lives of many families. Even in years when good yield can be achieved, millions of people depend on international food aid (FAO, 2005). 46 % of the people are undernourished. Since 1995 both the proportion and the number of undernourished people have decreased, but simultaneously the external food supply per person increased (FAO, 2005).

The CIA (2007) estimates that in 2004 almost half of the population lived below the national poverty line. The GDP per capita (PPP) amounts to 756 US $ (UNDP, 2006), more than 40 times lower than the Belgian GDP per capita. The Ethiopian GDP now grows at a rate of 8.5 % per year (CIA, 2007), but shows high annual deviations. The human development index, which looks further than merely the income statistics ranks the country 170 out of 177 (UNDP, 2006). In the recent past, the poverty has shown signs of decreasing gradually, as a result of a sustainable tackling of the problem, but there is still a lot to be done.

Tigray

Tigray is the northernmost of nine states in Ethiopia, occupying a total land area of about 8 million ha. It is located between 12°15’ N and 14°50’ N latitude and between 36°27’ E and 39°59’ E longitude (Hagos, 2005). Mekelle is the capital of the region. Figure 2.4 reveals the location of Tigray in Ethiopia, and the subdivision in four districts.

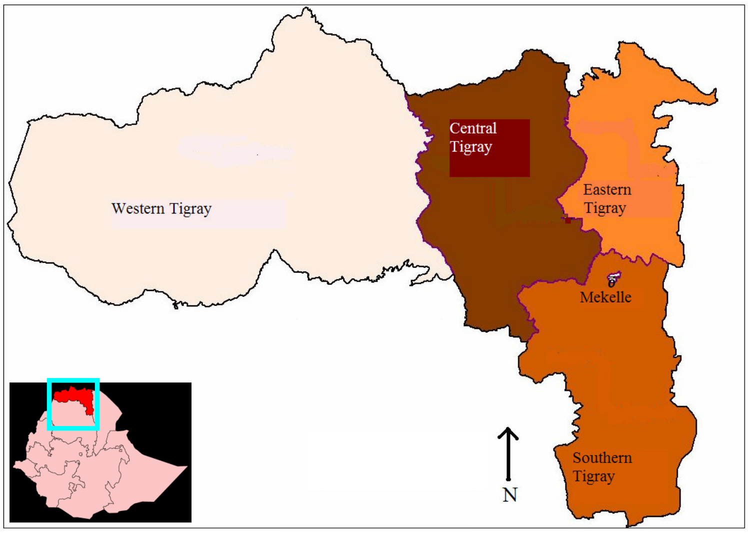


Figure 2.4: Tigray (Source: DPPA, 2007)

The population of Tigray counts more than 3.3 million people and is still growing at an annual rate of 3 %, while the annual growth rate of production is beneath the national average and remains under the population growth rate (CSA, 2006). Population density varies greatly according to favorable topographic and agro-ecological characteristics of the area (Swinnen and Maertens, 2006). Over 85 % of the inhabitants are active in the agricultural sector, which accounts for 64.5 % of the regional GDP (Tesfaye *et al.*, 2000). The region is the most food insecure of Ethiopia. The cereal food deficit reaches values of roughly 180,000 ton·year^{-1}. In 2004, 1,122,000 Tigray people required emergency food assistance; in 2003 the number was even nearly twice as big due to failure of the rain (FAO, 2005).

The landscape of the northern Highlands of Ethiopia is composed out of plateaus, surging hills and profoundly incised valleys. The highest tops rise up to more than 3000 m.a.s.l., but the altitude of the highlands ("dega") ranges from 2000 to 3000 m.a.s.l. (Hagos, 2005).

2.2.2 Climate

Ethiopia

Ethiopia has a tropical monsoon climate, varying throughout the country with altitude (Beltrando and Camberlin, 1993); the country disposes of arid, semi-arid and sub-humid climate zones (Alemayehu, 2003). A high heterogeneity in temperature and rainfall is noticeable. Figure 2.5 represents the rainfall distribution in Ethiopia.

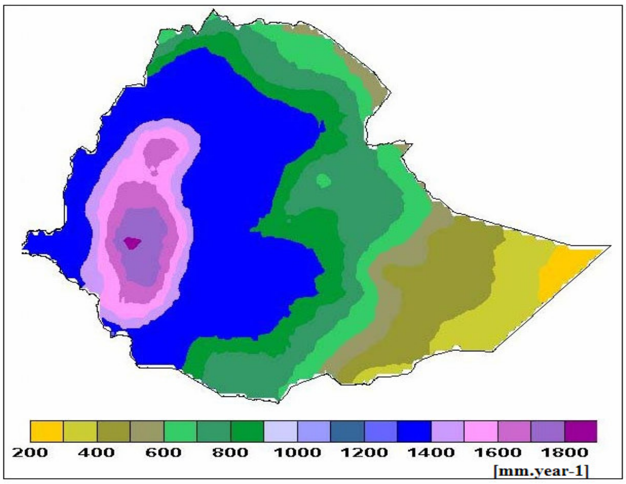


Figure 2.5: Rainfall distribution in Ethiopia (Source: Alemayehu, 2003)

Irregularity is a common aspect of rainfall in the whole country. Annual droughts and intra-seasonal dry spells are no exception and make the rainfed crop production vulnerable. Beltrando and Camberlin (1993) indicate the monsoon winds as the cause for the variable rainfall pattern. The greater part of the country is marked with a bimodal rainfall pattern, although in some regions two rainy seasons merge to form a unimodal pattern (Tesfaye and Walker, 2004).

Tigray

In Tigray, the most severe droughts occur as compared to other regions in Ethiopia. Rainfall is extremely erratic and often insufficient for rainfed crop production (Conway, 2000). The region's climate can be mainly defined as «Kolla» (semi-arid).

Rainfall is characterized as bimodal: 80 % of the annual rainfall is concentrated in the main rainy season («Meher (Kiremti)»), running from June to mid-September (Hagos, 2005). The short «Belg» season provides low rainfall from February to early May in particular areas. In figure 2.6, average rainfall and ET_0 in Mekelle are plotted. The length of the growing period (LGP) coincides with the period when rainfall exceeds 0.5 ET_0.

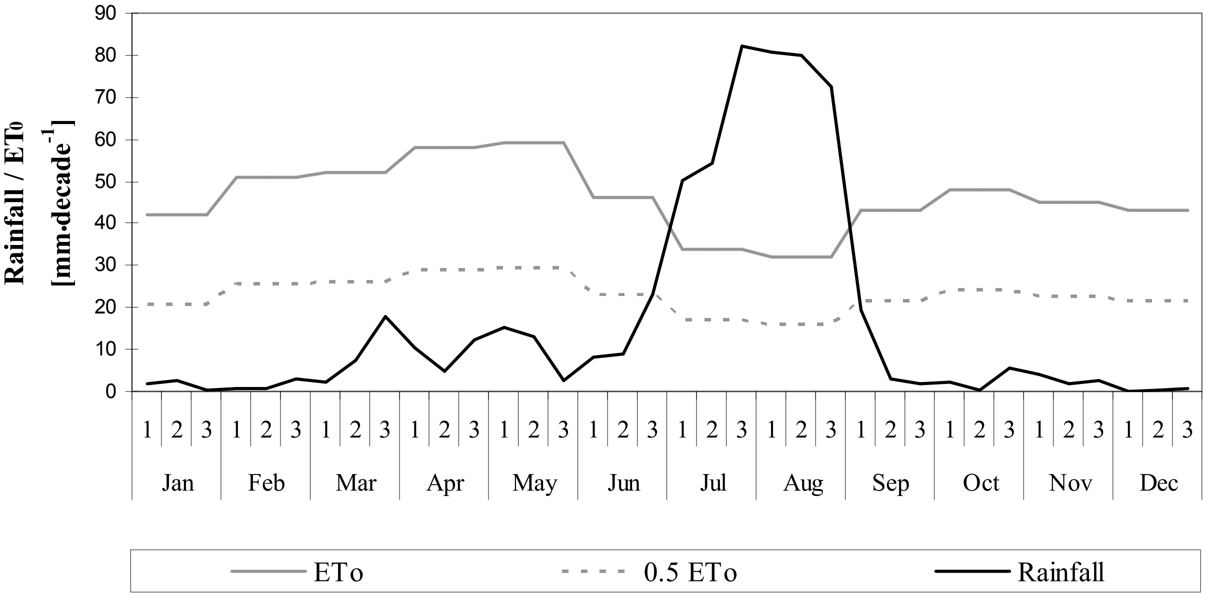


Figure 2.6: Rainfall and evapotranspiration in Mekelle, Tigray (Source: Climatic data from Mekelle airport 1994-2003)

The average annual rainfall ranges from 450 to 980 mm, with a coefficient of variation among years differing from 20 % in the western highlands to 49 % in east Tigray (Tesfaye, 2000). The average annual potential evapotranspiration amounts to 1,801 mm and is largely determined by solar radiation, which is fairly constant between years (Hagos, 2005).

The intensity of rain showers is to blame for water logging conditions and run-off causing rigorous soil erosion. Rainfall can peak to very high intensities (> 66 $mm \cdot h^{-1}$) of short duration, yet the majority falls with an intensity of less than 30 $mm \cdot h^{-1}$ (Nyssen *et al.*, 2005).

Average temperatures vary according to altitude and range from 22 °C in the highlands to above 26 °C in the lowlands (Hagos, 2005). Minimum and maximum temperatures for the region round Mekelle are plotted in figure 2.7.

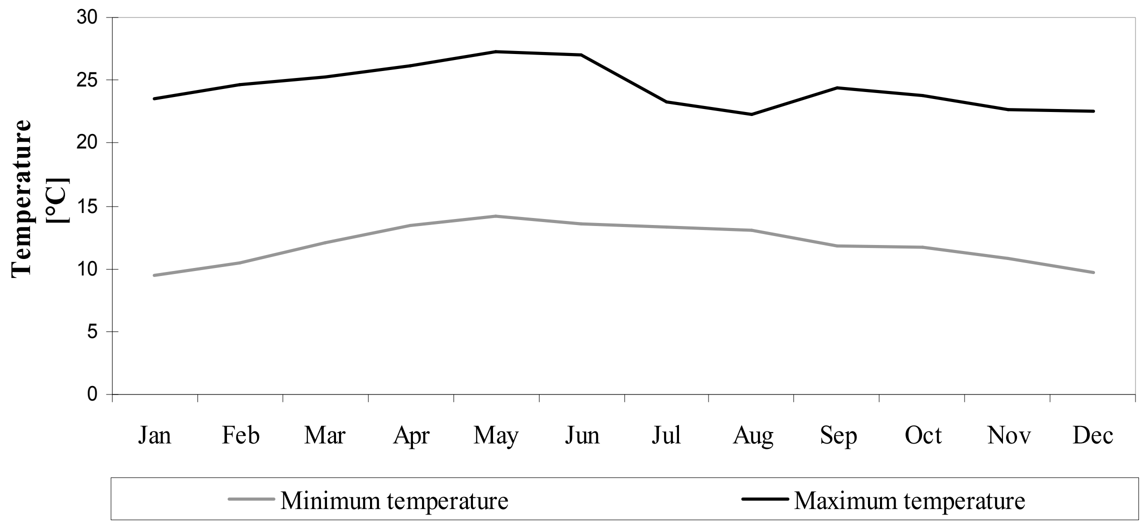


Figure 2.7: Minimum and maximum temperature in Mekelle, Tigray (Source: Climatic data from Mekelle airport 1994-2003)

2.2.3 Soils

Ethiopia

According to the Ministry of Agriculture (Alemayehu, 2003), about 19 soil types are represented throughout the country. Leptosols, nitisols, cambisols and regosols account for the majority of the soil entities. Soils in the whole country are characterized as very stony; part of them possesses a cemented horizon near the surface. Cultivation of these shallow soils poses high risks with regard to erosion. According to Bot *et al.* (1999), low cation exchange capacity (CEC), aluminium toxicity and salinity are only minor constraints in comparison with shallowness and erosion due to steep slopes.

Tigray

No systematic soil survey has been carried out in Tigray. Lithosols, Vertisols, Fluvisols, Gleysols, Arenosols and Luvisols occur (Hagos, 2005). Cambisols are abundant and extensively cultivated. The soils evolve generally on limestone or shale, have a loamy texture and are of moderate depth. Some of them appear brown-grey or black, are high in clay content and have a poor drainage. These soils show evidence of stickiness when wet, of firmness when dry. Although their chemical composition is of high quality, their physical properties make it hard to farm the land (Hagos, 2005). The dominant soil type in the surroundings of Mekelle is Calcic Camibsol or Typic Eutrochrept, according to Eylachew (1994).

2.2.4 Agriculture

Ethiopia

Over 80 % of the country's population is employed in the agricultural sector, and 50 % of the national GDP and even 60 % of the total exports of the Ethiopian economy find their origin in the primary sector (CIA, 2007). The country occupies an area of 113 million ha of which around 10 % is under agriculture (CIA, 2007). Livestock rearing is the major economic activity of farmers in the lowlands (Dejene, 2003). Smallholder farms, mainly under cultivation with cereals or leguminous plants, are dominant in the highlands. The subsistence farming is generally rainfed and yields are low because of the lack of use of fertilizer or pesticides, the absence of mechanization and the poor access to and the low return of credit (Alemayehu, 2003). Unsustainable land use compromises the quality of the arable land seriously (Nyssen *et al.*, 2004). Under the current land tenure system, the government owns all the land and leases small pieces to his citizens (Jayne *et al.*, 2003; Beyene *et al.*, 2006).

Tigray

Small-scale subsistence crop production dominates the agricultural practices in Tigray: farms are limited in size - not more than a mere one hectare (Jayne *et al.*, 2003; Beyene *et al.*, 2006), and show very low levels of specialization (risk-averse management) and mechanization (Alemayehu, 2003). Ploughing happens with a hand driven ox-plough or «maresha», harvest is manually carried out with a sickle. Tef, barley and wheat are the main crops grown in the state (CSA, 2006). Chickpea and beans supplement the seasonal yields. Lack of improved seeds and the absence of fertilizers and pesticides decrease productivity more than wherever in the country (FAO, 2005). Traditional forms of livestock rearing supply milk and meat, and are a complementary source of income. Cattle, sheep, goat and poultry are the dominant livestock. Donkeys act as beast of burden (Dejene, 2003).

Shortage of financial assets is one of the major hampering factors for farmers to get out of the poverty trap. Fifteen year ago, the Relief Society of Tigray, a government institution, started a microfinance program that tries to overcome the inaccessibility to credit and offers possibilities to poor to contract loans in group (Mees, 2000).

2.2.5 Water resources and irrigation

Ethiopia

Apart from the repeated droughts leading to famine in several parts of the country, Ethiopia is often appointed as *the water tower of Africa* (Swain, 1997; Berhane, 2003; Gebeyehu, 2003). There are twelve major river basins, from which the Nile basin is one (AQUASTAT, 2007), several lakes, and a number of wetlands (Tadesse, 2006). Most of the rivers arise in the inland country but become transboundary rivers and carry down their water to neighboring countries (Hagos, 2005; Tadesse, 2006). Although Ethiopia disposes of an annual water supply of 110 billion m^3, Hagos (2005) estimates that only 3.3 billion m^3 is used from which 1 % is allocated to industry, 6 % to the domestic sector and 93 % to agriculture.

Tigray

Tigray counts a number of perennial and seasonal streams, among which the Tekeze, the Mereb and the Danakil river. The rivers carry huge amounts of water that can be exploited as a source of hydroelectric power or for irrigation purposes, but the drainage loss of water to neighboring countries is enormous. Every year 9 billion m^3 water are lost as runoff. With only 50 % of this amount of water saved, enough land could be irrigated to feed three times the present population of Tigray (Hagos, 2005).

Historical research demonstrated that yet since centuries, traditional irrigation systems supplied with surface water were in use in Tigray (Tesfaye, 2000). Today, increased accessibility to irrigation practices and consequently less dependence on rainfed agriculture is one of the strategies of the agricultural development program of the Ethiopian government to increase the food security of the nation (UNESCO, 2004). Today, irrigation is mainly applied to vegetable crops. If irrigation systems are operational, the majority of them consist of seasonal or perennial river diversions or micro-dam and pond («horaye») systems that end in surface irrigation via unlined canals on farmer’s fields (Hagos, 2005; Haregeweyn *et al.*, 2006). Water is lost in considerable amounts as evaporation or seepage from conveyance and distribution canals, by deep percolation from irrigated fields and as runoff at the field ends (Hagos, 2005).

The existence of extended water stocks, although not yet applied in a sustainable way, holds prospects when the research into water productivity will have lead to a better understanding of crop water use and related yield.

2.3 Important Agriculture Crops in Tigray: barley and tef

2.3.1 Crop characteristics of barley

2.3.1.1 Ecology

Barley, *Hordeum vulgare L.* (figure 2.8), belongs to the Poaceae family and is the most widespread cereal (Ecoport, 2006). Worldwide, only wheat, rice and maize can compete with barley with regard to total cultivated area (MacGregor and Bhatty, 1993). Barley is an annual grass, reaching a height of roughly 1 m (Ecocrop, 2003). Some discussion has arisen about the center of origin of barley. Yet most authors believe the center of origin is located in Asia. According to Vavilov (1951), Ethiopia is a center of diversity for barley.

Figure 2.8: Mature barley spike (Source: USDA-NRCS PLANT Database) - Barley field (own source)

In Ethiopia, barley fields can be mainly found between 1,950 and 3,000 m.a.s.l. (Hailu and Van Leur, 1996), but the crop performs well in a broader altitude range (Ecocrop, 2003). Optimum development temperatures range from 15 to 20 °C, but temperatures in between 2 and 40 °C are tolerated. The crop does not require high labor inputs. Strong drawbacks of the plant are the susceptibility to fire, the lodging problem and the lack of resistance to biotic stress factors (Ecocrop, 2003).

Moisture performance

Excess humidity causes water logging, leading up to the plant's death. The crop requires a well-drained soil profile: an excess of water causes decay (Ecoport, 2006).

Compared to other cereals, barley produces each unit dry matter with less water, which makes it an interesting crop to evaluate CWP. Barley shows higher values for CWP for different levels of water availability than sorghum, wheat and maize (Sepaskhah and Ghahraman, 2004). Table 2.3 gives an overview of indicative values for CWP as mentioned by different authors.

Table 2.3: Indicative values for crop water productivity of barley in semi-arid environments

Conditions	**CWP** [kg·ha^{-1}·mm^{-1}]	**Reference**
Different barley varieties in Mediterranean area	8.7 - 13.7	Gregory *et al.* (1992) in Lopez and Arrue (1997)
Different barley varieties in Mediterranean area	5.9 - 9.5	Cantero-Martinez *et al.* (1996) in Lopez and Arrue (1997)
Barley variety in semi-arid environment	7.4 - 10.1	Bhutia and Singh (1990)

Barley plants, although liable to sterility, forced maturation and substantial yield reduction due to persistent droughts, perform relatively well under dry conditions (Sanchez-Diaz *et al.*, 2002; Lopes *et al.*, 2004). 200 mm precipitation per growing season is the absolute minimum. Optimal rainfall amounts from 500 to 1000 mm·year^{-1} (Ecocrop, 2003). Briggs (1978) believes that water stress in early growth periods can have a chastening influence in enhancing the drought-resistance of barley, and can prevent lodging. Stress conditions from the onset of shooting until the conclusion of anthesis are more critical for an optimal plant growth (Briggs, 1978).

It is believed that water stress, next to other factors, has a strong influence on the length of the growing stages of barley (Savin et Nicolas, 1996; Schelling *et al.*, 2003). Precocity, resulting in a shortening of the grainfilling period, is an important strategy of the crop to avoid the negative effects of water stress (Acevedo *et al.*, 1991; Vanoosterom and Acevedo, 1992; Mitchell *et al.*, 1996; Gonzalez *et al.*, 1999). Yet, the duration of the period between heading and maturity determines the final yield production (Savin and Nicolas, 1996; Schelling *et al.*, 2003). In this context, Schelling *et al.* (2003) describe a relationship between grainfilling duration on the one hand and grain quality and quantity on the other, with an optimum towards longer grainfilling periods, but with a threshold value. Bhutia and Singh (1990) and Sepaskhah and Ghahraman (2004) state that in case of water deficit the final yield and the HI decline indeed, but CWP increases.

Among barley varieties, different levels of CWP have been noticed. It is believed (Gunasekera *et al.*, 1994) that genotypes with a higher osmotic adjustment capacity maintain greater stomatal conductance under water stress. As a result, the photosynthesis rate remains higher and the crop yields better.

Soil performance

Even light acid soils bring on problems with aluminium toxicity, which can negatively affect the plants (Scott *et al.*, 1997). Barley performs better in calcareous soils, sufficiently represented in Ethiopia. Optimal soil pH lies between 6.5 and 7.5 (Ecocrop, 2003).

Deep, medium textured soils provide best yield results. No high demands are made up on soil fertility. The crop is often found in low-productive areas where other cereals fail to yield well. Salinity values of 10 $dS \cdot m^{-1}$ or more can be endured, though low values round 4 $dS \cdot m^{-1}$ give higher yields (Ecocrop, 2003). Severely compacted and impermeable soils can form difficulties for the developing plant (Hailu and Van Leur, 1996).

2.3.1.2 Morphology

Barley has two different kinds of root systems. Up to tillering stage, the plants develop only primary roots; after tillers have start to appear, secondary adventitious roots develop. Leaves are lance-shaped and face each other along the stem. The base of the leaves is wrapping the stem. Barley develops an oval caryopsis with a long or short spike, depending on the plant type. Grains can be white, blue or black in color (Ecoport, 2006).

2.3.1.3 Physiology

During its growth, this C_3 plant passes through three phenological stages: vegetative, reproductive and grainfilling stage. Table 2.4 and figure 2.9 give an overview of the successive phenological stages and their characteristics.

Table 2.4: Phenological stages of barley (Source: Briggs, 1987; Ecoport, 2006)

Phase	Description
Vegetative	Seed germination and plant emergence (5 - 10 days).
Tillering	Setting of the tillers: main culm first, followed by tiller shoots. Tillering stage defines the potential number of heads, and the maximum number of grains per plant.
Reproductive	Start with the initiation of floral primordia at top of the main culm and the tiller shoots.
- Jointing	- Upward extent of culm and elongation of the internodes (joints).
- Booting	- Expansion of spikes inside flag leaf sheath and swelling of leaf sheath.
- Heading	- Appearance of awns and outgrowth of heads roughly two days after booting. Heading stage defines the absolute number of heads per m^2.
- Flowering (anthesis)	- Occurrence of the first stamen (vaguely distinguishable).
Grainfilling	Grain formation manifested as a rise in length of the grains. It takes the grains several days to fill the available space inside the flower. Grains pass from milky-ripe over mealy ripe (soft and dry grains) to hard to thumbnail.
Maturation	Shrinking and drying of grains.

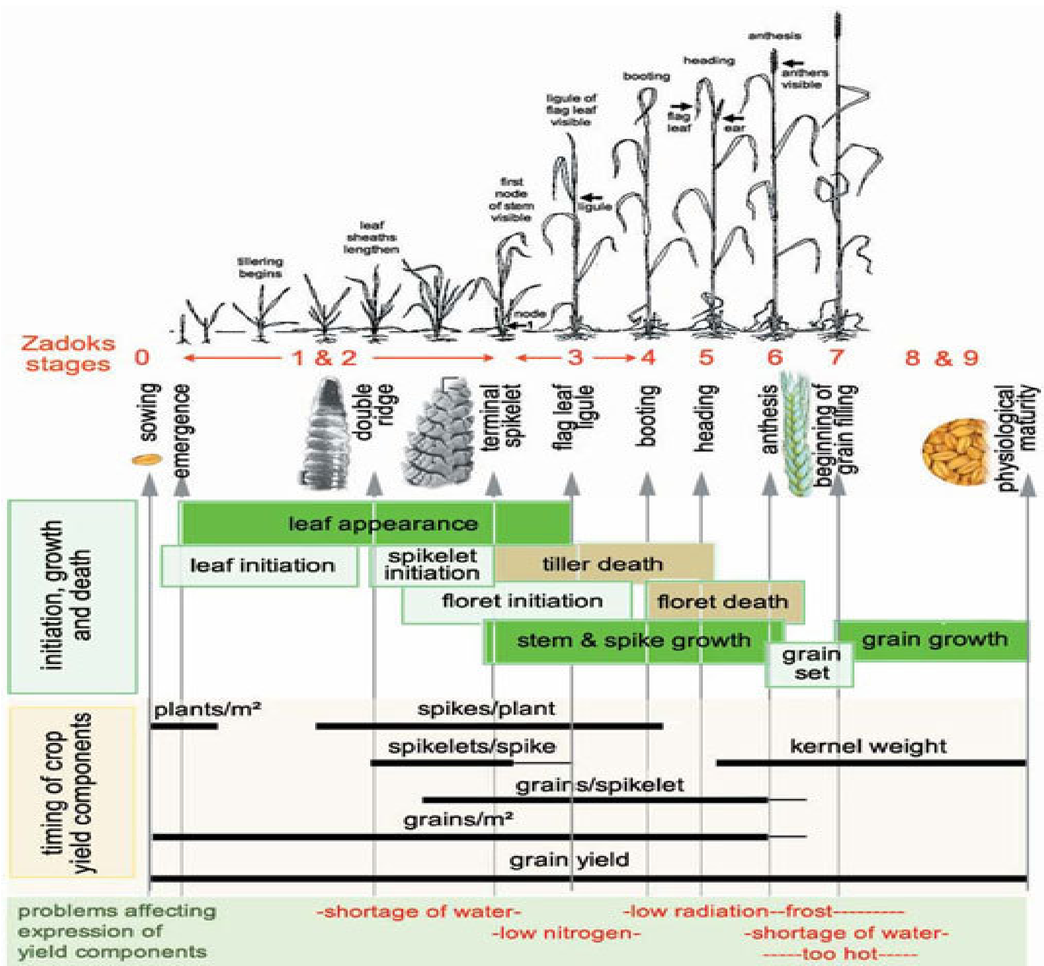


Figure 2.9: Phenological stages of barley (Source: Ecoport, 2006)

2.3.1.4 Diseases and pests

A wide array of infectious pathogens (viruses, bacteria, fungi, nematodes and fungi) is able to attack barley and affect the development of the crop by causing malfunction of plant processes. Diseases occur in dormancy or during plant growth (Mathre, 1997).

2.3.1.5 Barley in Ethiopia

Ethiopian people have been cultivating «Gebs (Segam)» for more than 5,000 years. The crop usually grows with little or no external inputs on the most unfavorable sites: on steep slopes, in areas with recurrent water stress and on land liable to erosion. In the highlands of Tigray, barley is the third most important staple food after tef and wheat (Hailu and Van Leur, 1996).

According to FAO (FAOSTAT, 2006), the average annual harvest in Ethiopia for the period 1996-2006 comprised 1.13 million ton grain from about 0.99 million ha. The productivity remains very poor with an annual average yield of 1.14 $ton \cdot ha^{-1}$, while in Western Europe values of 7.7 $ton \cdot ha^{-1}$ can be recorded (FAOSTAT, 2006). In 2006, barley accounted for 65 % of the gross national grain production and 51 % of the total area under cereal cultivation (FAOSTAT, 2006). Barley is a crop with a relatively stable yield. Differences between maximum and minimum production years are lower than for other cereals. Amount and distribution of rainfall are the most modifying factors in yield production (NRC, 1996). Figure 2.10 reflects the evolution in barley production, total harvested area and productivity for the past 14 years.

Usually, barley is grown in the main rainy season, in a monocropping system. Sowing dates fluctuate between May and July, depending on altitude, crop variety and most directly on the onset of the rain. Around Mekelle, the optimal sowing date runs from 1 to 15 June (Hailu and Van Leur, 1996). Weed competition is a major cause of yield reduction: up to 17 % reduction is possible. The competition is most critical during the first 30 days of the growing cycle. Manual weeding is indispensable in this period, but labor shortage caused by overlapping farmer activities might bring neglect of spuding up the weeds (Hailu and Van Leur, 1996). In Tigray, harvesting is done with a sickle 90 to 120 days after sowing from mid September to early October. Farmers behave risk-adverse and give preference to early maturing, low yielding varieties to avoid food shortage and frost at the end of the season (Sinebo, 2005).

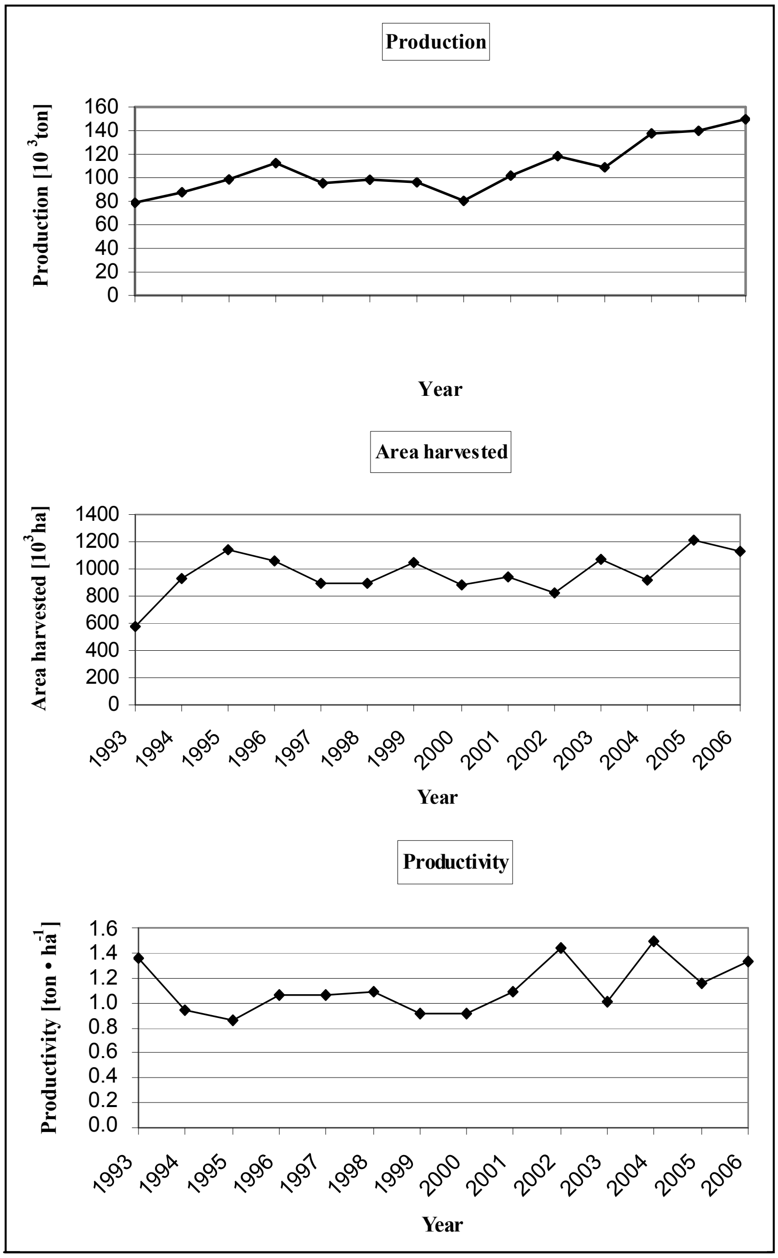


Figure 2.10: Evolution of production, total area harvested and productivity of barley in Ethiopia from 1993 to 2006 (Source: FAOSTAT, 2006)

Barley is cultivated for a number of purposes, mostly for human consumption and animal feed. A minor part is used as malting barley to brew local drinks. To decrease the dependency on a high-risk agriculture practice of mainly producing one crop (i.e. tef) and to diminish the monotony in the local diet, attempts have been made to introduce barley more generally (Hailu and Van Leur, 1996). People grow barley for self-support, or sometimes to sell in small quantities as a cash crop (Hailu and Van Leur, 1996). In 2002, FAO (FAOSTAT, 2006) reported the producer's price for 1 ton barley as 890 Ethiopian birr or 207 US dollar (PPP).

2.3.2 Crop characteristics of tef

2.3.2.1 Ecology

Tef, *Eragrostis tef* (Zucc.) Trotter (figure 2.11), descends from the Poaceae family. Vavilov (1951) has recognized Ethiopia as the center of origin and the center of diversity. For centuries, tef has formed and still forms the main staple food in Ethiopia (Ketema, 1993). Unlike many other traditional crops of Africa, tef is not in decline. Recently the crop has even begun crossing the Ethiopian borders and is by now grown among others in the United States, South Africa and India (NRC, 1996).

Figure 2.11: Tef spike in flowering stage and tef field (own source)

Tef is an herbaceous annual cereal, appearing in small tufts, on average 0.3 to 1.2 m in height. The fragile appearance makes tef very susceptible to wind (Ecocrop, 2003). Lodging generates another major worry. Post-harvest losses are minimized because of the good storage qualities of tef. This makes it a favorable crop in the battle against famine (Ketema, 1997). The average growing cycle takes roughly 4 months: early types mature in 70 to 120 days, late types can remain 160 days on the field before reaching maturity. Tef is a C_4 plant and thus more efficient in the production of carbohydrates than C_3 plants under warm and light conditions (Deckers *et al.*, 2001).

Several national yield trials pointed out that tef grows on a broad range of soil types and elevation, and under diverse agro-climatic conditions (Ketema, 1993). The most appropriate temperature range lies between 22 and 28 °C, but minimum temperatures up to 2 °C are tolerated (Ecocrop, 2003).

Moisture performance

Tef can grow in conditions with an annual precipitation varying between 300 and 2,500 mm·year^{-1}, with an optimum between 600 and 1,200 mm·year^{-1} (Ecocrop, 2003). The cereal crop is decently resistant to both high and low moisture stress, although damage due to waterlogging, especially on Vertisols, is often reported (Ketema, 1993).

Soil performance

The increasing necessity for suitable soils for other food crops, pushes cereals, including tef, often to marginal lands with adverse chemical and physical soil properties (Ketema, 1993). Tef grows on light as well as on medium and heavy textured soils. Even in very shallow soils (20-50 cm deep) the crop is able yield well. Optimal soil pH lies between 5.5 and 6.5, but calcareous soils with pH values above 8 do not pose significant restrictions on yield production. Soil compaction compromises good yield results (Hailu *et al.*, 2004), and saline undergrounds (> 4 dS·m^{-1}) are neither tolerated by tef plants (Ecocrop, 2003).

2.3.2.2 Morphology

Tef is a self-pollinating cereal with a fibrous root system. The leaves are narrow and folded. The elongated spikes can be met in different forms from loose to compact, and are 18 to 20 cm long. The grains appear no more than 2 mm in length and 1 mm in diameter, and can show up in a variety of colors from dark brown to white. Several morphological and botanical traits of an extent number of tef populations (Ketema, 1993) are given in table 2.5.

Table 2.5: Selected traits of tef (Source: Ketema, 1993)

Trait	Minimum	Maximum	Mean	+/-	SD
Days to germination	4	12	5	+/-	0.70
Days to maturity	62	123	93	+/-	7.36
Plant height [cm]	31	155	98	+/-	12.97
Grain yield/panicle [g]	0.3	3.0	0.9	+/-	0.34
Grain yield/plant [g]	4	22	8	+/-	4.01
Biomass yield/plant [g]	26	105	49	+/-	18.58
Straw yield/plant [g]	20	90	41	+/-	15.83
Harvest index [%]	7	38	17	+/-	5.51

2.3.2.3 The problem of lodging

Scientific articles with detailed information about tef's physiology are lacking. Yet, the problem of lodging has been well described. Ketema (1993) defines this phenomenon as 'an abnormal condition induced by internal and/or external factors, resulting in the displacement of the aerial parts of the plant from the upright position'. The plant appears hanging down. Periods of water logging at the beginning of the growing season, use of high seed doses, nutrient deficiency or quick, but infirm growth as a result of too high fertilizer doses causes the plants to lodge. Lodging is a sizeable problem in tef cultivations and can severely diminish yield - an average loss of 17 % is no exception - and turns harvesting more time consuming and troublesome (Ketema, 1993).

2.3.2.4 Diseases and pests

Tef is relatively resistant to diseases and pest before and after harvest (Deckers *et al.*, 2001). Tef rust caused by *Uromyces eragrostidis* Tracy and head smudge brought about by *Helminthosporium miyakei Nisikado* are the most important diseases that strike tef plants and can decrease yield considerably. Crickets frequently assail tef, among which the Welo bush-cricket (*Decticoides brevipennis* Ragge) forms the major source of trouble (Ketema, 1993).

2.3.2.5 Tef in Ethiopia

Tef is one of the most labor demanding cereals in Ethiopia. It requires a heavy plow management because of the minute size of tef seed and the difficulty with which the plants compete with weed. Traditionally, fields are plowed 3 to 5 times before sowing, depending on the soil type, the onset of the rainy season and the incidence of weed and water logging. In the light of the upcoming concept of conservation agriculture, several studies reveal conversely that ploughing the field more than once does not contribute substantially to a higher yield, provided that non-selective herbicides are used (Ketema, 1993).

Sowing is performed by hand at the beginning of the growing season. Seed (25-30 $kg \cdot ha^{-1}$ for broadcasting (Ketema (1993)) is left exposed on the field surface until mud runoff covers it. The tiny size of tef makes it difficult to control the seeding density and share-out when broadcasting, which often results in an unequal plant density in the field. This has an impact on the future distribution of nutrients during the remaining growing cycle (Ketema, 1993). Sowing is preferably done not too early in the rainy season to prevent too fast growth and subsequent lodging, and insect attacks (Ketema, 1993). Traditional harvest with a sickle takes place when the vegetative part of the plant colors yellow, generally between 60 en 120 days after sowing (Ketema, 1993).

The average annual harvest in Ethiopia in the period from 2002 to 2004 comprised 1.98 million ton tef grain from about 2 million ha, or 21 % of the gross national grain production and 29 % of the total area under cereal cultivation. However, the productivity remains poor with an annual average yield of 0.98 $ton \cdot ha^{-1}$ (CSA, 2006). Ketema (1997) mentions tef's low productivity as the most pressing disadvantage of the crop. The HI, the ratio of grain yield to total above-ground biomass, varies between 7 and 38 % (Ketema, 1993).

Higher market prices than those for the grains and straw of other cereals raised tef to the most favorite cash crop, even though many families only produce this low-risk crop for their own household (Hailu *et al.*, 2001). Tef is usually cultivated in rotation with other crops like chickpea or bean, and sometimes serves a rescue-crop, replanted by farmers in the short rainy season when other staple crops like maize and sorghum wilt and fail in default of sufficient rain.

Tef appears in the daily diet of Ethiopian people since thousands of years: the flour produced from the tef grain bears excellent «'ndjera», a typical flat pancake, the main dish in Ethiopia (Ketema, 1993). The plant finds its strength to continue as main component of the daily diet in its nutritional value. Tef is at least as nutritious as other cereals and even richer in some aspects: it is high in iron and calcium, and contains no gluten (Hailu *et al.*, 2001). Tef's straw serves as animal feed and is sometimes advantageously used as mud binder to reinforce walls of local houses (NRC, 1996).

In table I.1 (appendix I) several crop features of tef, maize, barley and faba beans are compared and ranked on an arbitrary scale.

Chapter 3

Experimental research

3.1 Materials and methods

3.1.1 Field design

To examine the CWP of barley and tef, a field experiment was set up to verify the crop response under different levels of water stress. All experiments were carried out at Mekelle University, Campus Enda Yesus in Mekelle (13.30 °N, 39.29 °E) at 2,212 m.a.s.l.. Both the trials with barley and those with tef occupied an experimental field on the campus. Each field consisted of 16 experimental units (3 by 3 m) in a randomized complete block design, with 4 treatments (T) and 4 replications (R) (figure 3.1). For all response variables, 4 replications per treatment were examined to analyze the data in a statistical correct way. Table 3.1 gives an overview of the different treatments.

R1T1	R1T4	R1T3	R1T2
R2T3	R2T2	R2T4	R2T1
R3T4	R3T1	R3T2	R3T3
R4T2	R4T3	R4T1	R4T4

Figure 3.1: Field layout of the experiment (barley and tef field)

Barley was sown in 15 rows per experimental unit; 20 plants were counted per row. 1 m space was left in between the experimental units. Tef, on the other hand, was broadcasted; the space in between the experimental units was narrowed to 0.5 m.

Table 3.1: Different treatments of the experiments

Treatment	Description
T1	No water stress (full irrigation after the rainy season)
T2	Possible water stress in all phenological stages (rainfed)
T3	No water stress in flowering stage (irrigation only in flowering stage)
T4	No water stress in flowering and in grainfilling stage (irrigation only in flowering and in grainfilling stage)

3.1.2 Field management

The fields on the university campus have been cultivated for several years before the experiment took place. Before sowing, the barley site was ploughed once; the experimental tef field underwent several plough cycles. Fertilizer was applied on both fields immediately before sowing in quantities as recommended by the government (Mulat *et al.*, 1997): 100 $kg{\cdot}ha^{-1}$ diammonium phosphate (45 g per experimental unit) and 100 kg $urea{\cdot}ha^{-1}$ from which 50 % before sowing and 50 % when the crop reaches mid-stage (22.5 g per experimental unit before sowing). Yet, a second fertilizer application was never carried out, because of unavailability of the concerned fertilizer.

Crop borders were installed where protection by other crops was absent. The lightly sloping barley field was equipped with small bunds, bordering every individual unit at a distance of 0.5 m to minimize runoff. There was no need for bunds in the tef field. In the course of the growing period, no thinning was performed. Weeding was carried out on a weekly basis in both fields.

In mid-season stage, certain barley plants were apparently attacked by loose smut (*Ustilago nigra*). The plants, little in number, were removed from the plots and the damage could be restricted. One experimental unit in the tef field was damaged to a large extent in the last week of September by a brazen squirrel that dug a hole in the ground. The animal was removed and no further damage was done, but part of the field was destroyed, affecting the later yield results. The complete block was left out of for statistical analyses.

3.1.3 Climate analysis

The climatic data specified in table 3.2 were recorded in the meteorological station at Mekelle University on a daily basis.

Table 3.2: Set of climatic data recorded on a daily basis at Mekelle University

Parameter	Units	Equipment
Mean temperature	°C	(Dry bulb) thermometer
Minimum / maximum temperature	°C	Minimum / maximum thermometer
Relative air humidity	%	Hygrometer
Evaporation	$mm \cdot day^{-1}$	Class A Pan
Wind speed	$m \cdot s^{-1}$	Wind speed meter (2 m height)
Sunshine	$h \cdot day^{-1}$	Campbell-Stokes sunshine recorder
Rainfall	$mm \cdot day^{-1}$	Simple rain gauge

Evaporation data acquired with the Class A Pan were inaccurate due to interference with birds during the dry season, even after the pan had been wire-netted. ET_0 data used in this dissertation were calculated with the software program EtoCalc (Raes, 2006) on basis of the FAO Penman Monteith equation (equation 3.1) with standard coefficients for the Angstrom formula and a standard albedo value of 0.23:

$$\mathbf{ET_0} = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T + 273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \qquad \text{(eq. 3.1)}$$

where ET_0 = reference evapotranspiration [$mm \cdot day^{-1}$]

Δ = slope of the vapor pressure curve [$kPa \cdot °C^{-1}$]

R_n = net radiation at crop surface [$MJ \cdot m^{-2} \cdot day^{-1}$]

G = soil heat flux density [$MJ \cdot m^{-2} \cdot day^{-1}$]

γ = psychometric constant [$kPa \cdot °C^{-1}$]

u_2 = wind speed at 2 m [$m \cdot s^{-1}$]

e_s = saturated vapor pressure deficit [kPa]

e_a = actual vapor pressure [kPa]

Input data for the software program existed of recorded maximum and minimum temperature, mean relative humidity, mean wind speed and hours of sunshine.

In order to verify if it would be possible to calculate ET_0 accurately if relevant data sets are missing, the effect of omission of one or more of the three latter data categories from the input of the software program was tested.

3.1.4 Soil analysis

3.1.4.1 Soil characterization

All experiments were done at Mekelle University, locally at the field or in the laboratory, except for the textural analysis and part of the soil water retention curve, which were completed in the laboratories at K.U.Leuven.

3.1.4.1.1 Soil texture

Soil samples were taken with an auger from three randomly chosen locations within each experimental field, and this repeatedly at 0.05, 0.2 and 0.4 m depth. The soil samples of the barley and tef field were transported to Belgium and subjected to a textural analysis in the laboratories of the K.U.Leuven.

The textural analysis was done by means of the pipette method (ISO 11277, 1998) with 20 g soil. After dry sieving through 2 mm, the samples were preliminary treated with 30 % hydrogen peroxide and with an excess of 1 $mol \cdot L^{-1}$ HCl for respectively the destruction of organic matter and the removal of carbonates. Elimination of HCl after all carbonates had been destroyed, brought on problems during centrifugation and decantation because of the persistent suspension of the clay particles. This could probably be ascribed to a drop in electrical conductivity below 0.1 $dS \cdot m^{-1}$ after the removal of HCl. Increasing centrifugation speed and time could overcome the problem. Subsequent dispersion of the samples was realized by means of a buffered 33 % sodium hexametaphosphate solution, followed by wet sieving at 53 µm. Pipette sampling occurred after a sedimentation time of 6 h 9 min 45 s at 30 °C at a depth of 100 mm.

3.1.4.1.2 Saturated hydraulic conductivity

The efficiency of water supply and the availability of water for plants strongly depend on the soil infiltration capacity - the amount of rainfall or irrigation water per surface area and per unit of time that enters the soil. The saturated conductivity (K_{sat}) - the infiltration rate when the soil water content is near saturation (SAT) - was determined by means of two methods: the double ring method and the inverse auger hole method.

In the surface layer, the saturated hydraulic conductivity was estimated by use of the double ring method (figure 3.2). The experiment was carried out in the rainy season, with soil water content near field capacity (FC). Three measurements were done simultaneously at randomly chosen sites on the experimental field.

Figure 3.2: Double ring infiltrometer

Each measurement set consisted of 2 stainless steel rings with different diameters, an inner and an outer ring, which were driven concentrically 0.15 m into the soil. The measurements were exclusively carried out in the inner ring; the outer ring served as a buffer for forcing vertical infiltration of water in the inner ring. This eliminated the problem of overestimating the hydraulic conductivity in the soil by three-dimensional flows.

The rings were filled with water and the difference in water depth, due to the infiltration of water into the soil, was carefully registered on a floater with graduated tape accurate to a millimeter. The registrations were done at different time intervals during 4.5 hours until the infiltration rate stabilized and the saturated conductivity could be registered.

The inverse auger hole method (Porchet method), was considered more appropriate for determining the saturated hydraulic conductivity at deeper depths (0.3 and 0.5 m). The method is based on an old percolation procedure that only takes into account a gravitational potential gradient and neglects the gradients due to pressure and matrix potentials (Kessler and Oosterbaan, 1974).

Two holes, approximately 0.078 m in diameter and respectively 0.3 and 0.5 m in depth, were augered at three randomly chosen locations within each experiment field, and filled with water. The surrounding soil was well saturated before recording the drop of water within the hole. The water level was measured for 4 hours with an interval increasing from 10 over 20 to 30 min. The readings were taken to the nearest millimeter on a graduated tape attached to a float, which was lowered into the hole.

The quantity of water infiltrated under saturated conditions could be determined based on Darcy's law, by means of equation 3.2:

$$\mathbf{K_{sat} = \frac{r}{2} \cdot \{[\log (h(t_1) + \frac{r}{2}) - \log (h(t_2) + \frac{r}{2})] \cdot (t_2 - t_1)^{-1}\}} \qquad \text{(eq. 3.2)}$$

where K_{sat} = saturated hydraulic conductivity [$mm \cdot s^{-1}$]

r = radius of the hole [mm]

$h(t_i)$ = water level in the hole at time i [mm]

t_i = elapsed time at moment i [s]

After the readings were taken, the reliability of the measurements was checked for consistency of the consecutive readings. Data are reliable when they fall in a reasonable alignment in the plot of $\log(h(t) + \frac{r}{2})$ versus t.

When the ring infiltrometer test and the inverse auger hole method are applied at a surface with similar dimensions, the quality of the measurements is supposed to be similar. The choice to apply the inverse auger hole method at deeper depths to determine the hydraulic conductivity was based on the simplicity and the measurement speed.

3.1.4.1.3 Bulk density

The bulk density (ρ_b) of each field was assessed by taking undisturbed samples of a known volume (1 dm^3) at different depths: 0.05, 0.2 and 0.4 m. The undisturbed sampling was carried out by manually driving a Kopecki ring into a in advance wetted soil. Three replications from each depth were taken from which the mean was computed. Samples were dried for 24 hours at 105 °C. Subsequently, ρ_b was calculated as given in equation 3.3:

$$\rho_b = \frac{\textbf{mass dry soil}}{\textbf{bulk volume soil}} \qquad \text{(eq. 3.3)}$$

where ρ_b = bulk density [kg·m^{-3}]

3.1.4.1.4 Hard layer

While soil samples were taken in the barley field, mention was made of a quasi-impenetrable hard layer at variable, but limited depth. This hard/plough pan did not only complicate the sampling, but also hampered the normal growth and penetration of crop roots. It seemed difficult to determine whether it concerned a plough pan caused by compacting tillage practices or a hard pan developed under natural soil conditions, i.e. clay eluviation.

Several augerings were done to determine the location of the hardpan in the underground. An additional analysis by way of the pipette method (ISO 11277, 1998) was performed at K.U.Leuven to determine the texture of the hard/plough pan.

3.1.4.1.5 Soil water retention curve

The moisture characteristic curve (pF-curve) was composed after analysis partially carried out in the laboratories at Mekelle University and partially in the laboratories of K.U.Leuven. The soil water content at FC and at wilting point (WP) can be deduced from the water retention curve. The water content at FC is the quantity of water that a well-drained soil holds against the gravitational force. It is the upper limit of the plant extractable water. The water content at WP is the soil water content at which plants stop extracting water and permanently wilt. It is the lowest limit of the plant extractable water (Raes, 2001).

Undisturbed soil samples of both experimental fields were taken in triplicate in the same way as described under 3.1.4.1.3 at three depths (0.05, 0.2 and 0.4 m) and were subsequently subjected to several values of under-pressure by means of sandbox equipment (1, 3, 7.5, and 10 kPa) and pressure plates (20, 30, and 100 kPa) at Mekelle University. Poor performance of the membrane apparatus in Mekelle obliged to continue the experiment in Leuven with disturbed samples in the membrane apparatus at high under-pressure (250 and 1580 kPa).

3.1.4.1.6 Runoff and curve number

Depending on specific soil characteristics, a certain amount of rainfall is lost as runoff over the soil surface or as deep percolation below the root zone of plants. This part of the rainfall cannot be utilized by plants, and is thus not effective. The remaining part that can be stored in the root zone and further serves as water supply for plants, is called effective rainfall and is given in equation 3.4 (Brouwer and Heibloem, 1986):

$$\mathbf{P_{eff} = P - RO - DP} \qquad \text{(eq. 3.4)}$$

where P_{eff} = effective rainfall [mm]
P = rainfall [mm]
RO = runoff [mm]
DP = deep percolation [mm]

The determination of the effective rainfall was important to calculate the irrigation requirement in the dry season as further explained in 3.1.6. In the dry season, when rain showers were limited in size and distribution over time, deep percolation could be ignored and only runoff should be taken into account.

Runoff could be estimated by means of the SCS curve number (CN) method. This method is based on hydrological soil characteristics, on land use and land management and on the present hydrological condition of the soil (SCS, 1972). Equation 3.5 gives the general CN-equation for runoff:

$$\mathbf{RO = \frac{(P - 0.2 \cdot S)^2}{(P + 0.8 \cdot S)}} \qquad \text{(eq. 3.5)}$$

where RO = runoff [mm]
P = rainfall [mm]
S = potential maximum retention after runoff begins [mm]

with $$\mathbf{S = \frac{1000}{CN} - 10}$$ (eq 3.5a)

where S = potential maximum retention after runoff begins [mm]
CN = curve number [-]

and $$\mathbf{P_{eff} = P - \frac{(P - 0.2 \cdot S)^2}{(P + 0.8 \cdot S)}}$$ (eq. 3.5b)

where P_{eff} = effective rainfall [mm]
P = rainfall [mm]
S = potential maximum retention after runoff begins [mm]

CN for the barley and tef field were estimated as indicated in table 3.3.

Table 3.3: CN for barley and tef field

Crop	Development stage	CN
Barley	mid-stage	94.0
Tef	initial stage	93.5
	mid-stage	93.0

It was only necessary to know CN in this particular development stages, because P_{eff} was only calculated in the dry season.

As mentioned earlier, bunds were installed round each experimental unit of the barley field as to impede runoff flowing from uphill experimental units to downhill experimental units. The bunds were constructed to restrain lower experimental units from receiving more water than higher experimental units, but could not prevent that water was lost as runoff.

3.1.4.2 Soil water content

The soil water content was monitored weekly with the gravimetrical method. When water doses were supplied, the water content was determined before the irrigation application. Soil samples were taken from each experimental unit at 0.05, 0.2 and 0.4 m depth. Immediately after sampling, samples were weighed, dried for 24 hours at 105 °C and weighed again. The mass soil water content θ_m (equation 3.6) and the volumetric soil water content θ (equation 3.7a) were calculated with equation 3.6 and 3.7b respectively. The amount of soil water could thereupon be expressed as an equivalent depth of water retained in the root zone W_r (equation 3.8). The soil water depth is the thickness of the water layer that will be obtained by extracting all the water out of the root zone and distributing the amount uniformly over the entire soil surface.

$$\boldsymbol{\theta_m = \frac{\text{mass soil water}}{\text{mass dry soil}} = \frac{\text{mass wet soil}}{\text{mass dry soil}} - 1} \qquad \text{(eq. 3.6)}$$

where θ_m = mass water content [$kg \cdot kg^{-1}$]

$$\boldsymbol{\theta = \frac{\text{volume soil water}}{\text{bulk volume soil}}} \qquad \text{(eq. 3.7a)}$$

where θ = volumetric water content [$m^3 \cdot m^{-3}$]

$$\boldsymbol{\theta = \rho_b \cdot \theta_m} \qquad \text{(eq. 3.7b)}$$

where θ = volumetric water content [$m^3 \cdot m^{-3}$]

ρ_b = bulk density [$kg \cdot m^{-3}$]

θ_m = mass water content [$kg \cdot kg^{-1}$]

$$\boldsymbol{W_r = 1000 \cdot \theta \cdot Z_r} \qquad \text{(eq. 3.8)}$$

where W_r = soil water content in the root zone [mm]

θ = volumetric water content [$m^3 \cdot m^{-3}$]

Z_r = thickness of the root zone [m]

When water is abstracted from the root zone and the soil water content decreases, a crop starts to experience water stress when the water uptake becomes more restricted than the potential crop evapotranspiration. To indicate this critical level, use is made of a threshold value (TH) for the root zone depletion, referring to the maximum amount of water that can be depleted below FC without inducing crop water stress. This amount, the readily available water (RAW), is expressed as a fraction of the total available soil water (TAW), as given in equation 3.9. TAW is the amount of water that a crop can theoretically extract from the soil, or the amount of water held in the soil between FC and WP, and is given in equation 3.10 (Raes, 2001). Figure 3.3 schematically represents the soil with the indication of TAW and RAW.

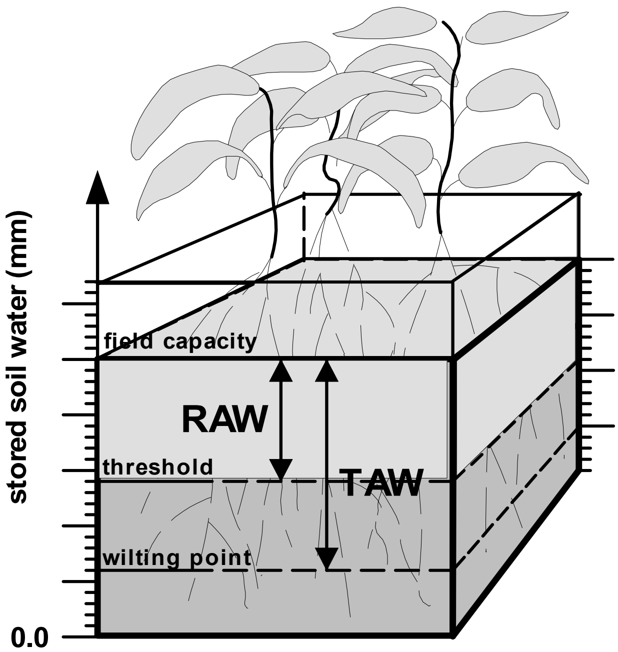


Figure 3.3: Schematic representation of TAW and RAW (source: Raes, 2001)

$$\mathbf{RAW = p \cdot TAW = p \cdot 1000 \cdot (\theta_{FC} - \theta_{WP}) \cdot Z_r} \qquad \text{(eq. 3.9)}$$

where RAW = readily available soil water in root zone [mm]

p = depletion factor, or the fraction of TAW that can be depleted before stress (stomatal closure) occurs [-]

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

θ_{FC} = volumetric water content at FC [$m^3 \cdot m^{-3}$]

θ_{WP} = volumetric water content at WP [$m^3 \cdot m^{-3}$]

Z_r = depth of root zone [m]

$$\mathbf{TAW = 1000 \cdot (\theta_{FC} - \theta_{WP}) \cdot Z_r} \quad \text{(eq. 3.10)}$$

where TAW = total available soil water in root zone [mm]

θ_{FC} = volumetric water content at FC [$m^3 \cdot m^{-3}$]

θ_{WP} = volumetric water content at WP [$m^3 \cdot m^{-3}$]

Z_r = depth of root zone [m]

3.1.5 Crop analysis

3.1.5.1 Evapotranspiration and crop coefficient

ET_0 is defined as the evapotranspiration of a theoretical crop with a height of 0.12 m, a crop resistance of 70 $S \cdot m^{-1}$ and an albedo of 0.23, characterized as a uniform lawn grass growing under standard conditions and fully covering the soil (Allen *et al.*, 1998). The FAO crop coefficient K_c is used to estimate the evapotranspiration rate of any other crop distinguishable from the standard crop by differences in canopy properties, ground cover and aerodynamic resistance. The crop evapotranspiration is calculated as in equation 3.11:

$$\mathbf{ET_c = K_c \cdot ET_0} \quad \text{(eq. 3.11)}$$

where ET_c = crop evapotranspiration [$mm \cdot day^{-1}$]

K_c = crop coefficient [-]

ET_0 = reference evapotranspiration [$mm \cdot day^{-1}$]

Allen *et al.* (1998) provide K_c values for several crops and for different crop stages accompanied with methods to extrapolate those values along the crop cycle. The coefficient integrates both soil evaporation and crop transpiration in one unique value per crop. As climate variations are incorporated into ET_0, K_c coefficients are to a large extent indifferent to climate. Thus, standard values for K_c can be transferred between locations (Allen *et al.*, 1998). K_c coefficients for barley and tef used in this dissertation are given in table 3.4.

Table 3.4: Crop coefficient (K_c) for barley and tef in different development stages

Crop	Development stage	K_c
Barley	initial stage	1.15
	mid-stage	1.15
	late season	0.25
Tef	initial stage	1.10
	mid-stage	1.10
	late season	0.55

The crop coefficients for barley were adapted from Allen *et al.* (1998). No coefficients were specified for tef in literature, but the estimated value, used in the field experiments, was fixed to the standard values for early harvested cereals. Simulations with AquaCrop after the field trials suggested other crop coefficients for tef as will be elaborated in Chapter 4.

When plants are scarce and small, the K_c coefficient in initial development stadia is largely determined by the frequency with which the soil surface is wetted (Allen *et al.*, 1998). In Tigray, the initial stage coincides with the rainy season, and the evaporation from the soil was considerable. Crop coefficients in initial stage were thus set at maximum.

3.1.5.2 Plant height

Values for maximum plant height can be useful to estimate above-ground biomass. Plant height was registered weekly by means of a simple ruler. Ten randomly chosen plants of every experimental unit were measured.

3.1.5.3 Fresh biomass

Barley

Every decade, the above-ground biomass of plants along 50 representative centimeters in the barley field was cut from three experimental units. In the laboratory, the mass of fresh plant components was recorded and further dried for 48 h at 65 °C. Subsequently, the dry biomass was determined. The biomass of several components of the plants (leaves, grains,…) were not defined individually.

Tef

Because tef was broadcasted, above-ground biomass was cut from a square of 0.2 by 0.2 m. Samples were collected every ten days from each tef unit. Fresh and dry biomass were defined analogously to the method described for barley.

3.1.5.4 Leaf Area Index

With an interval of seven days the leaf area index (LAI), defined as the one-sided leaf area projected horizontally on the ground (Asner *et al.*, 2003), was measured by means of the LAI-2000 Plant Canopy Analyzer (Li-Cor Inc., 1992). The amount of foliage is deduced from measurements of how quickly radiation is attenuated as it passes through the canopy. The LAI-2000 measures the attenuation of diffuse sky radiation at five zenith angles simultaneously.

Measurements were taken every week right before noon, with clear skies. Three pairs of two measurements, one right above canopy and the next below canopy, were taken crossways each experimental unit to improve spatial average. Use was made of the 90° view cap for all measurements to inhibit the sensor to look out the sides of the experimental unit.

3.1.5.5 Canopy cover

Data for crop canopy cover (CC) were not gathered at the field level, but were deduced from experimental LAI data. The relationship between LAI and CC (equation 3.12) was formulated after consultation of the equation of Ritchie (1974) and the revised equation developed by FAO based on several experimental data (FAO, written communication). Equation 3.12 produced results similar to those suggested by Ritchie (1974) and FAO:

$$\mathbf{CC = 1 - exp(-0.65 \cdot LAI)} \qquad \text{(eq. 3.12)}$$

where CC = canopy cover [%]

LAI = leaf area index [$m^2 \cdot m^{-2}$]

3.1.5.6 Normalized Difference Vegetation Index

NDVI is an index for evaluating the greenness of crops in a non-destructive way. The greenness in turn reflects the health status of the plants, and can give an idea of the progress of the canopy cover (Fetch *et al.*, 2003). NDVI is calculated as given in equation 3.13:

$$\mathbf{NDVI} = \frac{\mathbf{NIR - red\ VIS}}{\mathbf{NIR + red\ VIS}} \qquad \text{(eq. 3.13)}$$

where NDVI = normalized difference vegetation index [-]
NIR = reflection in near infrared band of spectrum [-]
red VIS = reflection in red band of visible spectrum [-]

Green, healthy crops reflect stronger in the NIR spectrum than unhealthy plants, and more than three times stronger than in the visible spectrum. Healthy plants give thus higher NDVI-values than plants in stress condition. NDVI measurements provide a suitable instrument to monitor changes in vegetation over time, and to predict potential grain yield (Fetch *et al.*, 2003).

The NDVI of the crops was planned to be taken every week, but due to failure of the equipment, no valuable measurements were executed on the barley field and only three times the tef field was submitted to the NDVI-measurement procedure. With the GreenSeeker Hand Held Optical Sensor Unit, Model 505 (Ntech Industries Inc.), the experimental units were crossed twice from one side to the other, oriented parallel to the replications, recording the spectral response of the plants.

3.1.5.7 Leaf stomatal resistance

Leaf stomatal diffusion conductance and resistance are important features in examining the physiological state of a plant. When plants experience water stress, stomata close and the leaf stomatal resistance for CO_2 increases. The quickness at which plants react on a water deficit by closing their stomata, can be an indication of their capacity to adapt to unfavorable situations of water availability, and consequently of their robustness to water stress.

The stomatal resistance was measured in the field during 6 consecutive days in a period when rainfed crops experienced severe water stress, after more than two weeks without rain or additional water supply. One leaf per plant and six plants per experimental unit were examined. Reference values were taken from stress free plants (under full irrigation). The measurements were done with the AP4 Porometer (Delta-T Devices Ltd.). The AP4 Porometer is a cycling porometer. The small cup of the porometer, which is clamped to the leaf, contains a relative humidity sensor. Water vapor emitted through the stomata of the leaf when transpiring, causes the relative humidity in the cup to rise. CO_2 follows the same path as water vapor in the opposite direction during photosynthesis processes.

3.1.5.8 Maximum root depth

The maximum root depth of a plant determines the maximum extent to which plants can extract water and nutrients from the soil, and is determined by soil physical and chemical features, by plant characteristics and water availability. Measurements were done by means of the excavation of roots of three plants per experimental unit after harvest.

3.1.5.9 Yield

To assess the yield results for barley and tef, the grain mass per experimental unit and the 1000-grain yield were determined. Total grain yield assesses crop productivity. 1000-grain yield can give an idea of the size and joined quality of grains.

3.1.5.10 Statistical analysis

Statistical analyses were conducted using SPSS 13.0 software (SPSS, 2004). Irrigation treatments served as fixed effects; differences among replications were observed as random effects. A one-way ANOVA test (SPSS, 2004) was used to check the homogeneity of variance of all sets of crop variables. In all cases, this resulted in the assumption of homogeneity at the 0.05 probability level. Subsequently, univariate analyses of variance (general linear models procedure) were conducted to determine the effect of different irrigation treatments. Post hoc multiple comparisons for observed means were done with LSD tests (SPSS, 2004) at the 0.1 probability level* and at the 0.05 probability level**.

3.1.6 Water supply management

Supplemental doses of water were given to the crops, which are typically cultivated under rainfed conditions, after the rainy season had come to an end to study the impact of diverse rainfall patterns. Appropriate doses were determined with the aim to satisfy the crop water demand in specific growth stadia as to prevent stress and yield reduction in this particular stadia, and to verify CWP under different levels of water stress. The irrigation water requirement, defined as the depth of water needed to meet the water loss through evapotranspiration of a disease-free crop growing under non-restricting soil conditions, was estimated as prescribed by Raes (1995). The net irrigation requirement (I_n) could be obtained by subtracting the expected gains of water from the crop evapotranspiration (equation 3.14a):

$$\mathbf{I_n = ET_c - P_{eff} - G_e - W_b} \qquad \text{(eq. 3.14a)}$$

where I_n = net irrigation requirement [mm]
ET_c = crop evapotranspiration [mm]
P_{eff} = effective rainfall [mm]
G_e = groundwater contributions [mm]
W_b = stored soil water [mm]

In the field experiments in Mekelle, groundwater contributed scarcely because the groundwater table was far removed from the root zone, and did not supply substantial amounts of water by way of capillary rise. On that account, factor G_e was neglected in equation 3.14a. Stored soil water was disregarded as well, because irrigation only started several days after the last shower of the rainy season, when the soil water content had dropped well below FC. Equation 3.14a was simplified to equation 3.14b:

$$\mathbf{I_n = ET_c - P_{eff}} \qquad \text{(eq. 3.14b)}$$

where I_n = net irrigation requirement [mm]
ET_c = crop evapotranspiration [mm]
P_{eff} = effective rainfall [mm]

Effective rainfall (P_{eff}) was assessed as indicated in 3.1.4.1.6. Crop evapotranspiration (ET_c) was determined as explained in 3.1.5.1. The latter calculations required estimations of the reference evapotranspiration (ET_0). Values for ET_0 were gathered from historical climatic data, registered at Mekelle airport from 1964 until 2004. Historical databases for daily minimum and maximum temperature, for monthly relative air humidity, wind speed and hours of sunshine were available, but for different periods of years. Data were analyzed with the software program EtoCalc (Raes, 2006). Several analyses were done to identify the most optimal combination of assorted databases of different climatic variables. Using limited datasets (1994-2003) of daily minimum and maximum temperature in combination with the available monthly statistics for relative air humidity, wind speed and sunshine hours for the same period, gave the most reliable results for ET_0 with little standard errors. Those estimations for ET_0 were considered appropriate to assess the net irrigation requirement of the crops. A summary of the irrigation doses applied to the barley and tef field can be found in appendix II.

3.2 Results and discussion

3.2.1 Climate analysis

Table 3.5 gives an overview of the climatic data recorded in the meteorological station at Mekelle University for the period corresponding with the growing season from July 1, 2006 to November 30, 2006. Significant was the difference between the data recorded in July and August on the one hand and the data recorded in September, October and November on the other: rainfall and relative air humidity were higher in the rainy season, while temperature, evaporation, hours of sunshine and wind speed were higher after the rainy season.

Table 3.5: Values for climatic data recorded on a daily basis at Mekelle University, 2006

	July	**August**	**September**	**October**	**November**
Mean monthly data					
Mean temperature [°C]	19.2	17.9	20.8	21.2	20.0
Minimum temperature [°C]	14.8	14.6	14.1	13.8	12.7
Maximum temperature [°C]	23.7	22.1	25.0	25.3	24.4
Relative air humidity [%]	70.8	81.2	63.0	55.7	55.3
Wind speed [$m \cdot s^{-1}$]	1.6	1.5	1.8	3.6	3.9
Sunshine [$h \cdot day^{-1}$]	5.1	4.3	8.1	10.0	10.5
Total monthly data					
Rainfall [mm][2]	225.5	304.0	49.0	8.0	0.0
Evapotranspiration [mm]	3.6	3.1	4.5	5.3	5.0

In figure 3.4 the mean temperature and total rainfall per decade for the whole growing season are plotted. Figure 3.5 shows the average rainfall per day, the mean daily ET_0 and 0.5 ET_0. The LGP equals the time span in which the amount of rainfall exceeds 0.5 ET_0. In the main growing season in 2006, the theoretical LGP lasted 72 days, from July until mid-September. Later, rainfall was totally absent or too low to sustain normal crop growth.

[2] Compared with other years, the rainy season of 2006 can be classified as wet, with a probability of exceedence of 16 %. The probability of exceedence was determined based on a frequency analysis of data of 16 years in the past, as explained in Chapter 4.

Figure 3.5 reveals a serious drop in rainfall in the second decade of July 2006. Stop-and-go rains were responsible for this phenomenon: after the rain started in June, it failed again in July, thus compromising the yield of fresh sown crops.

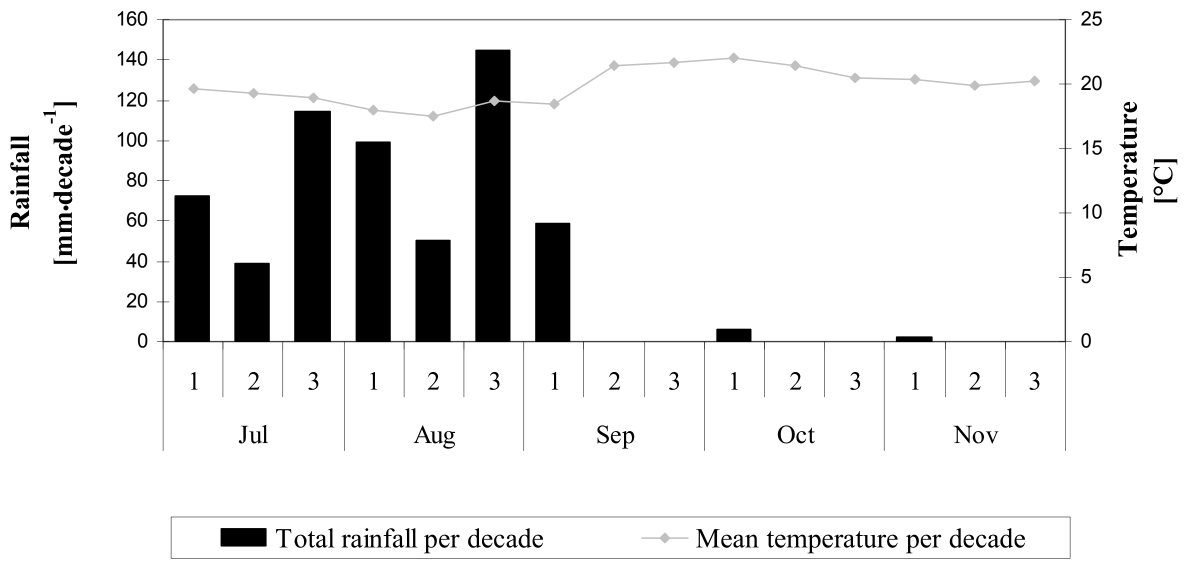


Figure 3.4: Mean temperature and total rainfall per decade in the main growing season of 2006 - Mekelle

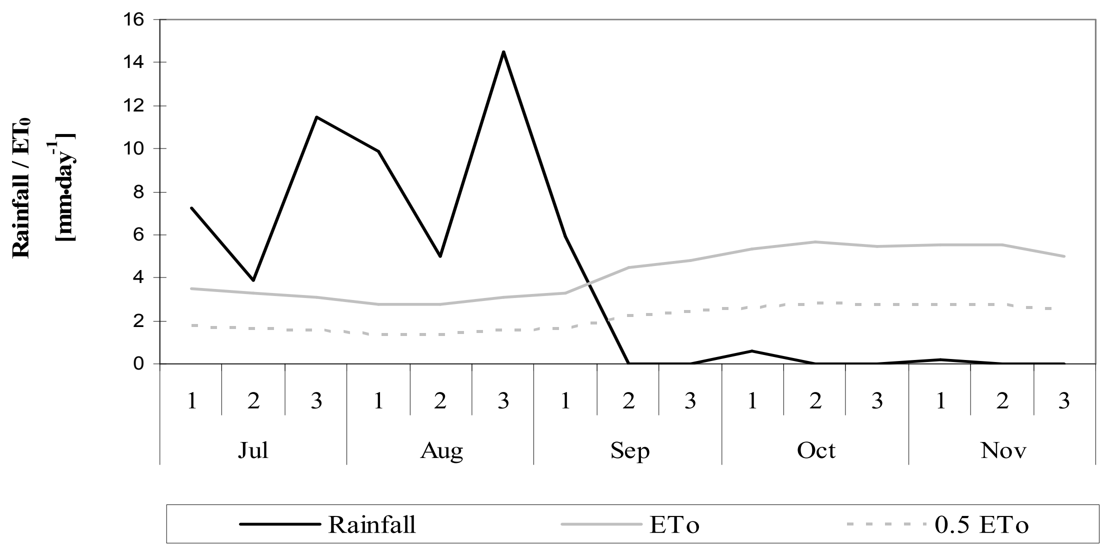


Figure 3.5: Average daily rainfall versus mean daily ET_0 and 0.5 ET_0 in the main growing season of 2006 - Mekelle

All values for ET_0 presented in the preceding figures, tables and used in calculations were calculated with the FAO Penman Monteith equation (equation 3.1) with recorded data for maximum and minimum temperature, mean relative humidity, mean wind speed and hours of sunshine. Values for ET_0 did not significantly differ when one of the three latter categories was omitted. When two or more categories were left out simultaneously, ET_0 values were only slightly lower. This observation confirms that even if data sets for humidity, wind speed and hours of sunshine are absent, reliable values for ET_0 can be obtained.

3.2.2 Soil analysis

3.2.2.1 Soil characterization

3.2.2.1.1 Soil texture

Barley

The pipette method revealed the composition of the soil as 24.77 % sand, 37.08 % silt and 38.15 % clay. With these results and according to Saxton and Rawls (2006), the soil of the barley site could be classified as a Clay Loam soil. The volumetric soil water content at saturation (θ_{SAT}), at FC (θ_{FC}) and at WP (θ_{WP}), K_{sat} and ρ_b were determined by using pedotransfer functions of Saxton and Rawls (2006). Table 3.6 gives an overview of the soil characteristics. In the ensuing work, theoretical values (based on pedotransfer functions) will be compared to values measured in the field.

Table 3.6: Soil characterization based on Saxton and Rawls' pedotransfer functions (2006) - barley

Soil depth [m]	**Texture class**	θ_{SAT} [vol%]	θ_{FC} [vol%]	θ_{WP} [vol%]	K_{sat} [mm·h^{-1}]	ρ_b [g·cm^{-3}]
0 - 0.1	clay loam	48.7	37.1	22.8	3.97	1.36
0.1 - 0.3	clay loam	48.8	37.5	23.3	3.66	1.36
0.3 - 0.5	clay loam	48.9	37.9	23.9	3.37	1.35
Average	clay loam	48.8	37.5	23.3	3.66	1.36

According to the World Reference Base for Soil Resources (WRB), the soil can be classified as a Vertisol (FAO/ISRIC/IUSS, 2001).

Tef

Using Saxton and Rawls' pedotransfer functions (2006) in combination with the results of the pipette method, the soil of the tef site could be classified as Silty Clay with 15.15 % sand, 41.31 % silt and 43.53 % clay. Theoretical values for θ_{SAT}, θ_{FC}, θ_{WP}, K_{sat} and ρ_b determined by means of the pedotransfer functions of Saxton and Rawls (2006) are presented in table 3.7.

Table 3.7: Soil characterization based on Saxton and Rawls' pedotransfer functions (2006) - tef

Soil depth [m]	**Texture class**	θ_{SAT} [vol%]	θ_{FC} [vol%]	θ_{WP} [vol%]	K_{sat} [mm·h^{-1}]	ρ_b [g·cm^{-3}]
0 - 0.1	silty clay	50.7	39.3	24.8	3.71	1.31
0.1 - 0.3	silty clay	51.0	40.3	26.4	3.09	1.30
0.3 - 0.5	silty clay	51.7	41.0	27.4	2.97	1.28
Average	silty clay	51.2	40.3	26.4	3.21	1.29

According to WRB, the soil can be classified as a Vertisol (FAO/ISRIC/IUSS, 2001).

3.2.2.1.2 Saturated hydraulic conductivity

Barley

Values for K_{sat} in the surface and deeper soil layers are shown in table 3.8. The experimentally obtained value for K_{sat} in the surface layer deviated to a large extent from theoretical values (table 3.6) and showed a high standard deviation. This was due to the inclusion of the third replica, for which a diverging value (25.00 mm·h^{-1}) was observed, probably due to an irregularity (i.e. a crack) in the underground. Exclusion of this value from the calculations of the mean K_{sat} lead to more persistent results with a minor standard deviation. Although this outcome coincides better with theoretically obtained values and gives a good reflection of K_{sat} of an homogenous assumed soil, the deviating value indicated that in reality infiltration could reach higher values due to anomalies (cracks) in the underground.

Deeper soil layers showed lower and more homogeneous values for K_{sat}. Relative standard deviations were here quite high because of the low overall saturated infiltration rate and the fact that precision could only be attained to the 1 mm-level. Empirical and theoretical (assessed with pedotransfer functions) values for K_{sat} in deeper soil layers lay in the same range. Results for barley and tef field are visualized in figure 3.6.

Table 3.8: Saturated hydraulic conductivity - barley

Soil depth [m]	**Empirical values** K_{sat} [mm·h^{-1}]	SD [mm·h^{-1}]	**Theoretical values (Saxton and Rawls, 2006)** K_{sat} [mm·h^{-1}]
0 - 0.1	16.75	7.90	3.97
0.1 - 0.3	4.03	0.55	3.66
0.3 - 0.5	2.50	0.40	3.37
Average	7.76	7.82	3.67

Tef

Table 3.9 summarizes the results of the determination of K_{sat} in the tef field. The empirical values for both the surface and the subsurface layers were similar to the theoretical values (obtained via pedotransfer functions). K_{sat} in the surface soil layer of the tef field showed fewer irregularities than K_{sat} of the barley field. Although no anomalies were observed during the experiment, the same remark as was made for the barley field endured: cracks or other irregularity in the underground could dramatically change the infiltration capacity of the soil. Deeper in the subsoil, infiltration decreased as compared to the surface soil layer. Results for barley and tef field are visualized in figure 3.6.

Table 3.9: Saturated hydraulic conductivity - tef

Soil depth [m]	**Empirical values** K_{sat} [mm·h^{-1}]	SD [mm·h^{-1}]	**Theoretical values (Saxton and Rawls, 2006)** K_{sat} [mm·h^{-1}]
0 - 0.1	5.78	1.68	3.71
0.1 - 0.3	3.00	1.28	3.09
0.3 - 0.5	2.58	1.56	2.97
Average	3.79	1.74	3.21

Both in the tef and the barley field, the decrease of K_{sat} towards lower soil layers can probably be attributed to the more dense constitution of deeper layers, where ploughing practices interfered to a less extent.

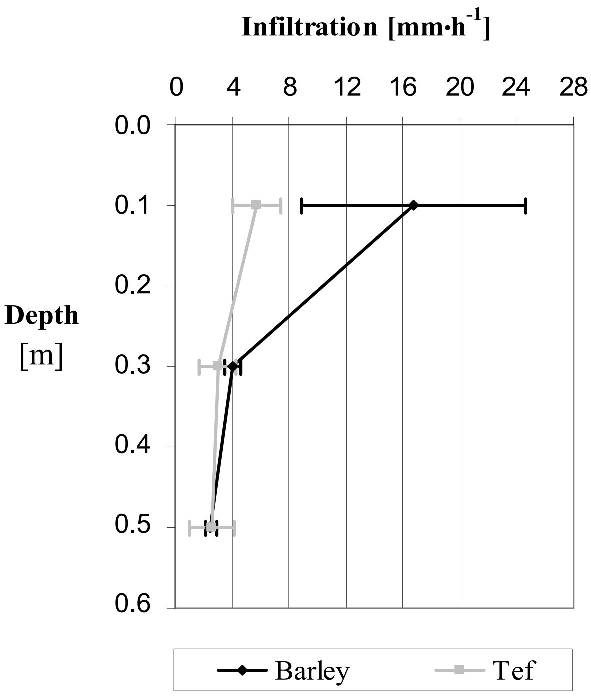


Figure 3.6: Saturated hydraulic conductivity - barley and tef. Horizontal bars indicate ± standard error

3.2.2.1.3 Bulk density

Table 3.10 and 3.11 give an overview of the experimentally determined ρ_d for the barley and for the tef field respectively. Values for ρ_d in the barley and the tef site lay in the same range. In both cases, the superficial horizont had a lower ρ_d than the layers underneath. This could be ascribed to a higher content in soil organic matter in the upper layer. Observed values matched well with theoretical values (obtained via pedotransfer functions). Since compaction was unavoidable when taking undisturbed soil samples from a sticky soil, the empirical values nevertheless overestimated the real ρ_d to some extent. Theoretical values seem more reliable.

Table 3.10: Soil bulk density - barley

	Empirical values		Theoretical values (Saxton and Rawls, 2006)
Soil depth [m]	**ρ_d** [g·cm^{-3}]	SD [g·cm^{-3}]	**ρ_d** [g·cm^{-3}]
0 - 0.1	1.43	0.07	1.36
0.1 - 0.3	1.47	0.02	1.36
0.3 - 0.5	1.51	0.06	1.35
Average	1.47	0.04	1.36

Table 3.11: Soil bulk density - tef

Soil depth [m]	Empirical values ρ_d [g.cm^{-3}]	SD [g.cm^{-3}]	Theoretical values (Saxton and Rawls, 2006) ρ_d [g.cm^{-3}]
0 - 0.1	1.31	0.03	1.31
0.1 - 0.3	1.47	0.08	1.30
0.3 - 0.5	1.47	0.03	1.28
Average	1.42	0.09	1.29

3.2.2.1.4 Hard layer

Barley

The depth of the hard pan was very unevenly distributed over the entire field. At the down-slope side of the light sloping barley field, the firm layer was observed at a depth of 0.12 to 0.31 m. At the up-slope side, the firm layer was situated at a depth of 0.53 to 0.90 m. Figure 3.7 gives a schematic illustration of the location of the firm layer in the underground.

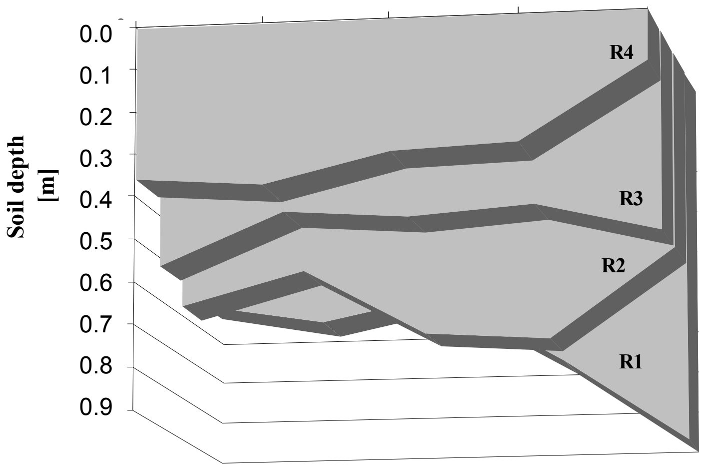


Figure 3.7: Soil depth above the hard layer - barley

After a textural analysis, Saxton and Rawl's (2006) pedotransfer functions revealed the texture of the hard layer as Loam to Sandy Loam with more than 45 % sand against an average value of 25 % sand in the rest of the profile. The disparity in clay content between the pan and the soil layers on top of it, was remarkable. An average difference in clay content of

20 %, or a drop from 38 % clay in the loose soil to 18 % clay in the hard pan was observable. The silt contribution in the soil remained more or less stable.

Although no decisive answer could be given about the origin of the firm layer, the recognition of the existence and the hardness of the layer was not less important[3]. Indeed, the layer impeded plant roots to extract water and nutrients from below the layer. The fact that the layer was not uniform in depth, did not posit a problem since replication blocks were laid parallel to the depth gradient.

3.2.2.1.5 Soil water retention curve

Based on the findings of the laboratorial analysis, a water retention curve (figure 3.8) was plotted to determine the water retention capacity of the soil. Table 3.12 summarizes the obtained values for the barley and the tef field.

Table 3.12: Empirical values for the soil water retention capacity - barley and tef

Pressure [kPa]	**pF**	**θ** [vol%]	
		Barley	**Tef**
1.0	1.0	47.7	49.4
3.0	1.5	45.8	47.1
7.5	1.9	42.8	44.9
10.0	2.0	41.9	44.1
20.0	2.3	40.2	41.9
30.0	2.5	39.3	41.5
100.0	3.0	35.9	38.1
250.0	3.4	40.8	34.9
1580.0	4.2	31.6	26.8

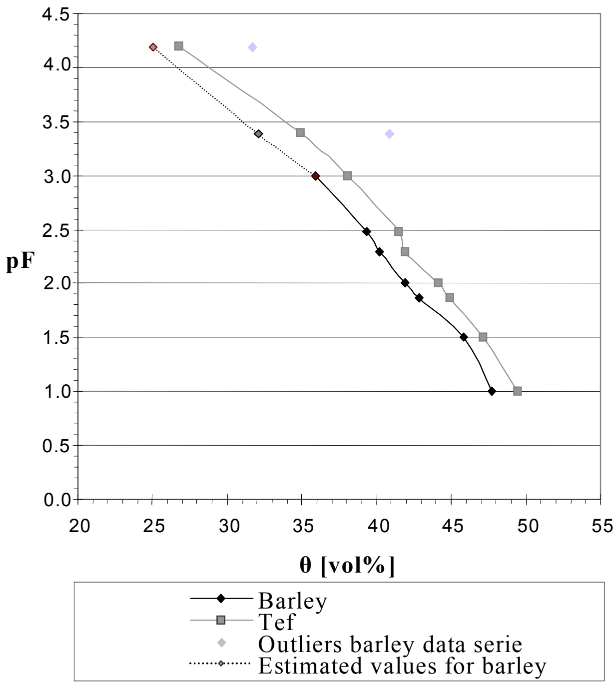


Figure 3.8: Soil water retention curve - barley and tef

[3] The existence of a firm layer in the experimental field gives a true reflection of the real situation in many Ethiopian soils. Soils are often shallow or possess an impenetrable plough pan.

Barley

In figure 3.8 it is visible that θ determined at pF 3.4 and 4.2 for the barley field deviated from the expected values. This deviation could be ascribed to the swelling and shrinking phenomenon, typical of soils with a high clay content. Wetting of the samples induced swelling of the soil, and a subsequent drop in soil density. Since analysis of θ at high pF values (3.4 and 4.2) was carried out in the laboratories of the K.U.Leuven with saturated (and thus expanded) soil samples, but for calculations after the analysis use was made of ρ_d determined in Mekelle, the sample density of the soil samples was overestimated. As a result, θ was overestimated as well. When calculations were made with an estimation for ρ_d of 1.07 $g\cdot cm^{-3}$, based on determination of the volume and dry weight of the samples, more realistic values for θ were obtained: 31.6 vol% at pF 3.4 and 24.9 vol% at pF 4.2.

θ_{SAT}, θ_{FC} and θ_{WP} as deduced from the soil water retention curve are compared with theoretical values (assessed with pedotransfer functions) in table 3.13.

Table 3.13: θ_{SAT}, θ_{FC} and θ_{WP} - barley

	Empirical values						**Theoretical values (Saxton and Rawls, 2006)**		
Soil depth [m]	θ_{SAT} [vol%]	SD_{SAT} [vol%]	θ_{FC} [vol%]	SD_{FC} [vol%]	θ_{WP} [vol%]	SD_{WP} [vol%]	θ_{SAT} [vol%]	θ_{FC} [vol%]	θ_{WP} [vol%]
0 - 0.1	50.8	5.5	39.5	1.6	23.8	1.1	48.7	37.1	22.8
0.1 - 0.3	50.1	1.5	38.3	0.7	25.2	0.5	48.8	37.5	23.3
0.3 - 0.5	51.6	4.5	40.1	1.7	25.8	1.3	48.9	37.9	23.9
Average	50.8	3.8	39.3	1.3	24.9	1.0	48.8	37.5	23.3

Tef

Soil samples of the tef field did not expand and as a result no outliers could be observed in the soil water retention curve. θ_{SAT}, θ_{FC} and θ_{WP} as deduced from the retention curve are compared with theoretical values (assessed with pedotransfer functions) in table 3.14.

From table 3.13 and 3.14, it is obvious that empirical values for θ_{SAT}, θ_{FC} and θ_{WP} matched well with theoretical values. The latter were less than 2 vol% lower than the experimental values and probably more realistic, since the problematic determination of ρ_d could distort the empirical values somewhat. However, differences between theoretical and empirical values were small, and both were probably a good estimation of the reality.

Table 3.14: θ_{SAT}, θ_{FC} and θ_{WP} - tef

	Experimental values						**Theoretical values (Saxton and Rawls, 2006)**		
Soil depth [m]	θ_{SAT} [vol%]	SD_{SAT} [vol%]	θ_{FC} [vol%]	SD_{FC} [vol%]	θ_{WP} [vol%]	SD_{WP} [vol%]	θ_{SAT} [vol%]	θ_{FC} [vol%]	θ_{WP} [vol%]
0 - 0.1	53.8	0.7	42.1	3.6	28.2	2.2	50.7	39.3	24.8
0.1 - 0.3	50.4	5.9	40.6	2.5	27.7	0.3	51.0	40.3	26.4
0.3 - 0.5	53.9	2.3	41.8	2.1	24.4	3.7	51.7	41.0	27.4
Average	52.7	3.0	41.5	2.7	26.8	2.1	51.2	40.3	26.4

3.2.2.2 Soil water content

The evolution of the soil water content throughout the growing cycle, expressed as an equivalent depth is plotted in figure 3.9 for barley and in figure 3.10 for tef. The water content at SAT, FC and WP, as determined by the pedotransfer functions of Saxton and Rawls (2006) are indicated on both figures, as well as the threshold value (TH) under which crops start experiencing water stress.

Figure 3.9a and figure 3.10a, 3.10b and 3.10c display an unrealistic drop of the soil water content below WP. This drop can probably be attributed to the overestimation of θ_{WP} (adopted from Saxton and Rawls (2006)) rather than to systematic errors in the gravimetrical procedure for the determination of the water content. It is possible that the clay content was overestimated in the textural analysis, since no oxides were removed from the soil samples before analysis, because there was no strong evidence for their existence. However, a small amount of oxides could have been present in the soil and, given their similar dimensions to clay particles, could have caused an overestimation of the clay content. In reality, the soil would be less rich in clay, and would hold less water at WP.

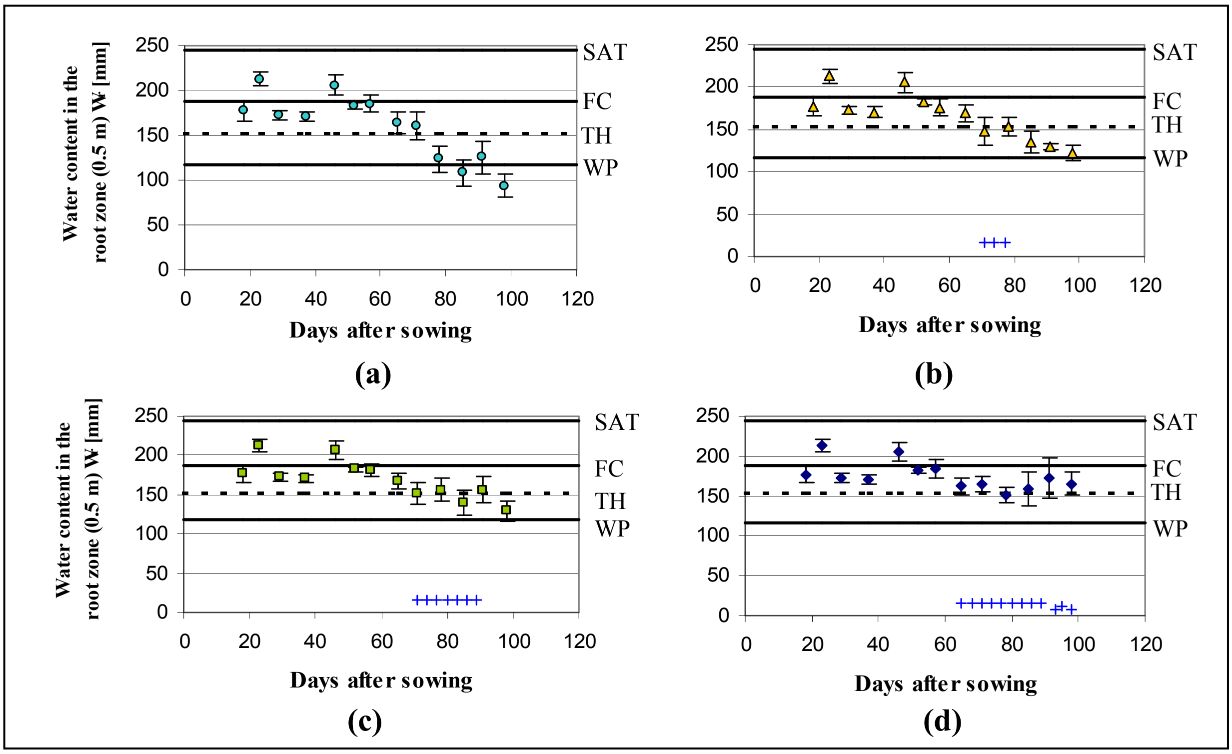


Figure 3.9: Water content in the root zone (W_r) for different irrigation treatments (with indication of the irrigation depth) - barley: (a) rainfed - (b) irrigation only in flowering stage - (c) irrigation only in flowering and grainfilling stage - (d) full irrigation. Vertical bars indicate ± standard error.

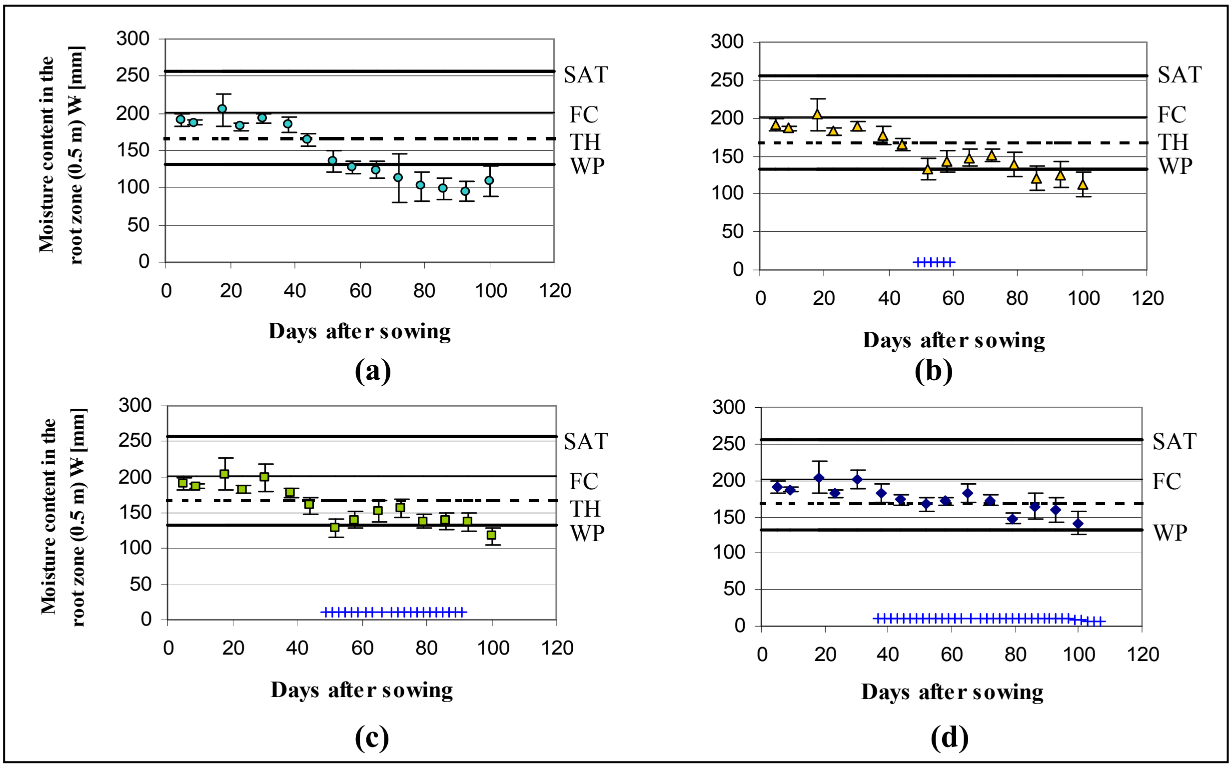


Figure 3.10: Water content in the root zone (Wr) for different irrigation treatments (with indication of the irrigation depth) - tef: (a) rainfed - (b) irrigation only in flowering stage - (c) irrigation only in flowering and grainfilling stage - (d) full irrigation. Vertical bars indicate ± standard error.

3.2.3 Crop analysis

Barley and tef were grown during the main growing season. Barley was sown on July 10, 2006, at the beginning of the main rainy season, directly after the first rains showed up. Tef was sown later in the rainy season, August 6, 2006, in accordance with habitual traditional practices in Tigray. Table 3.15 gives an overview of the development stages of both crops, as observed in the experimental fields.

Table 3.15: Crop development stages in the main growing season, 2006 - barley and tef

	Barley		**Tef**	
Development stage	**Date**	**Days after sowing**	**Date**	**Days after sowing**
Sowing	10/Jul		7/Aug	
Emergence	15/Jul	5	12/Aug	5
10% canopy cover	24/Jul	14	22/Aug	15
Full canopy cover	3/Sep	55	20/Sep	44
Flowering stage	6/Sep	58	25/Sep	49
Grainfilling stage	25/Sep	77	4/Oct	58
Senescence	6/Oct	88	7/Nov	92
Harvest	20/Oct	102	22/Nov	107

3.2.3.1 Plant height

Barley

Figure 3.11 shows the evolution of the barley plant height throughout the season. The plant height increased linearly during the first weeks of the growing cycle. After 73 days, almost in grainfilling stage, the crop reached its maximum height. Maximum plant height was nearly 1 m, considered an average maximum height in literature (Ecocrop, 2003). No significant difference between treatments could be observed at the 0.1 probability level. Results for maximum plant height are summarized in table 3.16.

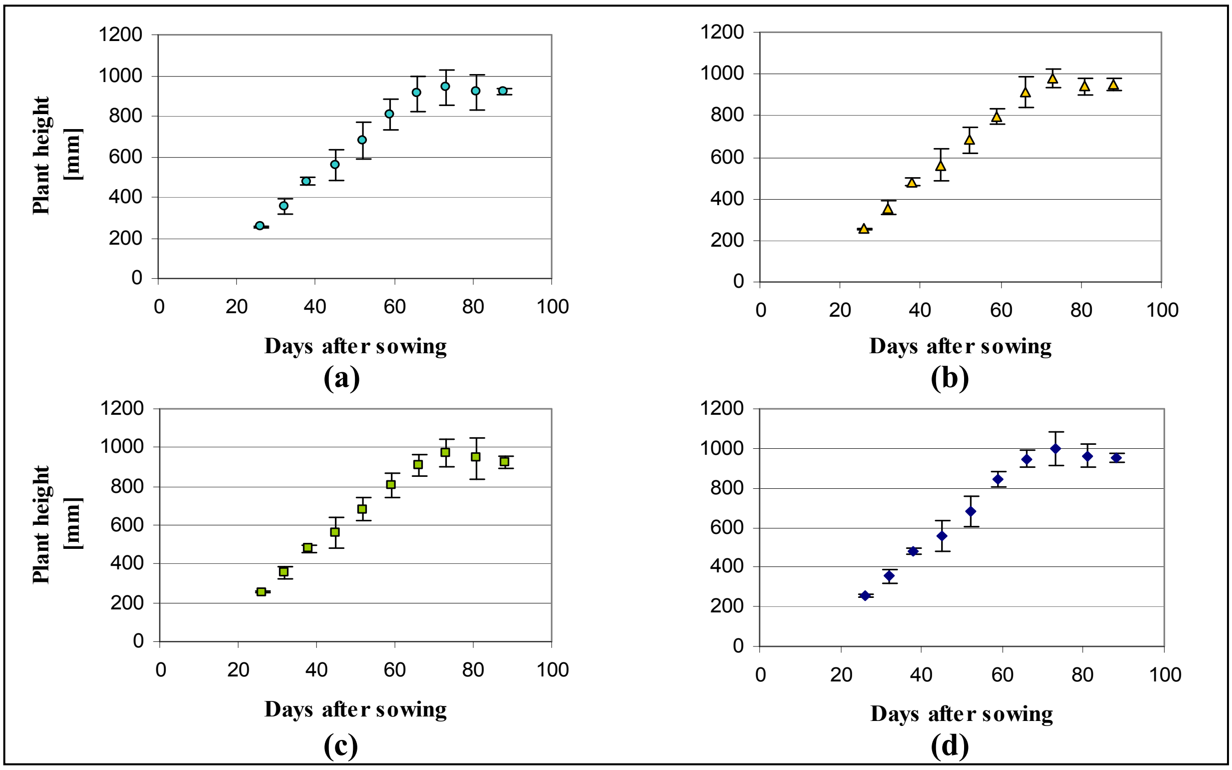


Figure 3.11: Plant height for different irrigation treatments - barley: (a) rainfed - (b) irrigation only in flowering stage - (c) irrigation only in flowering and grainfilling stage - (d) full irrigation. Vertical bars indicate ± standard error.

Table 3.16: Maximum plant height - barley and tef

	Maximum plant height [mm]*			
Irrigation treatment	**Barley - 73 days after sowing**	SD	**Tef - 46 days after sowing**	SD
Rainfed	941.3 a	88.2	332.0 a	19.0
Flowering	978.9 a	73.6	354.2 ab	27.2
Flowering + grainfilling	972.6 a	58.4	347.8 ab	19.0
Full	998.7 a	39.0	363.1 b	29.6

Values with the same letter are not significantly different (P < 0.1*).

Tef

In figure 3.12 the evolution of the tef plant height throughout the growing season is plotted. Plant height increased linearly in initial growing stadia. After 75 days, when the plants were in the grainfilling stadium, no substantial increase in height could be observed anymore. The maximum plant height stagnated below 0.4 m. This was rather low, according to different sources (Ketema, 1993; Ketema, 1997; Ecocrop, 2003). An explanation for the limited height can be found in the distribution density of the tef plants. Since the seed was broadcasted with a relative high seed dose and no thinning was performed in the course of the growing cycle, the availability of nutrients could have been a restricting factor for crop growth. The fact that the second fertilizer application was never carried out, and thus nutrients were not abundantly present, supports this supposition. Waterlogging conditions in the beginning of the growing cycle of tef could also have played a part in the poor development of the tef plants. In addition, the interference with tef plants, especially susceptible in young stadia, during measurement procedures could have contributed to the relatively poor performance of tef. Because no certitude existed about the genetic variety of the tef seed used in this experiment, it was impossible to verify if it concerned a variety characterized by its low height. As a result, it was difficult to establish if the limited plant height observed in the experiments was an abnormal phenomenon. Examination of other crop parameters could bring clarification. Results for maximum plant height and division in statistical groups are given in table 3.16.

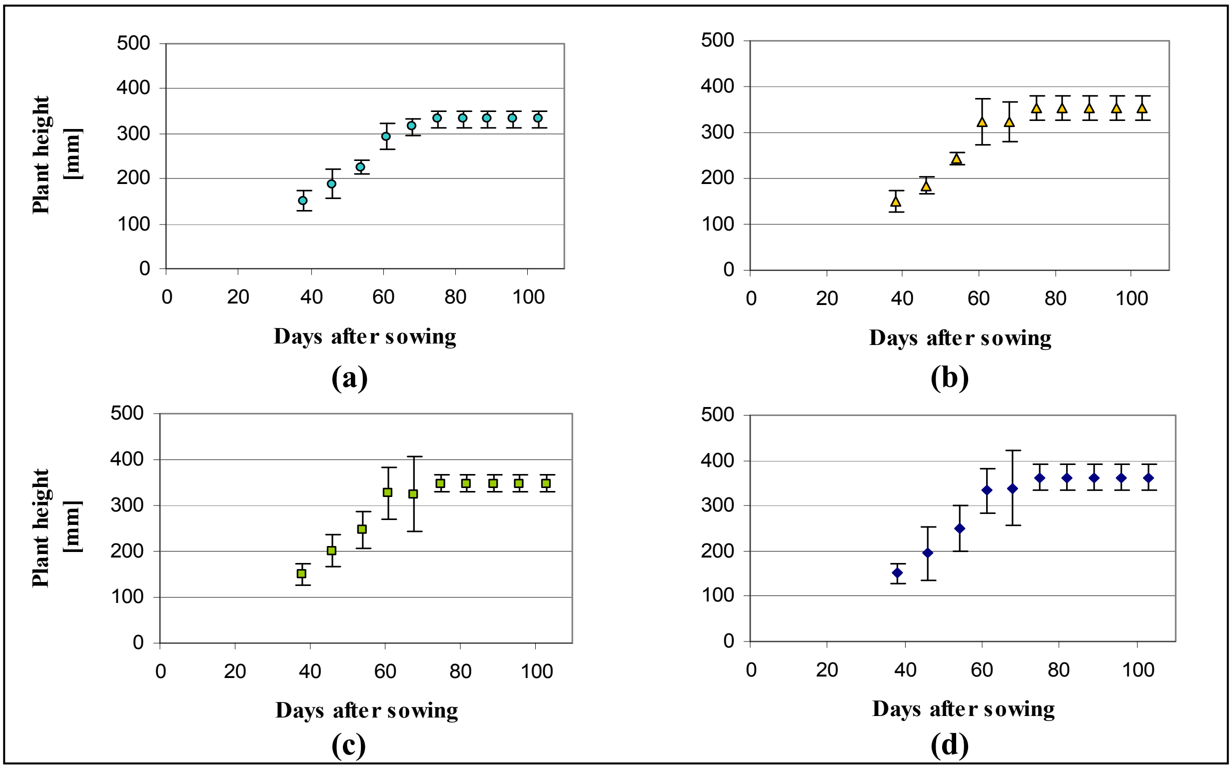


Figure 3.12: Plant height for different irrigation treatments - tef: (a) rainfed - (b) irrigation only in flowering stage - (c) irrigation only in flowering and grainfilling stage - (d) full irrigation. Vertical bars indicate ± standard error.

3.2.3.2 Biomass

Barley

The evolution of fresh and dry biomass (expressed in ton·ha^{-1}) throughout the growing season is plotted in figure 3.13 and 3.14 respectively. From figure 3.13, it can be seen that the fresh biomass increased linearly in early growing stages before reaching a maximum level and decreasing again. Before anthesis, growing leaves were responsible for mass gain. From anthesis onwards, the gain in biomass was mainly due to the growth of grains. Cause of the decline at the end of the growing cycle was the reduction in moisture content when grains reached maturity. The dry biomass (figure 3.14) showed likewise a linear increase at the beginning of the growing season, but stagnated later instead of decreasing again. The parabolic evolution of biomass is often reported for cereals. Total dry biomass for rainfed crops was 6.50 ton·ha^{-1}; crops with extra water supply in the growing cycle did not produce significantly more biomass. The value accorded with an average total barley biomass production in similar conditions of 6.1 ton·ha^{-1}, mentioned by Agegnehu *et al.* (2006).

It can be expectable that plants with water stress (rainfed) produced less biomass than their counterparts that experienced less or even no water stress. Statistical analysis however did not show significant differences between different levels of water availability at the 0.1 probability level. This finding could be attributed to the long time span when all plants received the same amount of rainfall before distinct doses of water were applied to the crops. In addition, the relatively large standard errors did not permit to specify significant differences. Table 3.17 summarizes the results for the analyses of fresh and dry biomass of barley in flowering stage (65 days after sowing) and at maturity (86 days after sowing).

Table 3.17: Fresh and dry biomass - barley

	Fresh biomass [ton·ha^{-1}]*				**Dry biomass** [ton·ha^{-1}]*			
Irrigation treatment	**65 days after sowing**	SD	**86 days after sowing**	SD	**65 days after sowing**	SD	**86 days after sowing**	SD
Rainfed	24.96 a	6.81	12.91 a	1.27	7.02 a	1.79	6.50 a	0.81
Flowering	24.96 a	6.81	16.75 a	3.87	7.02 a	1.79	7.83 a	1.58
Flowering + grainfilling	24.96 a	6.81	14.70 a	4.77	7.02 a	1.79	6.65 a	1.90
Full	24.96 a	6.81	16.45 a	5.93	7.02 a	1.79	7.13 a	2.62

Values with the same letter are not significantly different (P < 0.1*).

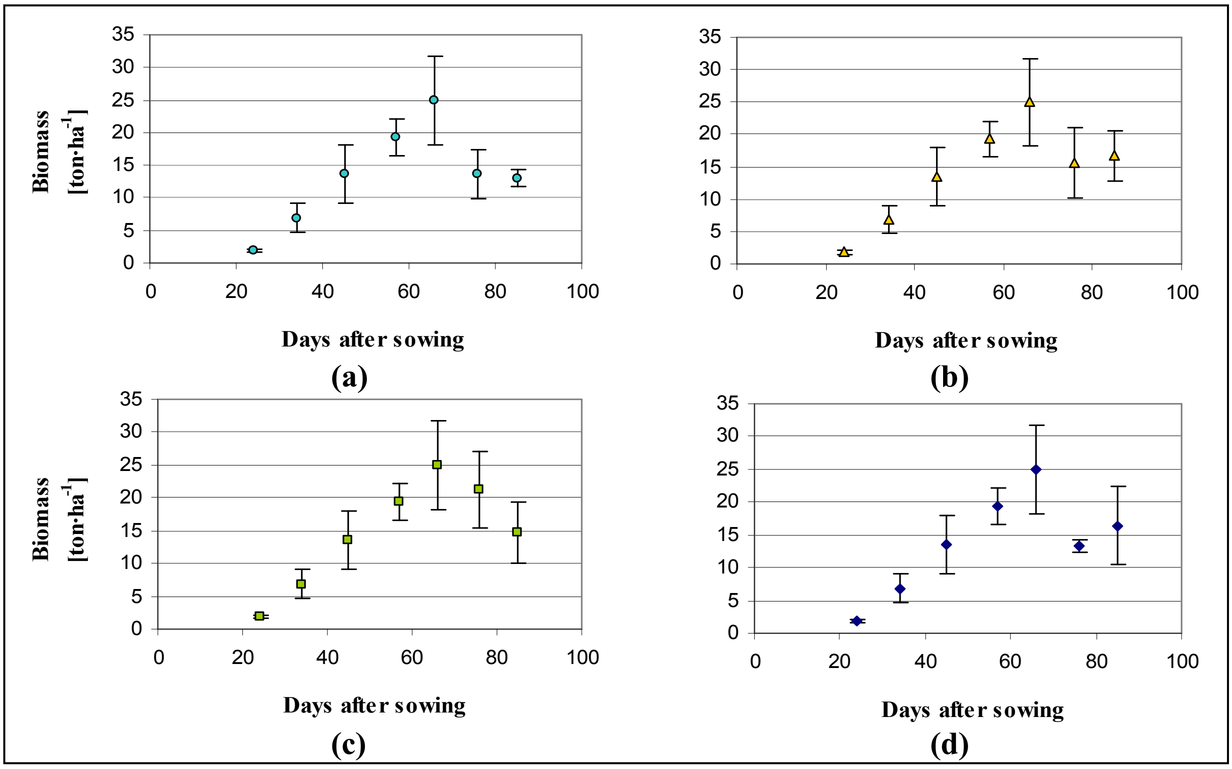


Figure 3.13: Fresh biomass for different irrigation treatments - barley: (a) rainfed - (b) irrigation only in flowering stage - (c) irrigation only in flowering and grainfilling stage - (d) full irrigation. Vertical bars indicate ± standard error.

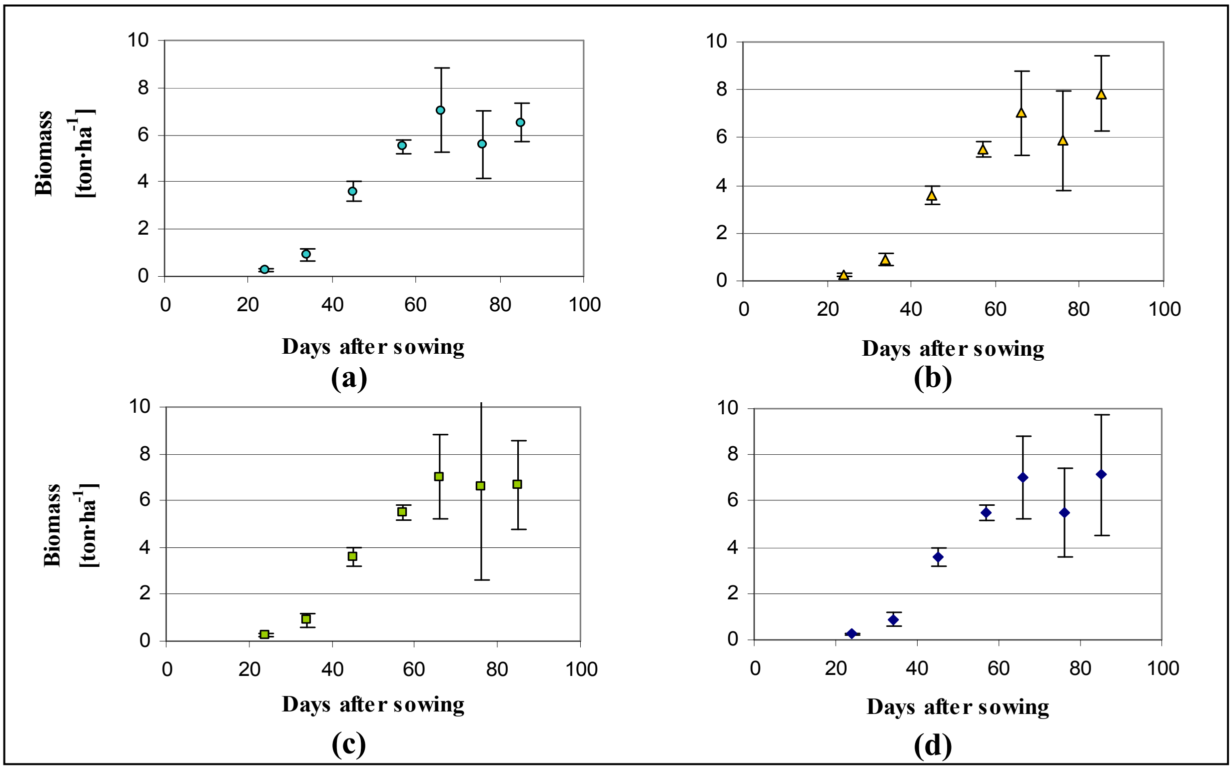


Figure 3.14: Dry biomass for different irrigation treatments - barley: (a) rainfed - (b) irrigation only in flowering stage - (c) irrigation only in flowering and grainfilling stage - (d) full irrigation. Vertical bars indicate ± standard error.

Tef

Figure 3.15 and 3.16 show the increase in respectively fresh and dry biomass as the growing cycle progresses. Both curves rose linearly before stagnation at a maximum level followed by a drop in biomass at the end of the season. In the case of fresh biomass, the decline in biomass when plants reached maturity was mainly due to a decrease in moisture content in the grains. The decline in dry biomass at the end of the growing cycle could be attributed to the fact that not all viable tillers carried spikes, and not all tillers survived to maturity. Dried or dead leaves, spikes and awns were broken and lost, resulting in lower total biomass. The parabolic evolution of fresh and dry biomass, the same as for barely, corresponded with the normal biomass development of cereals. The total dry biomass at harvest (102 days after sowing) varied between 2.58 and 3.41 ton·ha^{-1} for different irrigation treatments, which was slightly below the national average of 4.1 ton·ha^{-1} (Ketema, 1997). Since the national statistic was defined for rainfed crops, the observed total biomass of rainfed crops in the experiment was rather low. This observation supported the assumption elaborated above (in 3.2.3.3) that the tef plants did not perform excellently, possibly due to a nutrient deficit as a result of too dense distribution of the plants.

Fresh biomass of crops without water stress overtopped the fresh biomass of plants with water stress. When the evolution of the dry biomass was examined on the contrary, no significant differences could be descried. Table 3.18 summarizes the results of the statistical analyses of fresh and dry biomass of tef in early grainfilling stage (60 days after sowing) and at maturity (102 days after sowing).

Table 3.18: Fresh and dry biomass - tef

	Fresh biomass [ton·ha^{-1}]**						**Dry biomass** [ton·ha^{-1}]*					
Irrigation treatment	**60 days after sowing**		SD	**102 days after sowing**		SD	**60 days after sowing**		SD	**102 days after sowing**		SD
Rainfed	2.78	a	0.75	3.57	a	0.43	1.11	a	0.38	2.58	a	0.12
Flowering	3.01	a	0.72	4.78	ab	0.86	1.07	a	0.32	2.67	a	0.38
Flowering + grainfilling	2.97	a	1.22	5.03	b	1.53	1.08	a	0.50	2.91	a	0.61
Full	3.11	a	0.88	5.25	b	1.23	1.09	a	0.45	3.41	a	1.20

Values with the same letter are not significantly different ($P < 0.1$* and $P < 0.05$**).

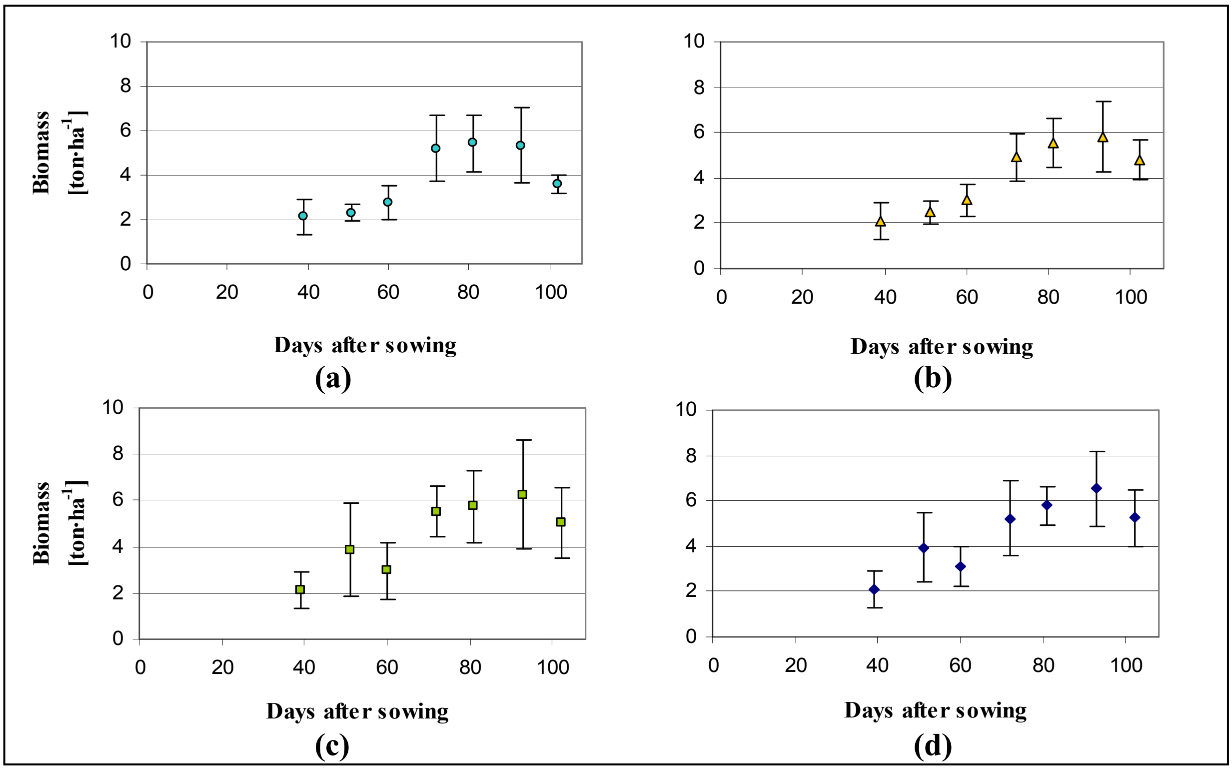


Figure 3.15: Fresh biomass for different irrigation treatments - tef: (a) rainfed - (b) irrigation only in flowering stage - (c) irrigation only in flowering and grainfilling stage - (d) full irrigation. Vertical bars indicate ± standard error.

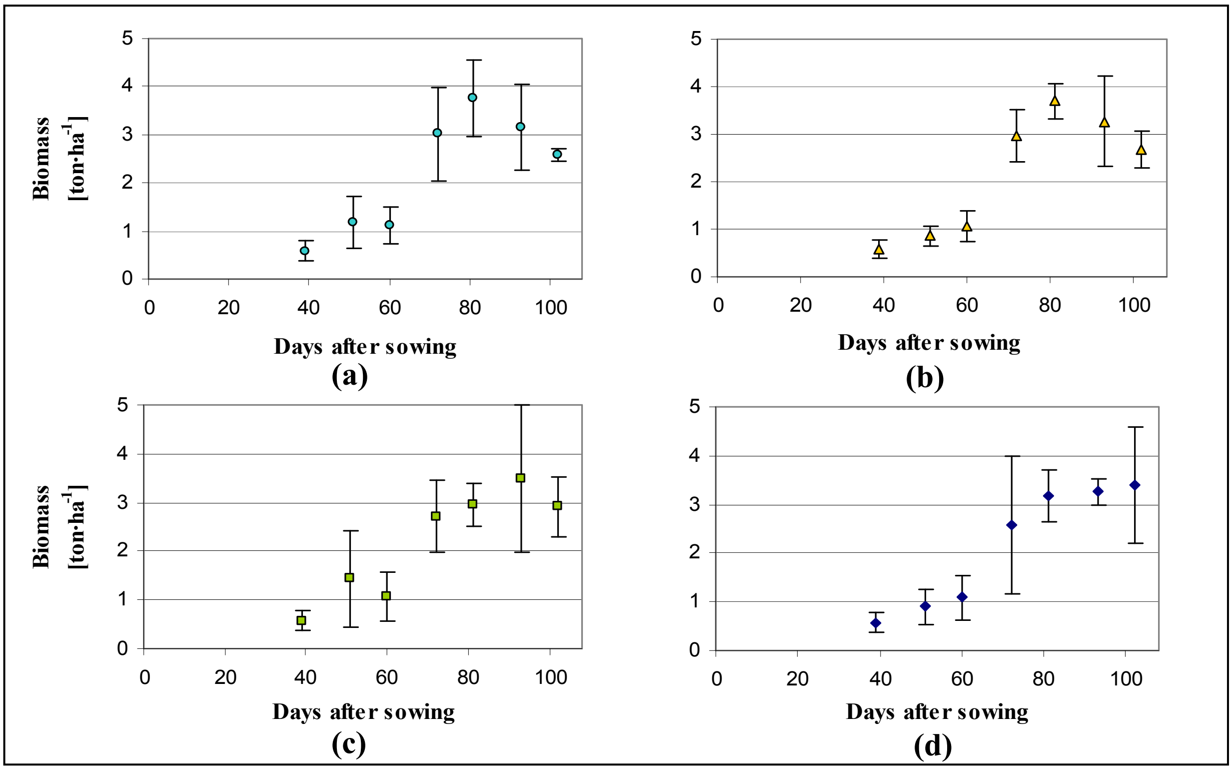


Figure 3.16: Dry biomass for different irrigation treatments - tef: (a) rainfed - (b) irrigation only in flowering stage - (c) irrigation only in flowering and grainfilling stage - (d) full irrigation. Vertical bars indicate ± standard error.

3.2.3.3 Leaf Area Index

Barley

LAI showed a parabolic change over time (figure 3.17). Maximum values were observed 67 days after sowing when plants were in flowering stage, and ranged between 2.4 and 2.8 $m^2 \cdot m^{-2}$ for different levels of water stress. The end of the growing season was characterized by lower LAI values. Not a loss of leaves was causal for this drop in LAI, but the discoloring of green leaves in the maturation process. The course of the LAI development with a peak after 67 days was in correspondence with the evolution of LAI for barley in literature. Absolute LAI was rather low when compared with data described in literature. Values close to 4.0 $m^2 \cdot m^{-2}$ are currently mentioned, and under optimal conditions peak values up to 6.9 $m^2 \cdot m^{-2}$ occur (Cantero-Martinez *et al.*, 2003; Adiku *et al*, 2006).

When LAI values were statistically analyzed, no significant differences between treatments could be observed. Table 3.19 gives an overview of the maximum values for LAI (67 days after sowing) and LAI at maturity (102 days after sowing).

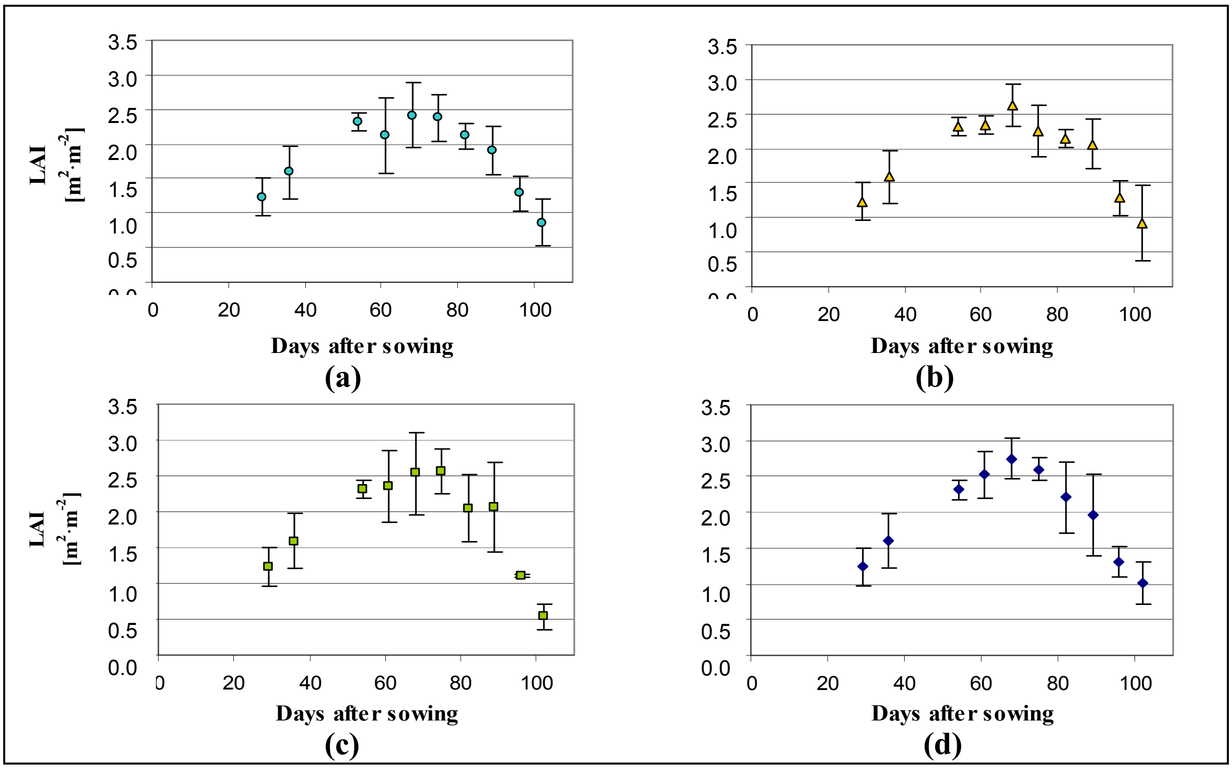


Figure 3.17: LAI for different irrigation treatments - barley: (a) rainfed - (b) irrigation only in flowering stage - (c) irrigation only in flowering and grainfilling stage - (d) full irrigation. Vertical bars indicate ± standard error.

Table 3.19: LAI - barley

	LAI [$m^2 \cdot m^{-2}$]*					
Irrigation treatment	**67 days after sowing**		SD	**102 days after sowing**		SD
Rainfed	2.41	a	0.47	0.86	a	0.34
Flowering	2.63	a	0.31	0.92	a	0.54
Flowering + grainfilling	2.53	a	0.57	0.54	a	0.18
Full	2.75	a	0.28	1.02	a	0.29

Values with the same letter are not significantly different ($P < 0.1$*).

Tef

Analogously to LAI of barley, figure 3.18 shows a parabolic change of LAI of tef over time, apart from two outliers in each data set. Since the outliers appeared for every set at the same moment, they could be ascribed to misuse or failure of the equipment and should not be considered in analyses. LAI reached a maximum after 83 days, a considerable time after the onset of the grainfilling stage. Maximum values varied between 2.05 $m^2 \cdot m^{-2}$ for crops without stress (full irrigation) and 1.47 $m^2 \cdot m^{-2}$ for rainfed crops. The empirically observed LAI values were very low, even for a fine grasslike cereal as tef.

At the end of the growing season, differences between LAI values proved evidence of the fact that rainfed plants ripened earlier than plants that experienced less water stress throughout the growing season (fully irrigated crops, and crops irrigated in flowering and grainfilling stage). Statistical analysis revealed significant differences between LAI of crops with diverse levels of water stress. Table 3.20 tabulates values and statistical groups for LAI 83 days after sowing (maximum values) and at maturity (104 days after sowing).

Table 3.20: LAI - tef

	LAI [$m^2 \cdot m^{-2}$]**					
Irrigation treatment	**83 days after sowing**		SD	**104 days after sowing**		SD
Rainfed	1.47	a	0.15	1.28	a	0.13
Flowering	1.65	ab	0.10	1.41	ab	0.14
Flowering + grainfilling	1.92	ab	0.48	1.73	c	0.11
Full	2.05	b	0.34	1.52	b	0.13

Values with the same letter are not significantly different ($P < 0.05$**).

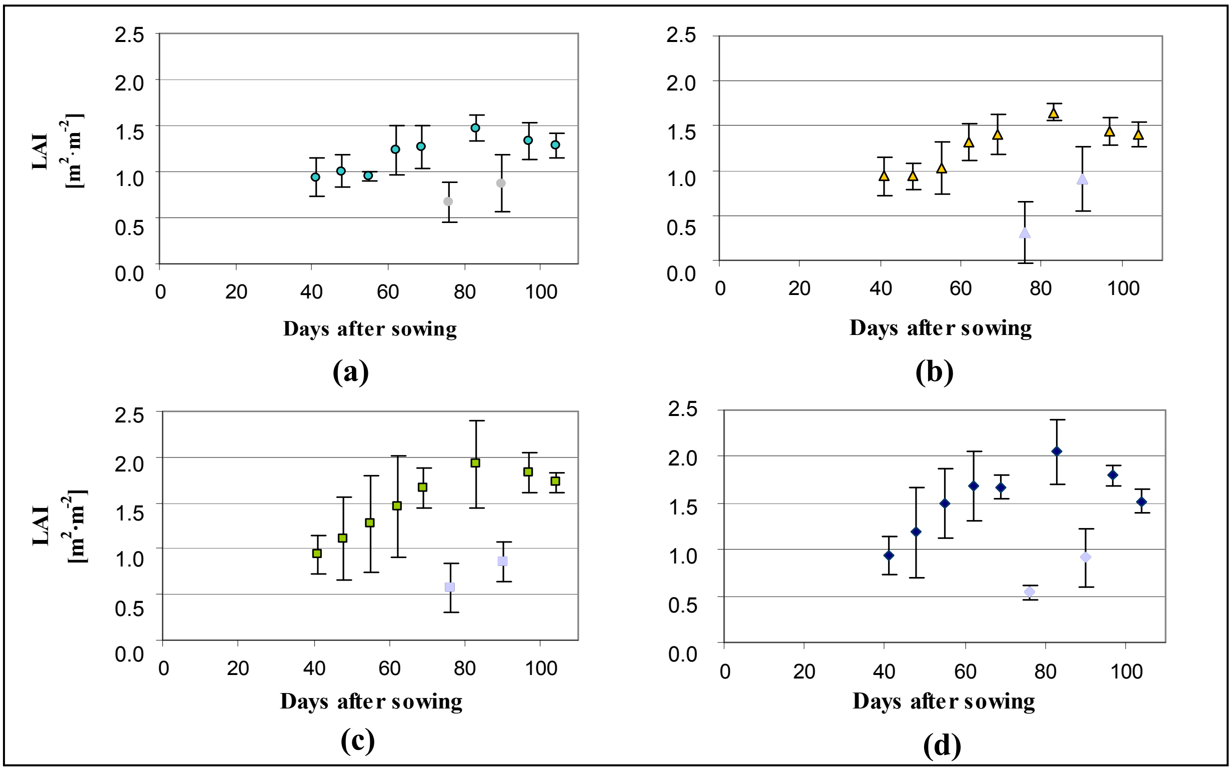


Figure 3.18: LAI for different irrigation treatments - tef: (a) rainfed - (b) irrigation only in flowering stage - (c) irrigation only in flowering and grainfilling stage - (d) full irrigation. Vertical bars indicate ± standard error. Symbols in light grey are outliers and should not be considered in analyses.

3.2.3.4 Canopy cover

Barley

Maximum CC was reached when plants did not suffer from water stress (full irrigation): the canopy covered 83 % of the ground after 67 days, when plants were in flowering stage. In subsequent phenological stages, CC decreased again because of dehydratation, wilting and drop of leaves. Figure 3.19 shows the evolution of CC over time. As for LAI, no significant differences could be found between CC of crops with diverse levels of water stress. In table 3.21 maximum CC (67 days after sowing) and CC at maturity (102 days after sowing) are tabulated.

Table 3.21: Canopy cover - barley

	CC [%]**					
Irrigation treatment	**67 days after sowing**		SD	**102 days after sowing**		SD
Rainfed	78.49	a	6.81	41.90	a	12.20
Flowering	81.61	a	3.89	42.60	a	21.56
Flowering + grainfilling	79.79	a	7.86	31.38	a	8.32
Full	83.07	a	3.15	47.71	a	10.41

Values with the same letter are not significantly different (P < 0.05**).

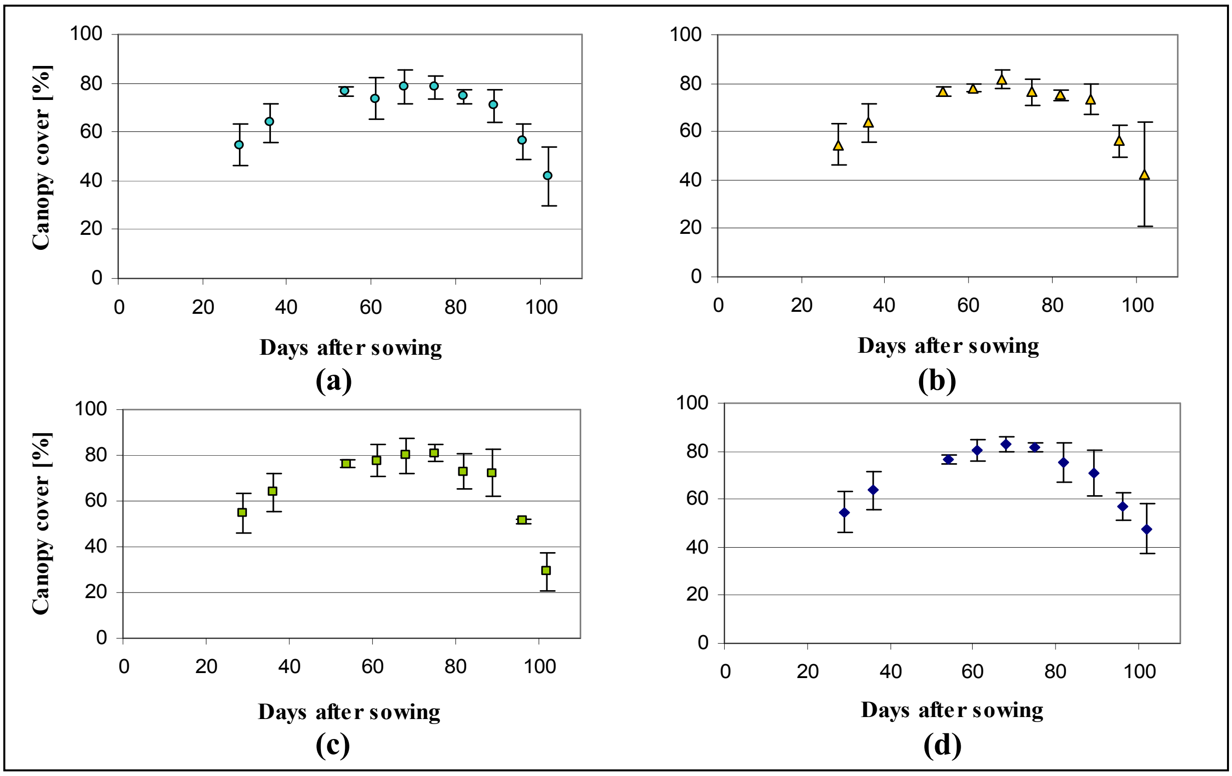


Figure 3.19: Canopy cover for different irrigation treatments - barley: (a) rainfed - (b) irrigation only in flowering stage - (c) irrigation only in flowering and grainfilling stage - (d) full irrigation. Vertical bars indicate ± standard error.

Tef

CC showed a parabolic change[4] over time with a maximum value after 83 days (figure 3.20). The maximum value of 73.6 % CC was reached by crops without water stress, and was significantly higher than CC of rainfed crops. At the end of the growing cycle, when CC decreased again because of dehydratation, wilting and drop of crop leaves, CC of crops

[4] Since CC was deduced from LAI, values on day 76 and day 90 after sowing were inaccurately measured and should be discarded in analyses.

irrigated in flowering and grainfilling stage was significantly higher than CC of crops that experienced more water stress during the growing cycle (rainfed crops and crops only irrigated in flowering stage). Table 3.22 shows the CC of tef for different levels of water supply and the division in statistical groups.

Table 3.22: Canopy cover - tef

	CC [%]**					
Irrigation treatment	**83 days after sowing**		SD	**104 days after sowing**		SD
Rainfed	61.47	a	3.70	56.44	a	3.65
Flowering	65.73	ab	2.31	59.75	ab	3.61
Flowering + grainfilling	70.35	ab	8.34	67.40	c	2.27
Full	73.14	b	5.64	62.61	bc	3.08

Values with the same letter are not significantly different ($P < 0.05$**)

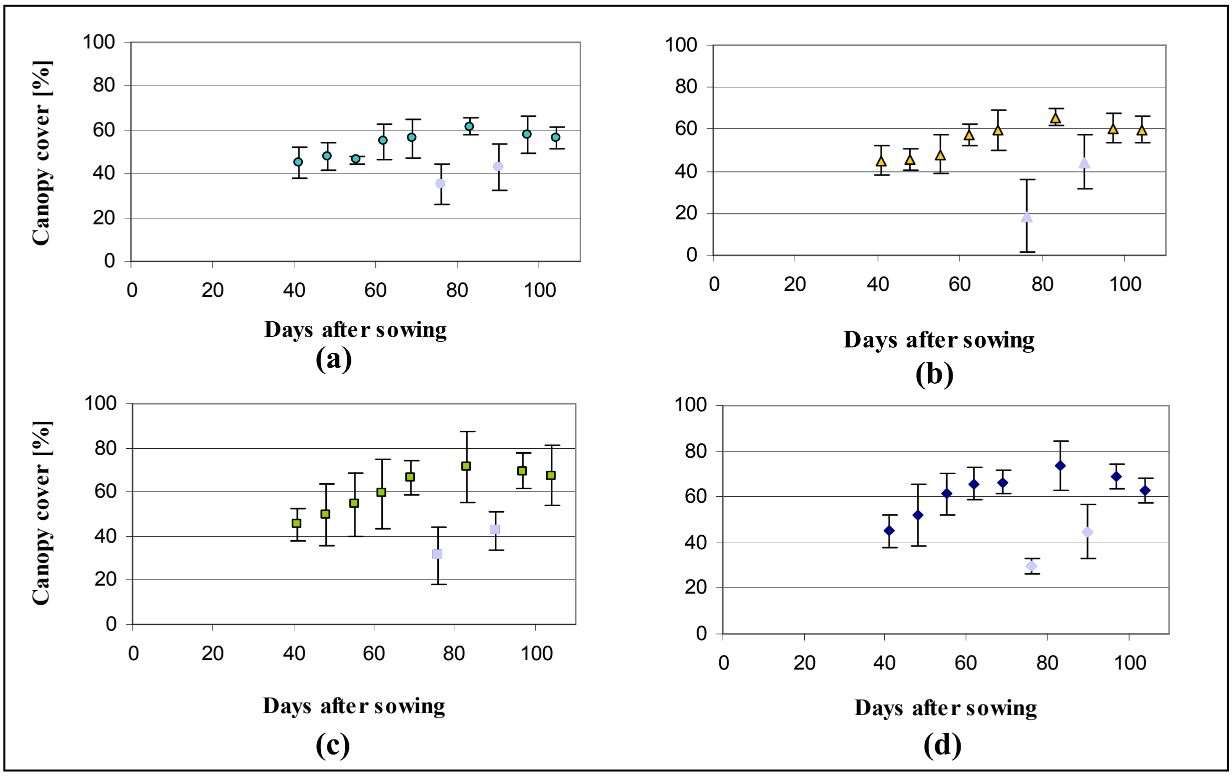


Figure 3.20:Canopy cover for different irrigation treatments - tef: (a) rainfed - (b) irrigation only in flowering stage - (c) irrigation only in flowering and grainfilling stage - (d) full irrigation. Vertical bars indicate ± standard error. Symbols in light grey are outliers and should not be considered in analyses.

3.2.3.5 Normalized Difference Vegetation Index[5]

Tef

Failure of the Greenseeker equipment confined the survey of NDVI to a series of three NDVI data sets, with an interval of 10 days. The available data did not permit to draw conclusions. Figure 3.21 and table 3.23 are given for comprehensiveness.

Table 3.23: NDVI - tef

	NDVI **					
Irrigation treatment	**58 days after sowing**		SD	**80 days after sowing**		SD
Rainfed	0.41	a	0.058	0.32	a	0.060
Flowering	0.50	b	0.029	0.38	b	0.021
Flowering + grainfilling	0.48	b	0.083	0.39	b	0.069
Full	0.52	b	0.091	0.42	b	0.071

Values with the same letter are not significantly different ($P < 0.05$**).

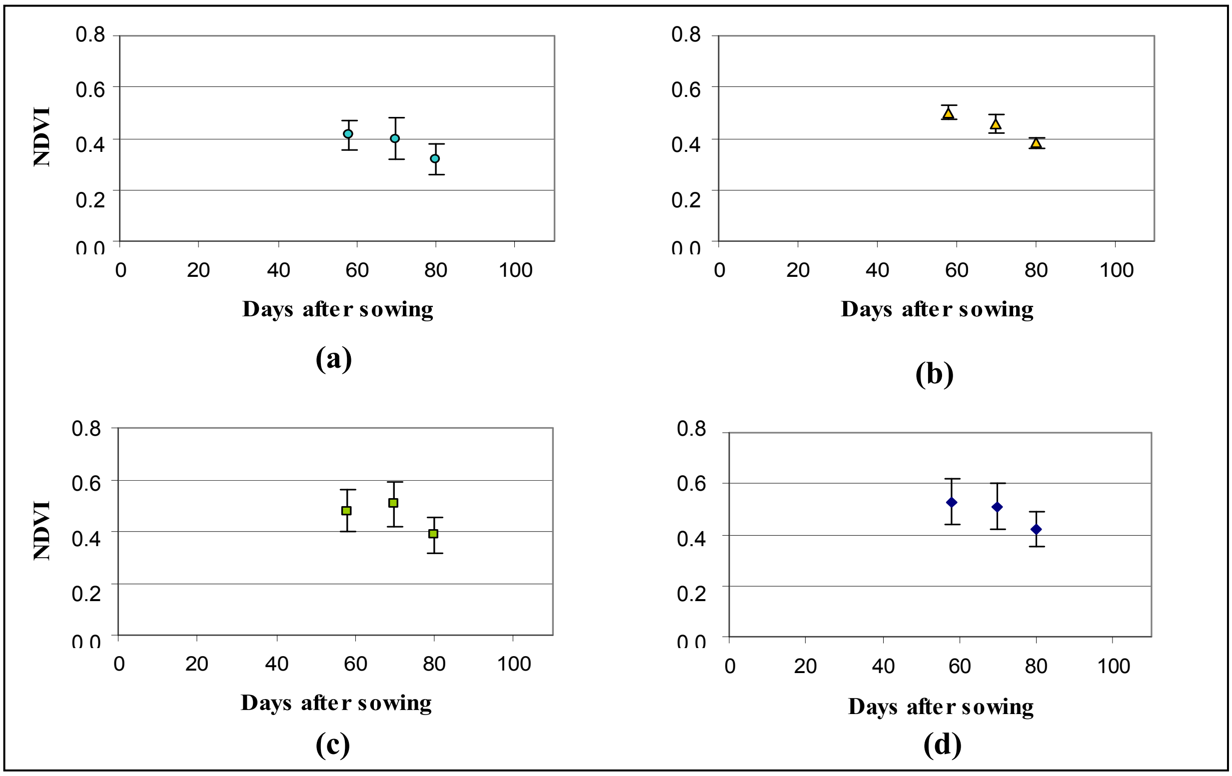


Figure 3.21: NDVI for different irrigation treatments - tef: (a) rainfed - (b) irrigation only in flowering stage - (c) irrigation only in flowering and grainfilling stage - (d) full irrigation. Vertical bars indicate ± standard error.

[5] Due to failure of the Greenseeker equipment, it was impossible to carry out a profound analysis of the NDVI of barley.

3.2.3.6 Leaf stomatal resistance

Barley

Comparison between stress free plants (full irrigation) and plants with water stress (rainfed), revealed a significant ($P < 0.1$) higher leaf stomatal resistance for plants with stress. Figure 3.22 shows leaf stomatal resistance during six consecutive days of barley plants with water stress. Stomatal resistance of plants without water stress is indicated for comparison. The soil water content in the root zone of the rainfed experimental units remained round 18 vol% throughout the measurement period. The first measurement was left out of consideration in analysis since problems with the equipment hindered reliable measurements on the first day.

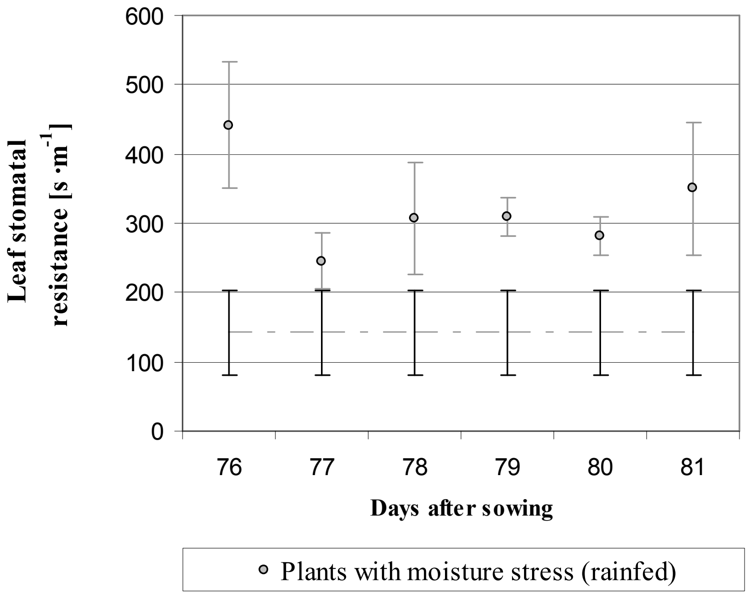


Figure 3.22: Leaf stomatal resistance in the dry season: comparison between stress free plants (dashed line) and plants with water stress - barley. Vertical bars indicate ± standard error.

The leaf stomatal resistance of plants that experienced water stress during the measurements lay close to the maximum stomatal resistance of barley plants, namely 310 $s \cdot m^{-1}$, reported by Körner *et al.* (1979). The average stomatal resistance in stress situations was 299 $s \cdot m^{-1}$ (± 39 $s \cdot m^{-1}$) or 2.1 times larger than the stomatal resistance of stress free plants, which amounted to 142 $s \cdot m^{-1}$ (± 62 $s \cdot m^{-1}$). The fully irrigated plants were probably not completely stress free, since the soil water content in their root zone was equal to 30 vol% and thus close to the threshold value at which plants start to experience severe water stress. This explained the somewhat high stomatal resistance of fully irrigated crops. According to Körner *et al.* (1979), leaf stomatal resistance of completely stress free C_3-plants is 2.9 to 4.3 times lower than in stress conditions, or between 64 and 103 $s \cdot m^{-1}$.

It would have been interesting to know the exact level of water deficit on which barley plants start to reduce their leaf stomatal conductance, in order to get an idea of the capacity of barley plants to adapt to unfavorable conditions of water availability. This knowledge can be achieved by following a sequence of increasing stomatal resistance of rainfed crops and the simultaneous registration of decreasing soil water content on the transition between rainy and dry season.

Tef

In accordance with the observations for barley, stress free tef plants showed lower leaf stomatal resistance than plants with water stress (figure 3.23). The soil water content in the root zone of the rainfed experimental units remained between 24 vol% and 22 vol%. The first measurement was left out of consideration in analysis, since problems with the equipment hindered reliable measurements on the first day.

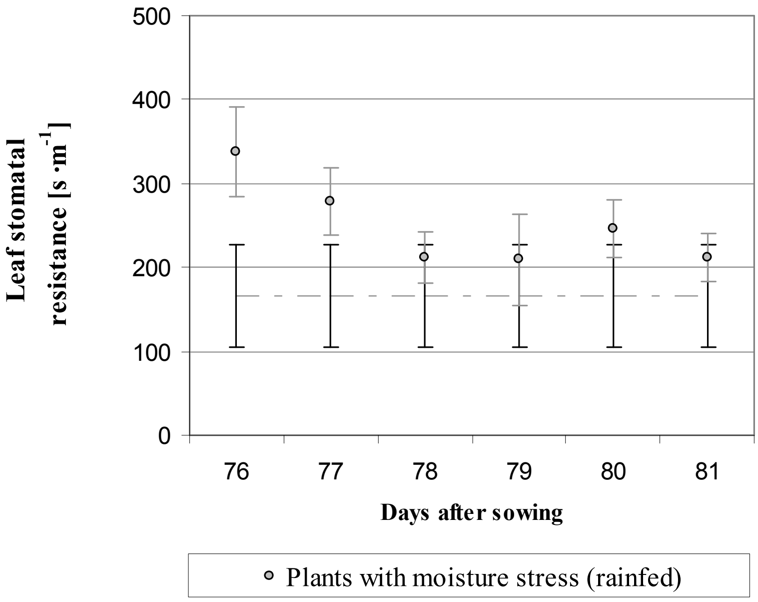


Figure 3.23: Leaf stomatal resistance in the dry season: comparison between stress free plants (dashed line) and plants with water stress - tef. Vertical bars indicate ± standard error.

The average stomatal resistance of tef plants in stress situations was 232 $s \cdot m^{-1}$ (± 30 $s \cdot m^{-1}$), and only 1.4 times higher than the average leaf stomatal resistance of plants with completely open stomata under optimal environmental conditions, namely 166 $s \cdot m^{-1}$ (± 72 $s \cdot m^{-1}$). The observations were in accordance with the conclusions of Körner *et al.* (1979) for C_4-plants. Literature with specific stomatal resistance data for tef is not available.

By analogy with barley, the experiment for tef did not give an answer about the exact level of water stress when stomata started to close or in other words, the resistance of tef to water stress conditions. The follow-up of stomatal resistance of rainfed crops right on the transition of rainy and dry season is necessary to gather the requisite data for this intention.

3.2.3.7 Maximum root depth

In the field, it turned out that the excavation of fragile plant roots was not possible without destruction of the finest, ending root parts. The measured length of the roots was thus a serious underestimation of the expected and in literature mentioned root depth of barley and tef. With the obvious destruction of roots in consideration, the root length determined by this method was assumed invalid and was compelled to be estimated. The assessment was based on a literature study and, in the case of barley, in addition on the presence of an impenetrable layer in the subsoil. Table 3.24 summarizes the estimated maximum root depth at the end of the initial stage and the absolute maximum root depth for barley and tef.

Table 3.24: Estimated root depth - barley and tef

	Estimated maximum root depth [m]	
	Initial stage	**Integral growing season**
Barley	0.3	0.5
Tef	0.2	0.5

Table 3.24 gives reasonable values for root depth of barley and tef, considering the hard layer at an average depth of 0.5 m in the barley field on the one hand, and the confined stature of tef on the other hand. Yet, the root depth is an important parameter in evaluating crop water productivity since it determines the extent to which plants can extract water from the soil. Poor estimations can have a grave influence on the simulated soil water balance.

3.2.3.8 Yield

Barley

With a maximum of 2.05 ton·ha^{-1} and slightly lower results for plants that experienced water stress, the productivity of barley in this experiment remained above the national average of 1.14 ton·ha^{-1}. Plants without water stress gave the highest total grain yield. However, a significant difference ($P < 0.05$) could not be observed neither with total yield of plants only irrigated in flowering stage, nor with total yield of rainfed crops. The total grain yield of plants irrigated in flowering and grainfilling stage was anomalously low. No explanation for this phenomenon was suitable. Probably errors occurred during the measurement procedure.

Determination of the 1000-grain yield gave more reliable results. Thousand grains of fully and partly irrigated plants had roughly the same mass, and all weighed significantly more than thousand grains produced by rainfed crops. Grains of plants that experienced less water stress than rainfed crops were thus of better quality (heavier). However, supplemental water doses on top of irrigation in flowering stage did not alter - positively or negatively - the grain quality or grain mass. The 1000-grain yield for rainfed crops was on average 56.65 g, which was slightly higher than the average value of 49 g for rainfed barley crops in more or less the same conditions found in literature (Agegnehu *et al.*, 2006). Table 3.25 gives an overview of the results of the determination of total grain yield and 1000-grain yield for barley.

Table 3.25: Total grain yield and 1000-grain yield - barley

	Yield **					
Irrigation treatment	**1000-grain yield** [g]		SD	**Total grain yield** [ton·ha^{-1}]		SD
Rainfed	56.65	a	1.94	1.84	ab	0.31
Flowering	60.89	b	1.26	1.91	b	0.14
Flowering + grainfilling	60.59	b	0.68	1.64	a	0.15
Full	60.94	b	1.48	2.05	b	0.21

Values with the same letter are not significantly different ($P < 0.05$ **).

Tef

Table 3.26 summarizes the results for total grain yield and 1000-grain yield of tef. Tef crops irrigated in flowering and grainfilling stage gave the highest total grain yield. With an average total yield of 0.98 ton·ha^{-1}, the productivity equaled the national average. Total grain yield of the fully irrigated plants and the plants only irrigated in flowering stage were lower, but no significant differences could be indicated. Total yield for the rainfed tef was low: 0.42 ton·ha^{-1}.

With regard to 1000-grain yield, fully and partly irrigated crops did not yield significantly different. Rainfed 1000-grain yield was somewhat lower. It was furthermore obvious that 1000-grain yield of tef was very low (between 0.73 and 0.82 g per 1000 grains) when compared to the mass of 1000 barley grains. Yet, the difference was not surprising given the minute size of tef grains. In literature, mention is made of even slightly lower average 1000-grain yield, roughly about 0.4 g (NRC, 1996).

Table 3.26: Total grain yield and 1000-grain yield - tef

	Yield **					
Irrigation treatment	**1000-grain yield** [g]		SD	**Total grain yield** [ton·ha^{-1}]		SD
Rainfed	0.73	a	0.039	0.42	a	0.11
Flowering	0.78	ab	0.013	0.86	ab	0.44
Flowering + grainfilling	0.81	b	0.017	0.98	b	0.51
Full	0.82	b	0.062	0.73	ab	0.43

Values with the same letter are not significantly different ($P < 0.05$ **).

3.2.3.9 Relationship between water productivity and land productivity

The relationship between water productivity and land productivity can be examined by plotting CWP against total yield (land productivity). According to Oweis and Hachum (2006), total yield and CWP follow a parallel increase up to a certain yield level. Beyond this critical level, incremental yield increase requires higher amounts of water, and CWP starts to decline.

Since no experiments were done in the field to determine the seasonal transpiration of the examined crops, no data were available to determine CWP in the strict sense of the word. Indeed, CWP was defined in equation 2.1 as the total grain yield produced by a crop divided by the total amount of water consumed by this crop (crop transpiration). Instead of verifying the relationship between grain yield and CWP, the relationship between grain yield and the ratio of total grain yield produced by a crop to the total amount of water applied to the crop (rainfall and irrigation) was examined.

Barley

In figure 3.24a, the total grain yield is plotted against the total amount of water applied to a crop (rainfall and irrigation). The yield results for the plants irrigated in flowering and grainfilling stage were not reliable and were disregarded in analyses. From figure 3.24a it is obvious that crops that experienced water stress yielded less, and thus could bring in less earnings. On the contrary, less supplemental water was applied, which meant less water costs and less labor forces needed. Depending on the relative scarcity of involved factors (water, labor,...), it could be more favorable to produce more grain yield per unit land (towards maximizing land productivity) while supplying extra water to crops, or to produce less grain but saving water and labor (towards maximizing water productivity). This decision making process is very complex and needs a thorough analysis, which goes further than the objective of this dissertation, because a whole of different variables has to be considered.

In figure 3.24b, the relationship between total grain yield and the ratio of total grain yield to total amount of water applied is plotted. The ratio can be interpreted as a form of water productivity. Crops with water stress showed significant higher values for water productivity than crops without water stress. The latter scored better with regard to land productivity.

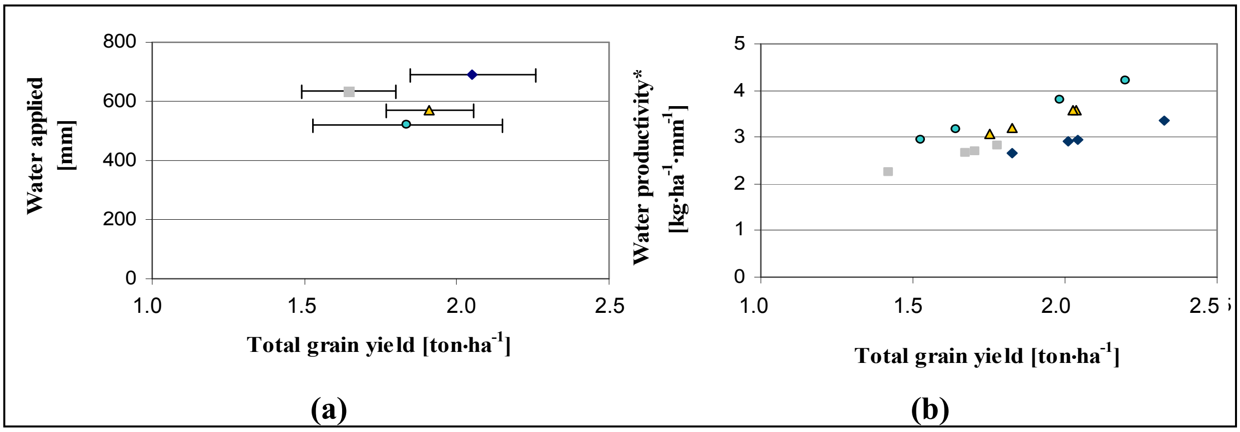


Figure 3.24: Relationship between total grain yield and (a) water applied / (b) water productivity (*ratio between grain yield and total amount of water applied) - barley
Rainfed   Irr. only in flowering   Full irr.
Horizontal bars indicate ± standard error. Symbols in light grey are not reliable.

The ratio between total amount of water applied and grain yield was relatively low when compared to values for CWP (as defined in equation 2.1: ratio between grain yield and total amount of water consumed by crops) in literature. This could be ascribed to the large surplus of water in the rainy season, when rainfall exceeded potential evapotranspiration. This surplus of water was not used by the plant to produce biomass or yield, but lost as deep percolation or runoff. Nevertheless, the lost water was included in the ratio between total amount of water applied and grain yield, and thus brought down the ratio. Table 3.27 summarizes values and statistical groups for water productivity.

Table 3.27: Water productivity - barley and tef

	Water productivity [$kg \cdot ha^{-1} \cdot mm$] **					
Irrigation treatment	**Barley**		SD	**Tef**		SD
Rainfed	3.53	b	0.59	1.33	ab	0.34
Flowering	3.36	b	0.25	2.24	b	1.15
Flowering + grainfilling	-		-	1.79	ab	0.93
Full	2.97	a	0.30	1.08	a	0.64

Values with the same letter are not significantly different ($P < 0.05$ **).

Tef

In figure 3.25a, total grain yield is plotted against the total amount of water applied to the crop (rainfall and irrigation). Total grain yield of crops that received different doses of supplemental water did not differ significantly, but all yielded better than rainfed crops. The same critical comment as for barley (cf. supra) could be made when interpreting the difference in yield and water applied between crops with different levels of water stress.

In figure 3.25b, the relationship between total grain yield and the ratio of grain yield to total amount of water applied is presented. Crops only irrigated in flowering stage showed higher values for water productivity than other crops. On average, these crops also yielded well compared to other crops. In this particular experiment, irrigating tef crops during the whole growing season did not avail anything to the quantity or quality of yield. Analogously to barley, the ratio between grain yield and total amount of water applied was relatively low when compared to values for CWP (as defined in equation 2.1: ratio between grain yield and total amount of water consumed by crops) in literature. The reason for this observation was explained above. Table 3.27 summarizes values and statistical groups for water productivity.

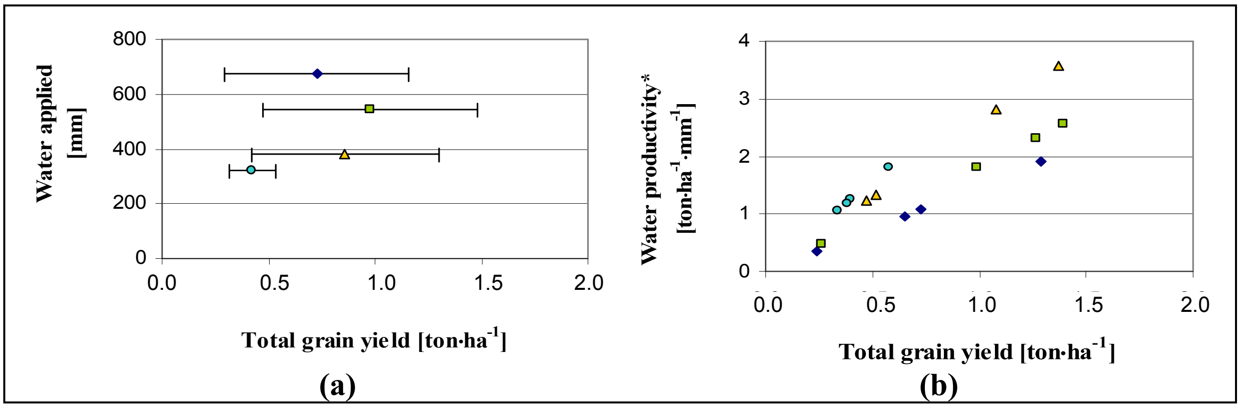


Figure 3.25: Relationship between total grain yield and (a) water applied / (b) water productivity (*ratio between grain yield and total amount of water applied) - tef
● Rainfed ▲ Irr. only in flowering ■ Irr. only in flowering and grainfilling ◆ Full irr.
Horizontal bars indicate ± standard error.

3.2.4 General discussion

Barley

In the above presentation of the field experimental results and concomitant discussion, it became clear that crop parameters of barley plants that experienced diverse levels of water stress, did not show up many significant differences. The logic explanation for this finding lies in the long time span during which all plants received the same amount of water in the form of rain. The early sowing date of barley and the relatively good rainy season in 2006 were jointly responsible for this phenomenon. In the particular case of this experiment, it is doubtful that reducing water stress in sensitive crop development stages can substantially increase water productivity or the quality or quantity of the yield. However, the experiment is only representative for a *good* rainy season with enough rain. Future research should reveal if improving the water availability of agricultural crops could ensure stable yields throughout years and good yield results in dry years.

Tef

Since tef was sown later in the rainy season, following the local customs, the time span during which all plants received the same amount of water was shorter than for barley. As a result, already throughout the growing season significant differences between several crop parameters of plants that experienced different levels of water stress manifested itself. Not at least in the final yield results significant differences became clear. The combination of observations for barley and tef indicated that the quality of the rainy season (few or much rain) had less influence on the performance of crops if they were sown later in the season. Again, it is too early to reach the conclusion that the increased water productivity, realized in this experiment by moderating crop water stress in sensitive stages (flowering and/or grainfilling), can be profitable to stabilize or improve yield. More complete and long-term research in the future is recommended.

Chapter 4

Calibration and validation of water productivity model AquaCrop

4.1 AquaCrop, the software program

The crop water productivity model AquaCrop (Raes *et al.*, 2006b; Steduto *et al.*, 2006) is a water-driven simulation model that requires a minimum of input parameters to simulate yield response to water. The model simulates the change of water stored in the soil throughout the growing season. The water content in the root zone determines the canopy development and the corresponding crop transpiration, which is converted in AquaCrop into biomass production and yield formation. AquaCrop is subdivided in four major compounds (Steduto *et al.*, 2006):

- The soil, with its water balance;
- The crop, with its development, growth and yield;
- The atmosphere, with its rainfall, evaporative demand and carbon dioxide concentration;
- The interrelationships between environmental conditions, stress development and crop responses.

To make simulations, AquaCrop requires input data consisting of climatic data, crop data, soil data and management data. However, the model contains a complete set of characteristics that can be selected and adjusted for different soil or crop types. Table 4.1 summarizes the input data, and specifies their origin for this particular study.

Table 4.1: Climate, soil and crop parameters for AquaCrop

Parameter	Specifications
Climate data	
- Rainfall	- Daily observations July-November 2006
- ET_0	- Daily observations July-November 2006 (processed with the software program EToCalc)
Soil data - Water content at SAT, FC, WP - K_{sat}	The soil profile was composed of a number of soil layers. For each layer, characteristics were specified, based on observations. [AquaCrop contains a complete set of characteristics that can be selected and adjusted for different soil types.]
Crop data - Plant density - Crop development - Crop coefficient (K_c) - Stress factors - Rooting depth - Water extraction pattern - Crop water productivity - Harvest index	A set of appropriate crop parameters was specified, based on observations. [AquaCrop is able to create a complete set of parameters that can be adjusted if additional information is available.]
Management data	
- Field management	- No specific characteristics were entered in the model [AquaCrop is suitable to enter data about soil fertility, mulching and surface practices (bunds, runoff,…).]
- Irrigation	- Irrigation doses were specified as applied on the field.

Converting the input parameters to a dynamic soil water content, AquaCrop is suitable:

- To assess crop water stress under rainfed conditions;
- To estimate yield response to water;
- To determine crop water productivity;
- To design irrigation schedules;
- To evaluate irrigation strategies (Raes *et al.*, 2006b; Steduto *et al.*, 2006).

4.2 Goodness of fit

To evaluate the goodness of fit between observed values in the experiments and simulated values in AquaCrop, three statistical goodness of fit estimators (Loague and Green, 1991) were used, namely the coefficient of determination (R^2), the root mean square error (RMSE) and the model efficiency (EF). The parameters are specified in table 4.2.

Table 4.2: Statistical parameters for testing the goodness of fit (Raes *et al.*, 2006a)

Statistical parameter	Explanation
R^2	**Coefficient of determination** - is the amount of variance explained by the model compared to the total observed variance. R^2 ranges from 0 to 1, indicating a better agreement for values closer to 1.
RMSE	**Root mean square error** - is a measure for the over- or underestimation of the measurements by the model. RMSE is expressed in percentage.
EF	**Model efficiency** - is a measure for the robustness of the model. EF ranges from minus infinity to 1, with higher values indicating a better agreement. If EF is negative, the model prediction is worse than the mean observation.

4.3 Results and discussion for barley

4.3.1 Soil water balance in the root zone

When initial simulations were made with soil parameters (θ_{SAT}, θ_{FC}, θ_{WP} and K_{sat}) as indicated in 3.2.2.1, the comparison between observed and simulated soil water content revealed that θ_{FC} and θ_{WP} in table 3.13 were overestimated. Figure 3.9 in 3.2.2.2 already suggested the overestimation of the soil water content at FC and at WP. A calibration on the soil water retention characteristics was carried out with the values listed in table 4.3.

Table 4.3: Soil physical parameters after calibration with AquaCrop - barley

Soil layer	**Depth** [m]	θ_{SAT} [vol%]	θ_{FC} [vol%]	θ_{WP} [vol%]	K_{sat} [mm·day^{-1}]
Layer 1	0 - 0.1	48.7	34.1	21.0	95.3
Layer 2	0.1 - 0.3	48.8	34.5	21.4	87.8
Layer 3	0.3 - 1.0	48.9	34.9	22.0	80.9

Values for θ_{SAT} and K_{sat} were adapted from Saxton. Simulations with values for those parameters as found in field experiments gave the same simulation results. Values for θ_{FC} and θ_{WP} in table 4.3 were obtained by lowering the values for θ_{FC} and θ_{WP} in 3.2.2.1 (table 3.6) with 3 vol% and 2 vol% respectively. The calibration on θ_{FC} and θ_{WP} resulted in better simulations. In figure 4.1 observed and simulated values for soil water content in the root zone are plotted for different irrigation treatments with the soil physical parameters of table 4.3.

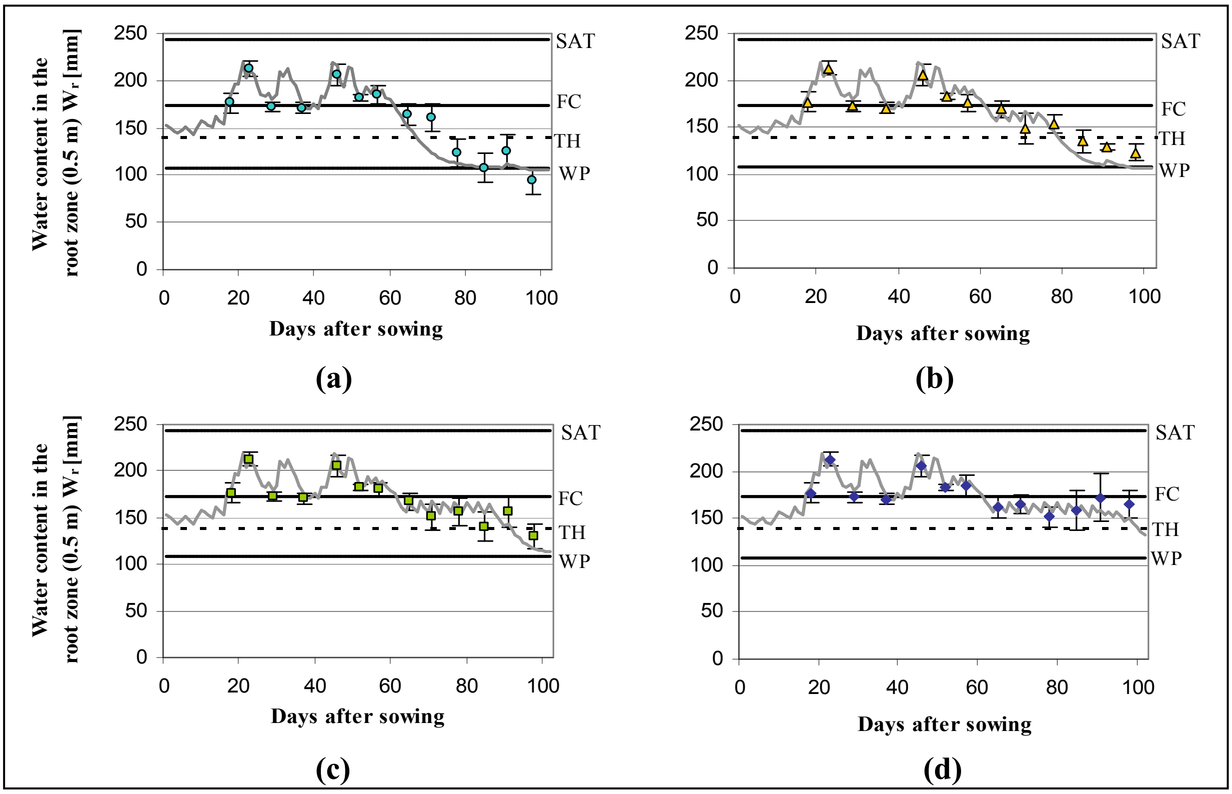


Figure 4.1: Observed (points) and simulated (line) water content in the root zone (W_r) for different irrigation treatments - barley: (a) Rainfed - (b) Irrigation only in flowering - (c) Irrigation only in flowering and grainfilling - (d) Full irrigation. Vertical bars indicate ± standard error.

From figure 4.1, it is readily perceptible that simulations fitted the observed soil water content well. Especially in the beginning of the growing season, observed and simulated soil water content matched very good. Later in the season, when rain had come to an end, simulations deviated somewhat from observations. The simulated soil water content seemed to drop too fast after the last rain or irrigation application. A conceivable explanation could be the overestimation of ET_c by AquaCrop, which made the soil water content to deplete faster in the model than in reality. Another possible line of reasoning presumed that plants in reality were able to extract water from deeper layers, which avoided the crops from depleting superficial layers immediately.

Notable was the soil water content 91 days after sowing: observed values for soil water content made a big leap upwards after an unusual rain shower in October. The leap was also visible in the simulations, but did not show the same magnitude. This finding could be ascribed to the discrepancy between the moment of soil sampling and the moment when the theoretic model simulated the effect of a single rain event, draining trough different soil layers.

Table 4.4 gives an overview of the statistical parameters that indicated the goodness of fit for the AquaCrop model. The parameters confirmed the good match between simulations and observations.

Table 4.4: Goodness of fit of the simulated water content in the root zone - barley

Treatment	**R^2** [-]	**RMSE** [%]	**EF** [-]
Rainfed	0.894	12.89	0.867
Flowering	0.928	10.94	0.827
Flowering + grainfilling	0.889	9.027	0.842
Full	0.841	7.771	0.792

Appendix III contains figure III.1 where observed and simulated soil water content in the root zone are plotted against each other.

4.3.2 Canopy cover

A calibration on crop characteristics was carried out to improve the similarity between simulated and observed values for both W_r and CC. Values for diverse crop parameters, given in appendix IV, were based on observations, but additionally adapted to increase the goodness of fit, and completed when observed data were missing. Figure 4.2 shows the evolution of observed and simulated values for CC in time for different treatments. Table 4.5 summarizes the goodness of fit parameters. Both the figure and the table demonstrated that simulations and observations for CC were similar for all treatments.

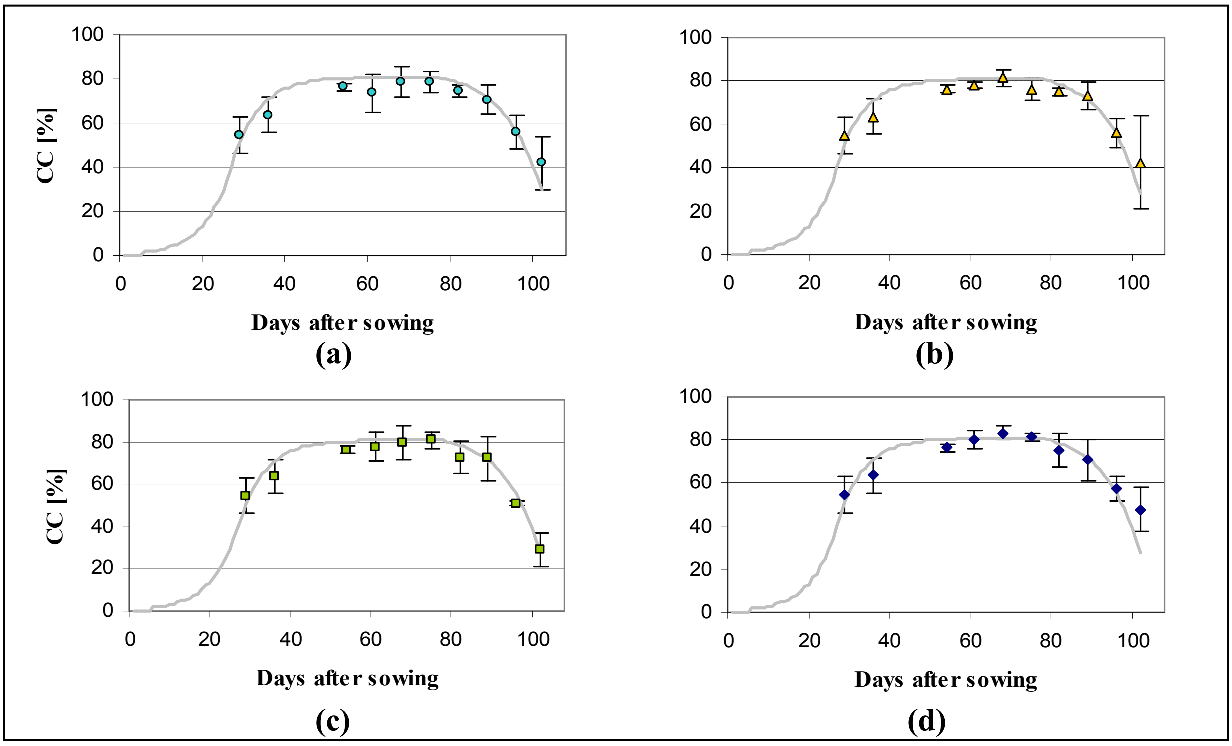


Figure 4.2: Observed (points) and simulated (line) canopy cover for different irrigation treatments - barley: (a) Rainfed - (b) Irrigation only in flowering - (c) Irrigation only in flowering and grainfilling - (d) Full irrigation. Vertical bars indicate ± standard error.

Table 4.5 shows a high R^2 and EF for all treatments. RMSE indicated a low under- or overestimation of the observed values by the model for all treatments. Simulations for crops only irrigated in flowering and grainfilling stage performed better for all statistical parameters. This could be ascribed to the simulation of CC 102 days after sowing: while observations and simulations were similar for this treatment, they deviated to a large extent for the three remaining treatments.

Table 4.5: Goodness of fit of the simulated canopy cover - barley

Treatment	**R^2** [-]	**RMSE** [%]	**EF** [-]
Rainfed	0.958	5.479	0.782
Flowering	0.936	5.813	0.773
Flowering + grainfilling	0.964	3.830	0.940
Full	0.888	6.947	0.656

In appendix V observed and simulated CC are plotted against each other.

4.3.3 Crop water productivity

Figure 4.3 and 4.4 show the normalized CWP of barley as the slope of the relationship between dry above-ground biomass and the cumulative ratio between active transpiration (T_a) and evapotranspiration (ET_0) for fully irrigated crops. Observed values for dry above-ground biomass were plotted against the cumulative ratio between simulated T_a and ET_0. Initially, only observations for fully irrigated plants were used to verify the relationship because in this particular case no assumptions had to be made about the potential drop of crop transpiration in case of water stress, which gave more certainty about the nature of CWP.

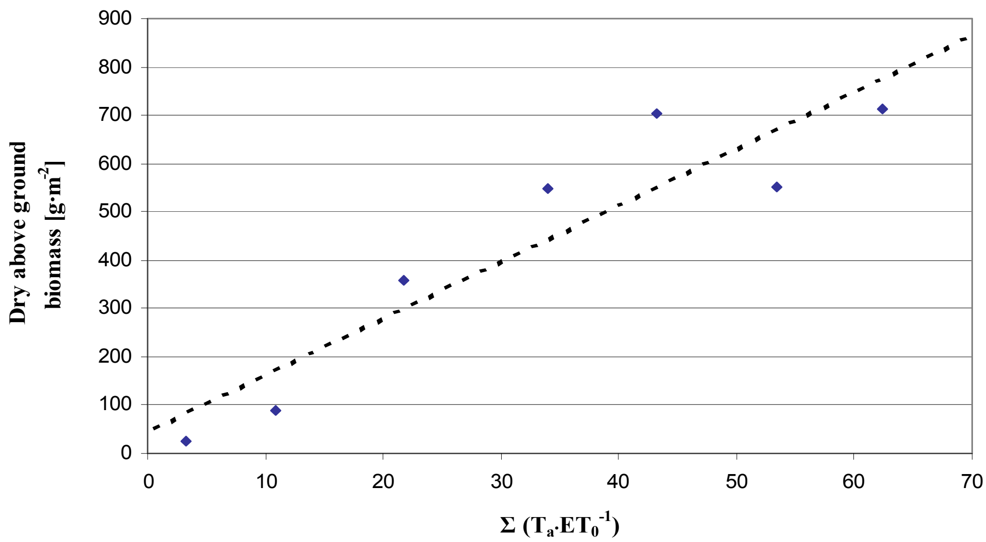


Figure 4.3: Crop water productivity for crops without water stress - barley ---- Trend line

The combination of figure 4.3 and table 4.6 make clear that values for normalized CWP lay very close to 13.4 $g \cdot m^{-2}$ as suggested by the Steduto *et al.* (2007) for C_3 crops.

Table 4.6: Equation and R^2 for crop water productivity - barley

Corresponding figure	**Observations**	
	Trend line equation	**R^2 [-]**
Figure 4.3 (crops without stress only)	y = 11.80 x + 41.35	0.86
Figure 4.4 (all crops)	y = 12.53 x + 29.07	0.88

In figure 4.4, observed values of dry above-ground biomass for different irrigation treatments are plotted against the cumulative ratio between simulated T_a and ET_0 to verify the constancy of normalized CWP in situations with water stress.

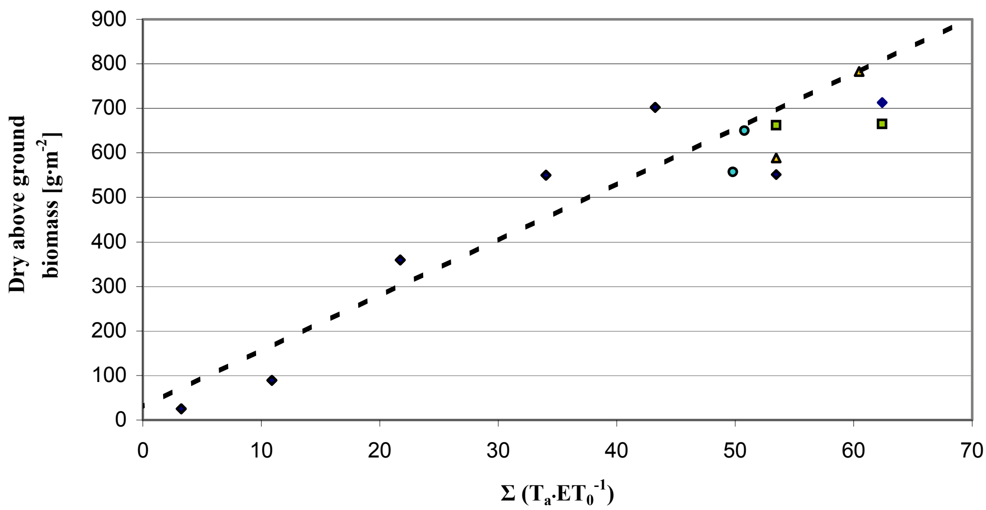


Figure 4.4: Crop water productivity for crops with different levels of water stress - barley

○ Rainfed △ Irr. only in flowering □ Irr. only in flowering and grainfilling ◆ Full irr.
---- Trend line

Figure 4.4 and table 4.6 together reveal that normalized CWP for irrigated as well as for rainfed crops lay close to 13.4 g·m^{-2}. Partly or not irrigated plants corroborated even better the constancy hypothesis of normalized CWP, although results were satisfactory for all treatments. These conclusions can be seen as a support to the theory of the conservative behavior of normalized CWP. Since crop transpiration was normalized for reference evapotranspiration, the influence of a particular climate type can be ruled out, and results can be extended to other climate types. This is an interesting perspective to disseminate the knowledge about CWP to other regions inside and outside Ethiopia. However care must be taken when drawing conclusions, since all crops - even rainfed - experienced only mild water stress. Further research on barley crops with more severe water stress is recommended.

4.3.4 Yield estimates

Observed and simulated values for yield are plotted in figure 4.5. Observations and simulations did not show good correlation. R^2 was 0.012. The reason for this low correlation coefficient was rather due to errors in the observed values, as explained in 3.2.3.9 than due to wrong simulation results by the model.

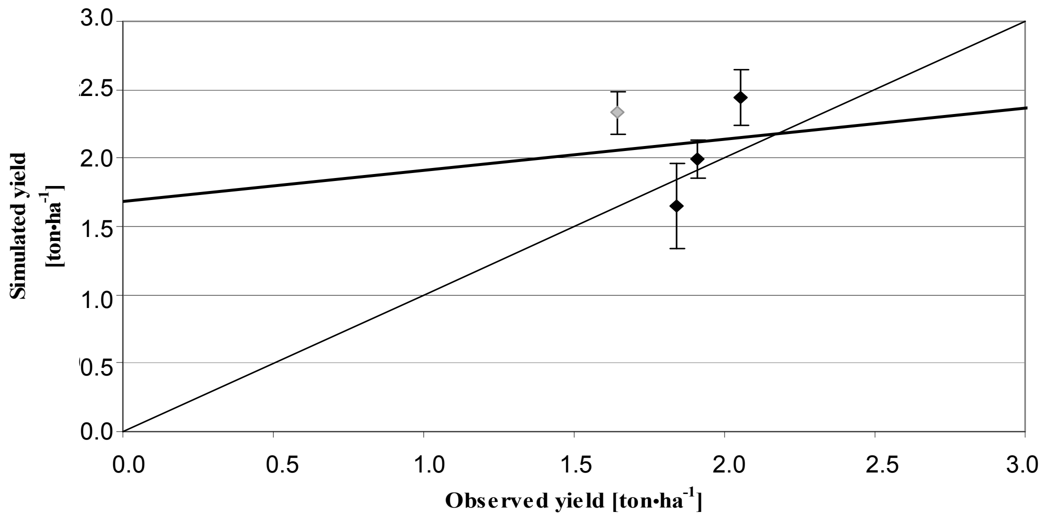


Figure 4.5: Observed vs. simulated yield - barley ▬ Trend line —— Bisector

Symbols in light grey are outliers.

4.4 Results and discussion for tef

4.4.1 Soil water balance in the root zone

By analogy with the barley field, comparison between observations and initial simulations of the soil water content revealed that θ_{FC} and θ_{WP} in table 3.14 were overestimated. Figure 3.10 in 3.2.2.2 suggested likewise an overestimation of the water content at FC and at WP. A calibration on the soil water retention characteristics was carried out with the values listed in table 4.7.

Table 4.7: Soil physical parameters after calibration with AquaCrop - tef

Soil layer	**Depth** [m]	θ_{SAT} [vol%]	θ_{FC} [vol%]	θ_{WP} [vol%]	K_{sat} [mm·day^{-1}]
Layer 1	0 - 0.1	50.7	34.6	21.8	89.0
Layer 2	0.1 - 0.3	51.0	35.5	23.3	74.2
Layer 3	0.3 - 1.0	51.7	36.1	24.1	71.3

Values for θ_{SAT} and K_{sat} were adapted from Saxton. Simulations with values for those parameters as found in field experiments gave the same simulation results. Values for θ_{FC} and θ_{WP} in table 4.7 were obtained by lowering the values in 3.2.2.1 as adapted from Saxton with 5 vol% and 3 vol% respectively. The calibration on θ_{FC} and θ_{WP} resulted in better simulations. In figure 4.5, the evolution of the observed and simulated soil water content in the root zone is plotted for different irrigation treatments.

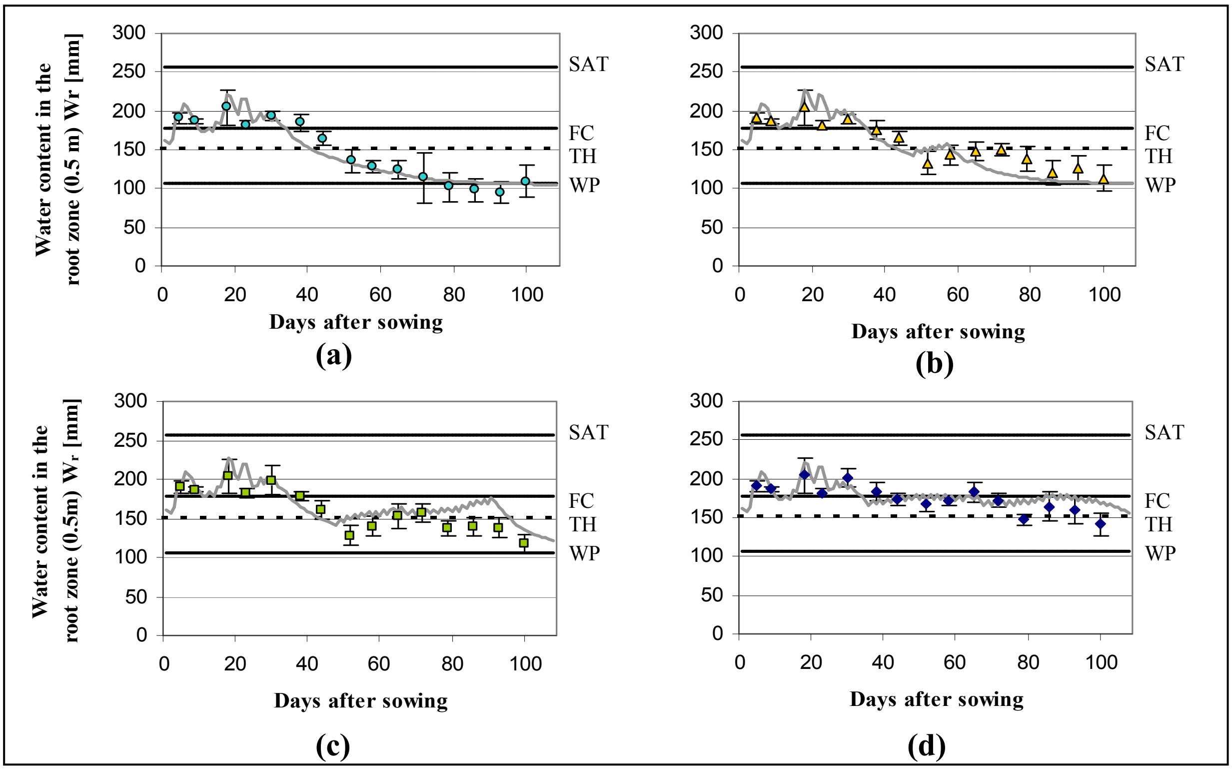


Figure 4.6: Observed (points) and simulated (line) water content in the root zone (W_r) for different irrigation treatments - tef: (a) Rainfed - (b) Irrigation only in flowering - (c) Irrigation only in flowering and grainfilling - (d) Full irrigation. Vertical bars indicate ± standard error.

Simulations for rainfed crops matched well with observations in the field. However, simulations for the remaining treatments deviated largely from the observed soil water content. The divergence was more pronounced in the second half of the growing season, after the rains had come to an end. For plants irrigated for a longer time span (full irrigation and irrigation in flowering and grainfilling stage), the simulations overestimated the observed soil water content. In case crops were only irrigated in flowering stage however, the simulations remained below the observations. No certainty existed about the cause of the mismatch; the lack of fit can be ascribed to the model for an unusual crop like tef, to inaccuracy in the determination of the soil water content in the field carried out by a third person, or to the fact that the level of water stress undergone by tef plants was relatively high.

The parameters to evaluate the goodness of fit of the model (table 4.8) were in agreement with the observations in figure 4.5. Simulations for the rainfed crops were relatively good and scored well for all parameters. The remaining treatments however showed lack of fit.

Table 4.8: Goodness of fit of the simulated water content in the root zone - tef

Treatment	**R^2** [-]	**RMSE** [%]	**EF** [-]
Rainfed	0.887	13.607	0.878
Full	0.528	14.389	0.304
Flowering + grainfilling	0.695	19.022	0.494
Flowering	0.838	18.063	0.588

In figure III.2 in appendix III the observed and simulated soil water content in the root zone are plotted against each other.

4.4.2 Canopy cover

A calibration on crop characteristics was carried out to improve the simulations. Input values for different crop parameters, given in appendix IV, were based on observations, but additionally adapted and completed to increase the goodness of fit. Figure 4.7 shows the evolution of observed and simulated values for CC over time for different treatments.

Leaving the outliers out of consideration, simulated CC matched quite well with observed values. Lack of fit was mainly observable in the beginning of the growing season, in the upward trend of the CC curve. Especially when relatively high levels of water stress occurred (rainfed and irrigation in flowering stage), AquaCrop seemed to simulate the CC curve differently from the observed curve. Simulated curves for crops with water stress showed an initial increase in CC equal to the initial increase of CC of crops without water stress (full irrigation) before the curve suddenly lopped off because of water deficit. Observations revealed another progress: from the start on, when only a minute level of water deficit could be determined, crops started to develop CC slower, more gradually. This finding could probably be ascribed to the incomplete calibration of AquaCrop for the specific tef crop.

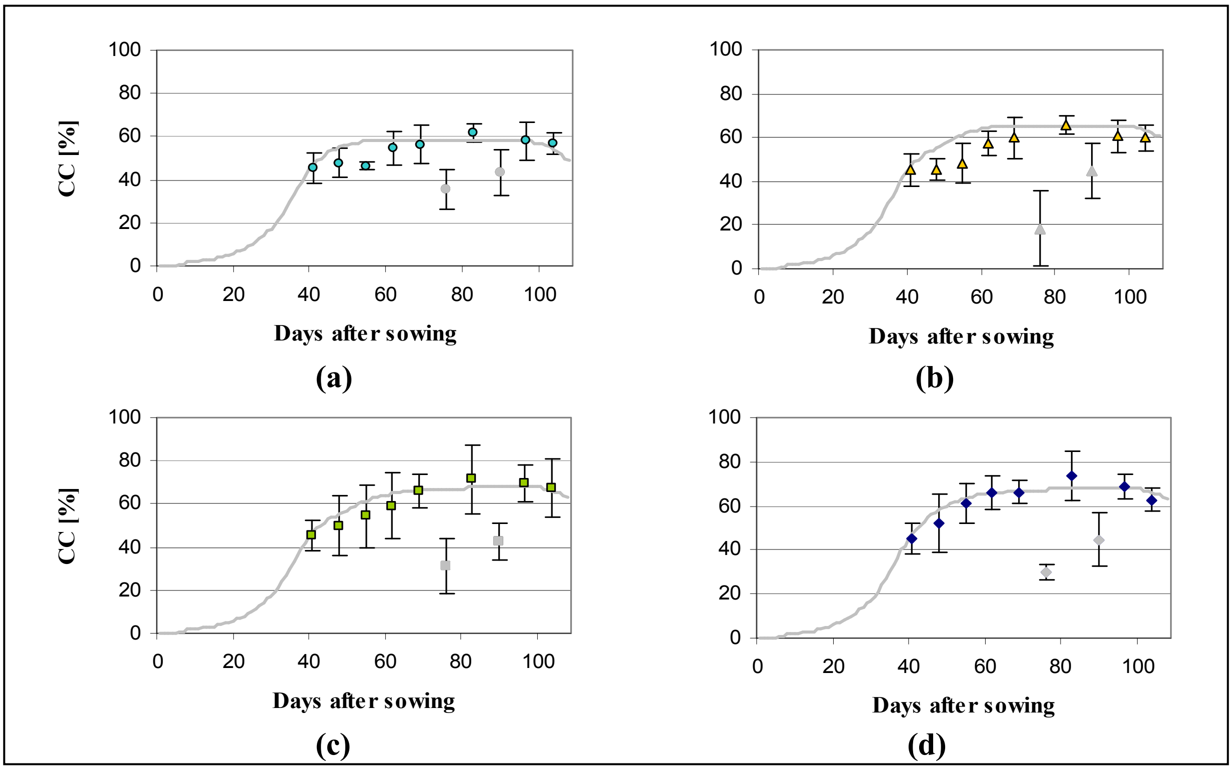


Figure 4.7: Observed (points) and simulated (line) canopy cover for different irrigation treatments - tef: (a) Rainfed - (b) Irrigation only in flowering - (c) Irrigation only in flowering and grainfilling - (d) Full irrigation. Vertical bars indicate ± standard error. Symbols in light grey are outliers and should not be considered in analyses.

Table 4.9 summarizes the statistical parameters to evaluate the goodness of fit of the model as regards to CC. In accordance with figure 4.7, simulations for crops that experienced larger water stress are inferior. R^2 and EF for rainfed crops are extremely low.

Table 4.9: Goodness of fit of the simulated canopy cover - tef

Treatment	**R^2** [-]	**RMSE** [%]	**EF** [-]
Rainfed	0.312	5.345	0.111
Full	0.895	3.275	0.857
Flowering + grainfilling	0.876	3.934	0.814
Flowering	0.698	6.693	0.173

In figure V.2 in appendix V the observed and simulated CC are plotted against each other.

Figures and tables under 4.2.2.1 and 4.2.2.2 and related appendices indicate that the simulations made with AquaCrop for tef are poor. The quality of analyses with output data from AquaCrop should be interpret with this information in mind.

4.4.3 Crop water productivity

Figure 4.8 shows the normalized CWP of tef as the slope of the relationship between observed dry above-ground biomass and the cumulative ratio between simulated T_a and ET_0 for fully irrigated crops. The assumption that normalized CWP of tef, a C_4 crop, would lie between 25.0 and 32.0 $g{\cdot}m^{-2}$, was refuted. Conversely, the thesis of Steduto *et al.* (2007) about the constancy of normalized CWP seemed to be endorsed by the experimental data: observed values for above-ground biomass increased linearly with the cumulative ratio between T_a and ET_0; R^2 was 0.91. Normalized CWP was fixed on 7.65 $g{\cdot}m^{-2}$ as can be read from the trend line equation in table 4.10. Prudence is in order when final conclusions about CWP are made. Indeed, CWP is dependent on the actual crop transpiration, which was poorly simulated by the model as a result of unsatisfying model calibration.

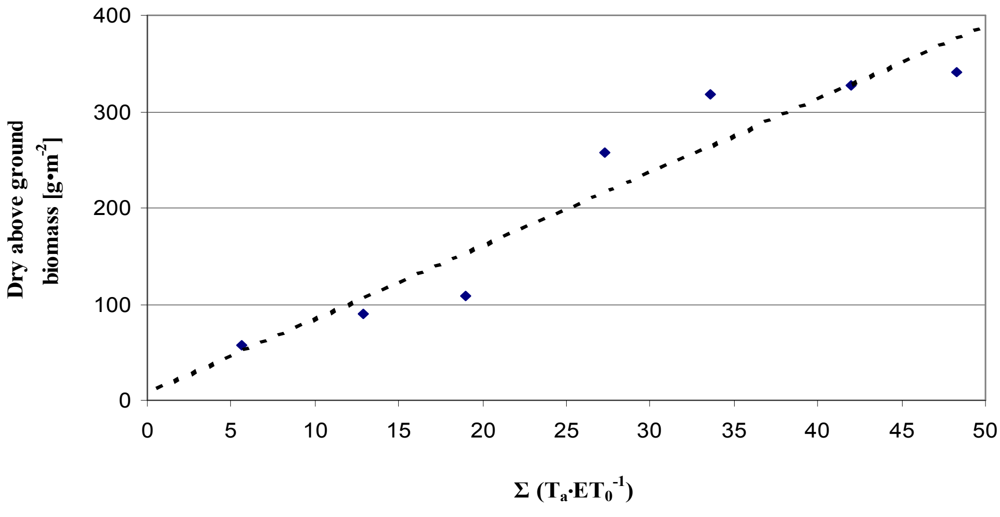


Figure 4.8: Crop water productivity for crops without water stress - tef ---- Trend line

In figure 4.9, observed values for dry above-ground biomass for different irrigation treatments are plotted to verify the constancy of normalized CWP in situations with water stress.

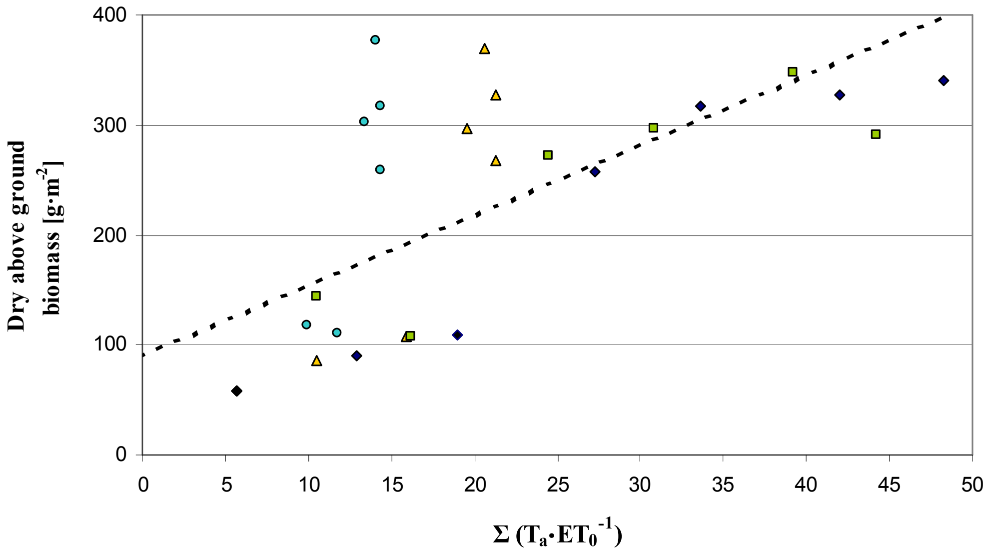


Figure 4.9: Crop water productivity for crops with different levels of water stress - tef

○ Rainfed △ Irr. only in flowering □ Irr. only in flowering and grainfilling ◆ Full irr.
---- Trend line

Figure 4.9 dismisses the conservative nature of normalized CWP for crops under water stress. Rejection of linearity could be mainly attributed to crops under severe water stress (rainfed and irrigation in flowering stage). Above-ground biomass of crops that encountered less severe water deficit (irrigation in flowering and grainfilling stage) showed a nearly linear relationship with the cumulative ratio between T_a and ET_0.

Table 4.10: Equation and R^2 for crop water productivity - tef

Corresponding figure	Observations	
	Trend line equation	R^2 [-]
Figure 4.8 (crops without stress only)	y = 7.65 x + 8.00	0.91
Figure 4.9 (all crops)	y = 6.41 x + 88.88	0.46

Again, mention has to be made of the fact that conclusions were drawn based on data from a model with a problematic calibration. More experimental data should be gathered for a more dependable calibration, and to verify or reject the findings of this dissertation.

From the same point of view, it seemed appropriate not to compare observed and simulated yield of tef, since the latter was not reliable.

4.5 Simulation results for dry, normal and wet years

4.5.1 Objectives

A good calibrated and validated model allows to simulate the soil water balance, canopy development and final yield for different types of years. Since only the calibration with AquaCrop for barley was considered to be reliable, yield predictions for different years were only determined for barley. It seemed appropriate to collect more experimental soil and crop data for tef in future research work in order to perform a new calibration before predicting yield for tef.

4.5.2 Soil and crop data

Input for yield estimations in AquaCrop consisted of crop and soil parameters for barley as established in experiments in 2006 and if necessary adjusted in the calibration process. For the sake of completeness, the crop parameters are summarized in table 4.11.

Table 4.11: Crop parameters of barley as input in AquaCrop

Parameter	**Value**
CC_0 [%]	1.40
Max. CC [%]	81
CGC [%·day^{-1}]	0.16
Full canopy [days after sowing]	57
Flowering period [days after sowing]	60 - 75
Kc coefficient [-]	1.15
Rooting depth in initial and mid-stage [m]	0.3 - 0.5
Soil water depletion factor (p) for stress related to leaf expansion growth [-]	0.30 - 0.60
Soil water depletion factor (p) for stress related to stomatal closure [-]	0.55 - 1.00
Soil water depletion factor (p) for stress related to early canopy senescence[-]	0.85 - 1.00
Crop water productivity [g·m^{-2}]	14.0
Harvest index [%]	23

4.5.3 Meteorological data

Meteorological data were gathered for different years between 1984 and 2003. Rainfall data, collected at Mekelle airport, were available for 16 years in this series (data for 1986 and 1989-1991 were lacking). Reference evapotranspiration for these 16 years was determined with the software program EToCalc (Raes, 2006) as explained in Chapter 3.

A frequency analysis of rainfall in the main rainy season (June - September) was carried out by means of the software package Rainbow (Raes *et al.*, 1996). The probability of exceedence was estimated by the formula developed by Weibull; a log10 scale transformation was carried out on the rainfall events to obtain a normal distribution of the events. Years were classified as dry, normal and wet. Additionally two intermediate classes were defined: dry (normal) years with and wet (normal) years. Table 4.12 gives an overview of the classification criteria based on the probability of exceedence (PE).

Table 4.12: Classification criteria for different years based on probability of exceedence (PE)

Type of year	**Probability of exceedence (PE)** [%]
Main classes	
Dry	PE $\geq$ 80 %
Normal	80 % > PE > 20 %
Wet	PE $\leq$ 20 %
Intermediate classes	
Dry (normal)	80 % > P $\geq$ 70 %
Wet (normal)	30 % $\geq$ P > 20 %

4.5.4 Onset of the growing season

The onset of the growing season for different years between 1984 and 2003 was not documented, and had to be estimated. A good timing of planting dates is of uppermost importance for crop production in rainfed agriculture, especially in semi-arid regions where the rainy season can start with light showers followed by dry spells (Raes *et al.*, 2004). The onset criteria in this study were based on the observation of a specific amount of rain over an arbitrary period of several days, combined with the FAO provision for the growing season, that is ‘rainfall in decade exceeds 0.5 ET_0 in decade’. In addition to this FAO criterium, the onset criteria were arbitrary defined as the generally accepted stipulation of at least 40 mm rain in maximum 15 days. The '40 mm in 15 days' criterium usually postpones the planting date in comparison with another international criterium (25 mm in 7 days), but diminishes the risk of failure appreciably (Raes *et al.*, 2004).

4.5.5 Results and discussion

Table 4.13 assembles total rainfall in the main rainy season, the classification of the concerned year, the probability of exceedence, the return period, which is the reciprocal of the probability of exceedence, the generated planting date, and the expected yield for different years in the period 1984-2003.

Table 4.13: Rainfall characteristics, generated planting date and expected grain yield for different types of years in the period 1984-2003

Year	Rainfall characteristics				Generated planting date	Expected grain yield [ton·ha^{-1}]
	Rainfall in the main rainy season (June-September) [mm]	Class	Probability of exceedence [%]	Return period [year]		
1984	241.2	dry	96	1.04	9/jul	0.271
1985	330.8	dry	80	1.26	8/jul	1.660
1987	433.7	normal	49	2.05	24/jun	2.202
1988	834.2	wet	2	54.89	2/jul	2.189
1992	374.6	normal	67	1.50	9/jul	1.582
1993	338.9	dry (normal)	78	1.29	21/jun	1.996
1994	535.8	wet (normal)	24	4.12	21/jun	2.587
1995	557.3	wet (normal)	21	4.86	3/jul	2.005
1996	340.3	dry (normal)	77	1.30	1/jul	1.105
1997	359.9	dry (normal)	71	1.41	2/jul	1.466
1998	639.5	wet	10	9.55	28/jun	2.179
1999	675.6	wet	8	13.04	3/jul	1.976
2000	399.2	normal	59	1.69	5/jul	1.794
2001	492.7	normal	33	3.01	23/jun	2.104
2002	334.1	dry (normal)	79	1.27	1/jul	1.142
2003	351.2	dry (normal)	74	1.36	15/jul	1.483

Table 4.13 reveals a high degree of variability between years. Total rainfall varied between scarcely 241 mm in 1984 (exceeded in almost every year) to more than 834 mm in 1988 (with an occurrence of one out of 55 years). Suggested plant dates ran from June, 21 to July, 15. Early planting dates generated a greater risk for false starts and damage to young crops. Sowing later in the season lowered the risks but enlarged the possibility that early rainfall would leach nutrients and that the economic value of cash crops would plummet (Raes *et al.,* 2004). Total yield ranged between a poor 0.271 ton·ha^{-1} in 1984, an extremely dry year, and a maximum of 2.587 ton·ha^{-1} in 1994, a wet year[6]. Yield did not follow total rainfall in the rainy season strictly. Dry years were coupled with lower total yields; wet years with higher yields, but exceptions occurred as can be seen in figure 4.10.

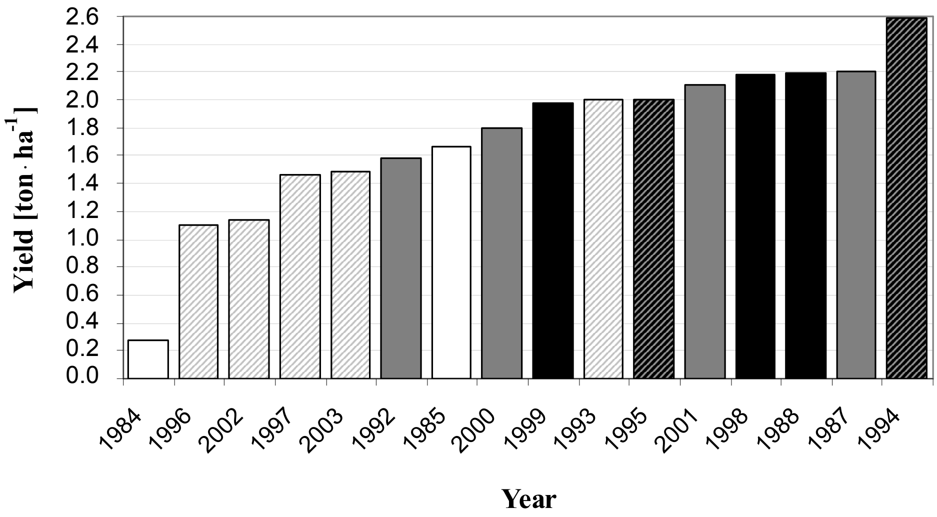


Figure 4.10: Grain yield simulation for barley in AquaCrop for different years in the period 1984-2003 □ Dry ▨ Dry (normal) ■ Normal ▩ Wet (normal) ■ Wet

Average total yield in dry years was 1.30 ton·ha^{-1}, which was significantly lower ($P \leq 0.05$) than average yield in normal (1.92 ton·ha^{-1}) or wet (2.19 ton·ha^{-1}) years. When the extreme dry year 1984 was left out of consideration, the average total yield in dry years amounted to 1.48 ton·ha^{-1}, which was still significantly lower than the average yield in normal or wet years. Between normal and wet years no significant difference in yield could be observed. Figure 4.11 illustrates these observations.

[6] Remarkable was the difference in year classification when a frequency analysis was applied to the total rainfall per year, instead of to seasonal rainfall. Several normal and wet (normal) years in this classification (with total yearly rainfall that can be assumed normal) had a dry main growing season. The limited rainfall in the main growing season was then supplemented with relative high amounts of rain in the short rainy season.

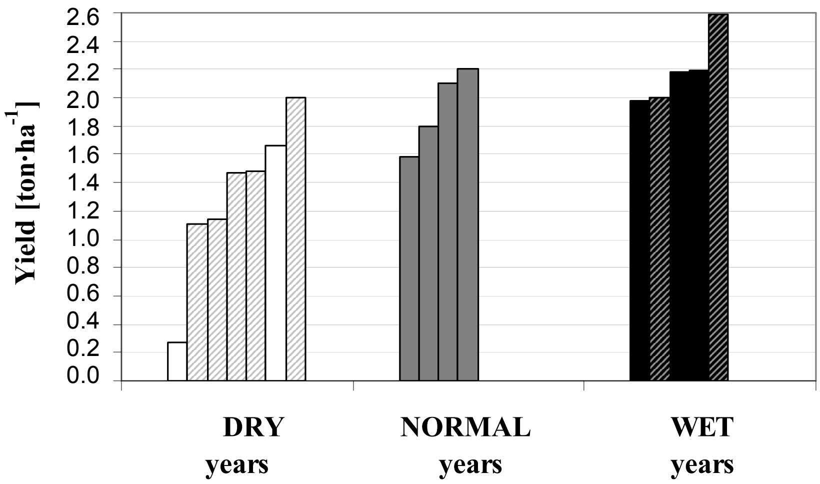


Figure 4.11: Grain yield simulation for barley in AquaCrop in dry, normal and wet years, classified by total seasonal rainfall in the period 1984-2003

□ Dry □ Dry (normal) ■ Normal ■ Wet (normal) ■ Wet

Yield simulations with the model made clear that in the main growing season, rain above roughly 400 mm rainfall did not significantly contribute to an increase of yield. This was an interesting finding within the aim to give advice to farmers. Furthermore the extreme high yield in 1994, a year with not exceptionally high rainfall, but with sufficient rain in the second half of the growing season, exemplified the fact that in combination with total rainfall, other factors (i.e. distribution) played a part in the final yield formation.

The above findings make it possible not only to review years in the past, but also to predict crop yield (for barley) based on the rainfall in the growing season.

Conclusions and recommendations

Experimental research

Throughout the whole growing season of barley and tef, parameters of both crops were collected to assess the crop response to different levels of water availability. Analysis of crop parameters revealed few significant differences for both crops between treatments with diverse levels of water supply.

In the barley field, no significant difference for any crop parameter could be observed during the growth cycle. This could be ascribed to the long time span during which treatments did not receive (distinct) water supplements, and thus developed analogously with the same water supply in the form of rainfall. Significant differences were only observed related to the final yield. With regard to 1000-grain yield, rainfed treatments yielded inferior to treatments with a surplus of water ($P < 0.05$). Concerning the total yield in tons per hectare, crops that received a water surplus after the rainy season scored better than rainfed crops. Plants with water stress showed significant higher values for water productivity than crops without stress. In the particular case of this experiment, it is doubtful that reducing water stress in sensitive crop development stages of barley can substantially increase water productivity or yield production compared to rainfed production. The early sowing date of barley and the relatively good rainy season in 2006 were jointly responsible for this phenomenon.

In the tef field, crop parameters showed more often significant differences between treatments, especially towards the end of the growing cycle when the rainy season was over and treatments differed due to the distinct surplus of water applied to plants. In general, plants without water stress (full irrigation) or with a minimum of water stress (irrigation in flowering and grainfilling stage) performed better than the remaining plants with more water stress (rainfed / only irrigation in flowering stage). This observation corroborates the assumption that plants are sensitive to water stress in flowering and grainfilling stage. With regard to total grain yield and 1000-grain yield, the crops that received a water supplement only in this two sensitive stages yielded best. In this particular experiment, irrigating tef crops during the whole growing season did not avail more yield. The highest values for water productivity were recorded for crops with mitigated water stress only in flowering stage. The quality of the rainy season (few or much rain) seemed to have less influence on the performance of crops because they were sown later in the season. Again, it is too early to reach the conclusion that the increased water productivity, realized in this experiment by moderating crop water stress in sensitive stages, can be profitable to stabilize or improve yield. More complete and long-term research in the future is recommended.

Validation of AquaCrop

The calibration of the crop water productivity model AquaCrop for barley and tef in the specific region of Tigray was carried out by simulating the soil water balance and the crop development curve of rainfed crops. Input data for climate, soil and crop characteristics in AquaCrop were determined in field experiments, or estimated after consultation of literature if no experimental results were available. A minimum of crop and soil parameters, originally gathered from field experiments, was calibrated in the model. Calibration on θ_{FC} and θ_{WP} resulted in slightly lower values for this soil water retention characteristics in the model as compared to values experimentally determined or recommended by Saxton and Rawls' pedotransfer functions (Saxton and Rawls, 2006). The calibration was justified by the observation that the weekly determination of the soil water content in the field dropped below WP (experimentally determined) at a certain moment, which is impossible in theory. The subsequent comparison of simulated values and observed experimental values for barley was very good. For tef conversely, the calibration could not lead to a good similarity between simulations and observations and output data were thus not reliable. More long-term research is requisite, for tef is a very specific crop and little is known yet about its physiology, and more specifically about its response to a (severe) water deficit.

After calibration of the model with rainfed crops, crops under irrigation were validated. A water supplement was applied to crops, which are typically cultivated under rainfed conditions to study the impact of diverse rainfall patterns. Climate, crop and soil input data for the model were kept unchanged; only the applied amount of water by irrigation was adapted. Once validated, the software model can be used in the future to predict the soil water balance, canopy development and grain yield of barley on different soil types and under different rainfall conditions and diverse management practices. For tef, AquaCrop cannot be used yet for the prediction of crop development and yield.

Crop water productivity

With the knowledge of the crop transpiration calculated by AquaCrop, it was possible to determine the CWP of barley. Analysis of the relationship between dry above-ground biomass and the cumulative ratio between T_a and ET_0 revealed a linear relation, proving the conservative nature of normalized CWP, which represents the slope of this relationship. When only crops without water stress were taken into account - and thus no assumption about the reduction of transpiration in conditions with water stress had to be made - the normalized CWP reached 11.80 $g{\cdot}m^{-2}$. The combined analysis of crops with and without water stress, fixed the CWP on 12.53 $g{\cdot}m^{-2}$. Both values lie within a reasonable interval around 13.4 $g{\cdot}m^{-2}$, the postulated value for normalized CWP of C_3-plants in literature.

The constant nature of normalized CWP - in this dissertation only proven for barley under limited water stress - rejects the possibility to improve the physiological productivity of the water consumed by crops by moderating water stress in particular crop stadia. However, the overall water productivity can be enhanced by modifying a number of other elements involved in the performance of crops related to water supply (soil evaporation, harvest index, distribution of nutrients,...), that can be subject of future research. Yet, the robustness of normalized CWP offers perspectives to move findings of research to other regions.

Future research on barley crops that experienced more severe levels of water stress is recommended, since conclusions of this dissertation could only be made for crops with relatively mild water stress as a result of the relative good rainfall in the major part of the season in 2006. Although not completely consistent because of the poor calibration of AquaCrop for tef, the observation that plants with severe water stress were responsible for the rejection of the conservative behavior of CWP in the case of tef can be seen as a suggestion to examine CWP more profoundly in situations with severe water stress.

Yield simulation

After the crop water productivity model had been successfully calibrated and validated, estimations of grain yield in the past and the future for barley in this specific agroclimatic area could be made. A frequency analysis was carried out with historical rainfall data in order to determine dry, normal and wet years. Comparison of the predicted yield and the types of years revealed that in general crops yielded less in dry years than in normal and wet years, and that the yield difference between normal and wet years was not significant. Exceptions occurred (dry years with high yields) and were indicative for the importance of rainfall distribution, next to absolute rainfall amount in regions with unreliable rainfall.

Recommendations

Next to the general recommendations for future research, formulated in the above conclusions, the following recommendations are made to improve the data collection at the experimental field level:

- Although the weather station at Mekelle University allowed to collect a complete set of climate data in the direct environment of the field experiments, a better maintenance of the station and in particular of the evaporation pan would make it possible to confirm ET_0 calculated with the software packet EToCalc.
- A series of field and laboratory experiments contributed to the valuable characterization of the soil in the experimental fields. Determination of the soil water content was carried out weekly by means of the gravimetrical method. This method delivered an adequate view on the evolution of the soil water balances of the fields, but concerning the significance of this water balance in the study of water productivity, it is recommended to follow up the soil water content more frequently to build a more complete data base.
- With regard to the collection of crop parameters (height, biomass, LAI, leaf stomatal resistance, yield), it should be advised to avoid disturbing the growing crops while cutting fresh biomass or passing through crop rows, since the interference can affect the crop development. It is recommended to apply areas in the experimental fields that will be guarded against sampling.
- Given the key role of the canopy cover development in the calibration and validation of AquaCrop, a more meticulous follow up of this canopy cover of the growing crops is recommended.
- To be able to estimate crop stress coefficients, essentially to estimate crop water productivity, a well considered series of measurements in successive phenological stages and under different conditions of water stress should be carried out with the porometer.
- It is important to devise a good method to determine the plant root depth accurately, because this parameter is of major importance to estimate the depth to which a plant can deplete water from the soil, and thus influences the water balance.

References

Acevedo, E., Craufurd, P.Q., Austin, R.B., Perez-Marco, P. (1991). Traits associated with high yield in barley in low-rainfall environments. J.Agr. Sci. 116: 23-36.

Adiku, S.G.K., Reichstein, M., Lohila, A., Dinh, N.Q., Aurela, M., Laurila, T., Lueers, J., Tenhunen, J.D. (2006). PIXGRO: A model for simulating the ecosystem CO_2 exchange and growth of spring barley. Ecol. Model. 190: 260-276.

Agegnehu, G., Ghizaw, A., Sinebo, W. (2006). Yield performance and land-use efficiency of barley and faba bean mixed cropping in Ethiopian highlands. Europ. J. Agronomy 25: 202-207.

Alemayehu, M. (2003). Ethiopia. Country Pasture/Forage Resource Profile. FAO, Rome, Italy. Available online at http://www.fao.org/ag/AGP/AGPC/doc/Counprof/Ethiopia/ Ethiopia.htm [last checked: 22-02-2007].

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. (1998). Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome, Italy. 300 p.

AQUASTAT (2007). FAO's Information System on Water and Agriculture [online]. FAO, Land and Water development division. Available at http://www.fao.org/ag/agl/aglw/ aquastat/main/index.stm [last update 2007, last visited 02/04/07].

Asner, G., Scurlock, K., Hicke, J. (2003). Global synthesis of leaf area index observations: implications for ecological and remote sensing studies. Global Ecol. Biogeogr. 122: 191-205.

Beltrando, G., Camberlin, P. (1993). Interannual variability of rainfall in the eastern horn of Africa and indicators of atmospheric circulation. Int. J. Climatol. 13: 533-546.

Berhane, G. (2003). Present and future water resources development in Ethiopia related to research and capacity building. In: Water and land management research and capacity building priorities for Ethiopia. Proceedings of an international workshop held at ILRI, Addis Ababa, Ethiopia, 2-4 December 2002. McCornick P.G., Kamara, A.B., Tadesse, G. (eds.). IWMI, Colombo, Sri Lanka, and ILRI, Nairobi, Kenya. 27-37.

Bessembinder, J.J.E., Leffelaar, P.A., Dhindwal, A.S., Ponsioen, T.C. (2005). Which crop and which drop, and the scope for improvement of water productivity. Agr. Water Manage. 73: 113-130.

Beyene, A., Gibbon, D., Haile, M. (2006). Heterogenity in land resources and diversity in farming practices in Tigray, Ethiopia. Agr. Syst. 88: 61-74.

Bhutia, N.K., Singh, G.D. (1990). Study on yield and water use efficiency of barley in response to moisture regimes and sources of nitrogen. Haryana Journal of Agronomy 6.1: 76-77.

Bot, A.J., Nachtergaele, F.O. ,Young, A. (1999). Land Resource Potential and Constraints at Regional and Country Levels. World Soil Resources Report No. 90. FAO, Rome, Italy. Available online at www.fao.org/ag/agl/agll/oldocsl.jsp [last visited 03/0307].

Briggs, D.E. (1978). Barley. Chapman and Hall Ltd., London, UK. 612 p.

Brouwer, C., Heibloem, M. (1986). Principles of irrigation water needs. In: Irrigation water management. Training manual no. 3 [online]. FAO, Rome Italy. Available at http://www.fao.org/docrep/S2022E/s2022e00.HTM [last visited 04/04/07].

Cantero-Martinez, C., Villar, J.M., Romagosa, I., Fereres, E. (1996). Growth and yield responses of two contrasting barley cultivars in a Mediterranean environment. Eur. J. Agron. 4: 317-326.

Cantero-Martinez, C., Angas, P., Lampurlanes, J. (2003) Growth, yield and water productivity of barley (Hordeum vulgare L.) affected by tillage and N fertilization in Mediterranean semiarid, rainfed conditions of Spain. Field Crop. Res. 84: 341-357.

CIA (2007). World Factbook 2007 [online]. Central Intelligence Agency (CIA). Available at https://www.cia.gov/cia/publications/factbook/geos/et.html [last update 08/02/07, last visited 22/02/07].

Conway, D. (2000). Some aspects of climate variability in the North East Ethiopian highlands - Wollo and Tigray. Sinet: Ethiopian Journal of Science 23: 139-161.

Cosgrove, W.J. (2003). Water security and peace. A synthesis of studies prepared under the PCCP-Water for Peace process. UNESCO, Paris, France. 108 p. Available online at http://unesdoc.unesco.org/images/0013/001333/133318e.pdf [last visited 03/04/2007].

CSA (2006). Central Statistics Agency of Ethiopia [online]. Available at http://www.csa.gov.et/ [last update 10/07-/06, last visited 26/02/07].

Deckers, J., Yizengaw, T., Negeri, A., Ketema, S. (2001). Eragrostis tef (Zuc.) Trotter. In: Crop production in Tropical Africa. Raemaekers R.H. (ed.), Directorate General for International Co-operation, Brussels, Belgium. 96-101.

Delta-T Devices Ltd.. AP4 Porometer UM v3: instruction manual. Cambridge, UK.

Dejene, A. (2003). Integrated Natural Resources Management to Enhance Food Security. The Case for Community-Based Approaches in Ethiopia. Envrionment and Natural Resources Working Paper no. 16. FAO, Sustainable Development Department, Rome, Italy. 58 p. Available online at http://www.fao.org/DOCREP/005/Y4818E/y4818e00.htm#Contents [last visited 04/04/07].

DPPA (2007). Disaster Prevention and Preparedness Agency. Map center. [online]. Available at http://www.dppc.gov.et/pages/Maps.htm [last udate 2007 , last checked 02/04/07].

Doorenbos, J., Kassam, A.H. (1979). Yield Response to Water. FAO Irrigation and Drainage Paper No. 33. FAO, Rome, Italy. 193 p.

Ecocrop (2003). Ecocrop. Plant Production and Protection Information System [online]. FAO. Available at http://ecocrop.fao.org/ [last update: 28/01/03, last checked 27/02/07].

EcoPort (2006). Ecoport. The consilience engine [online]. Cooperation between the University of Florida, the FAO and the National Museum of Natural History (NMNH) of the Smithsonian Institution. Available at http://ecoport.org [last update 17/11/06, last visited 02/02/07].

Eylachew, Z. (1994). Properties of major soils of Ethiopia. Report on National Soil Reference Collection. FAO/UNDP, Addis Ababa, Ethiopia.

FAO (2002). Crops and Drops. Making the best use of water for agriculture. FAO, Rome, Italy. 26 p. Available online at ftp://ftp.fao.org/docrep/fao/005/y3918E/y3918e00.pdf [last visited 03/04/07].

FAO (2003a). Agriculture, food and water. FAO, Rome, Italy. 69 p. Available online at http://www.fao.org/docrep/006/y4683e/y4683e00.htm [last visited 24/02/07].

FAO (2003b). Ministrial Meeting on Water for Food and Agriculture. Issue Paper. FAO, prepared jointly by the Ministry of Agriculture, Forestry and Fisheries of Japan and the Land and Water Development Division of the Food and Agriculture Organization of the United Nations, Rome, Italy. 21 p. Available online at ftp://ftp.fao.org/docrep/fao/005/y4607e/y4607e00.pdf [last visited 02/04/07].

FAO (2003c). Unlocking the Water Potential of Agriculture. FAO, Rome, Italy. 70 p. Available online at http://www.fao.org/docrep/006/y4525e/y4525e00.htm#Contents [last visited 02/04/07].

FAO (2005). Special Report Ethiopia - January 2005. Mission to Ethiopia. 28 January 2005. FAO/WFP Crop and Food Supply, Rome, Italy. 35 p. Available online at http://www.fao.org/docrep/007/J3958e/J3958e00.htm [last visited 04/04/07].

FAO/ISRIC/IUSS (2001). Lecture notes on the Major Soils of the World. World Resources Reports 94, FAO, Rome, 334 p.

FAOSTAT (2006). FAOSTAT, FAO Statistical Data [online]. FAO. Available at http://www.fao.org/faostat/foodsecurity/ [last update 2006, last visited 04/04/07].

Fetch, T.G., Steffenson, B.J., Pederson, V.D. (2003). Predicting agronomic performance of barley using canopy reflectance data. Can. J. Plant Sci. 84: 1-9.

Gebeyehu, A. (2003). Research and development in land and water resources. In: Water and land management research and capacity building priorities for Ethiopia. Proceedings of an international workshop held at ILRI, Addis Ababa, Ethiopia, 2-4 December 2002. McCornick P.G., Kamara, A.B., Tadesse, G. (eds.). IWMI, Colombo, Sri Lanka, and ILRI, Nairobi, Kenya. 3-10.

Gonzalez, A., Martin, I., Ayerbe, L. (1999). Barley yield in water-stress conditions. The influence of precocity, osmotic adjustment and stomatal conductance. Field Crop. Res. 62: 23-34.

Gregory, P.J., Tennant, D., Belford, R.K. (1992). Root and shoot growth, and water and light use efficiency of barley and wheat crops grown on a shallow duplex soil in a Mediterranean-type environment. Austr. J. Agr. Res. 43: 555-573.

Gunasekera, D., Santakumari,M., Glinka, Z., Berkowitz, G.A. (1994). Wild and cultivated barley genotypes demonstrate varying ability to acclimate to plant water deficits. Plant Sci. 99: 125-134.

Hagos, E.Y. (2005). Development and Management of Irrigated Lands in Tigray, Ethiopia. Dissertation for the Degree of Doctor. Wageningen University and the UNESCO-IHE Institute for Water Education. Delft, the Netherlands. 265 p.

Hailu, G., Van Leur, J. (eds.) (1996). Barley Research in Ethiopia. Past Work and Future Prospects. Proceedings of the First Barley Research Review Workshop, 16-19 october 1993, Addis Abeba. IAR/ICARDA, Addis Abeba, Ethiopia. 195 p.

Hailu, T., Getachaw. B., Sorrells, M. (eds) (2001). Narrowing the Rift. Tef Research and Development. Proceeding of the International Workshop on Tef Genetics and Improvement, 16-19 October 2000. Ethiopian Agricultural Research Organization, Addis Abeba, Ethiopia.

Haregeweyn, N., Poesen, J., Nyssen, J., De Wit, J., Haile, M., Govers, G., Deckers, J. (2006). Reservoirs in Tigray (northern Ethiopia): Characteristics and Sediment Deposition Problems. Land Degrad. Dev. 17: 211-230.

ISO 11277 (1998). Soil Quality - Determination of particle size distribution in mineral soil material - Method by sieving and sedimentation. International Organization for Standardization. Geneva, Switzerland. 30 p.

IWMI (2000). World water supply and demand: 1995-2025. IWMI, Colombo, Sri Lanka. 29 p. Available online at http://www.iwmi.cgiar.org/ [last visited 03/04/07].

IWMI (2006). Annual Report 2005/2006. IWMI, Colombo, Sri Lanka. 51 p. Available online at http://www.iwmi.cgiar.org/ [last visited 03/04/07].

Jayne, T.S., Yamano, T., Weber, M.T., Tschirley, D., Benfica, R., Chapoto, A., Zulu, B. (2003). Smallholder income and land distribution in Africa: implications for poverty reduction strategies. Food Policy 28: 253-275.

Kebebew, A., Hailu, T., Arnulf, M., Tiruneh, K., Fufa, H. (2001). Quantitative trait diversity in tef [Erasgrostis tef (Zucc.) Trotter] germplasm from Central and Northern Ethiopia. Genet. Resour. Crop Ev. 48: 53-61.

Kessler J. and Oosterbaan R. J. (1974). Determining hydraulic conductivity of soils. In: Drainage Principles and Applications. de Ridder, N. A., Takes, C. A. P., van Someran, C. L., Bos, M. G., Messemaekers van de Graaf R. H., Bokkers A. H. F.. International Institute for Land Reclamation & Improvement, Wageningen, the Netherlands. 292-294.

Ketema, S. (1993). Tef (Erasgrostis tef): breeding, genetic resources, agronomy, utilization and role in Ethiopian agriculture. IAR, Addis Abeba, Ethiopia. 102 p.

Ketema, S. (1997). Tef [Eragrostis tef (Zucc.) Trotter]. Promoting the conservation and use of underutilized and neglected crops. 12. Insitute of Plant Genetics and Crop Plant Research, Gatersleben / International Plant Genetic Resources Insititute, Rome, Italy. 47 p.

Körner, C., Scheel, J.A., Bauer, H. (1979). Maximum Leaf Diffusive Conductance in Vascular Plants. Photosynthetica 13: 45-82.

LI-COR Inc. (1992). LAI-2000 Plant Canopy Analyzer: instruction manual. Lincoln Nebraska, USA.

Loague, K. and Green, R.E. (1991). Statistical and graphical methods for evaluating solute transport models: Overview and application. J. Contam. Hydrol. 7: 51-73.

Lopes, M.S., Nogues, S., Araus, J.L. (2004). Nitrogen source and water regime effects on barley photosynthesis and isotope signature . Funct. Plant Biol. 31: 995-1003.

Lopez, M.V., Arrue, J.L. (1997). Growth, yield and water use efficiency of winter barley in response to conservation tillage in a semi-arid region of Spain. Soil Til. Res. 44: 35-54.

MacGregor, A.W., Bhatty, R.S. (eds) (1993). Barley: Chemistry and Technology. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA. 486 p.

Mathre, D.E. (ed.) (1997). Compendium of Barley Diseases. The American Phytopathological Society. St Paul, Minnesota, USA. 90 p.

Mees M. (2000) Zoom microfinance. SOS Faim, Brussels, Belgium. Available online at http://sosfaim.org/pdf/en/zoom/ZoomDecsiEng.pdf [last visited 04/04/07].

Meinzen-Dick, R.S., Rosegrant, M.W. (eds.) (2001). 2020 Focus 9: Overcoming Water Scarcity and Quality Constraints. IFPRI, Washington, USA. 28 p. Available online at http://www.ifpri.org/2020/focus/focus09.asp#dl [last visited 02/04/07].

Mitchell, J.H., Fukai, S., Cooper, M. (1996). Influence of phenology on grain yield variation among barley cultivars grown under terminal drought. Aust. J. Agr. Res. 47: 757-774.

Mulat D., Ali S., Jayne T.S. (1997). Promoting fertilizer use in Ethiopia: the implications of improving grain market performance, input market efficiency and farm management. Working paper 5. Grain market research project. Ministry of economic development and cooperation, Addis Ababa, Ethiopia.

NRC, Board on Science and Technology for International Development (1996). Lost Crops of Africa: Volume I: Grains. National Academy Press, Washington DC, USA.

Ntech Industries Inc.. GreenSeeker Hand Held Optical Sensor Unit, Model 505: instruction manual. Ukiah, California, USA.

Nyssen, J., Poesen, J., Moeyersons, J., Deckers, J., Haile, M., Lang, A. (2004). Human impact on the environment in the Ethiopian and Eritrean highlands - a state of the art. Earth-Sci. Rev. 64: 273-320.

Nyssen, J., Vandenreyken, H., Poesen, J., Moeyersons, J., Deckers, J., Mitiku, H., Salles, C., Govers, G. (2005). Rainfall erosivity and variability in the Northern Ethiopian Highlands. J. Hydrol. 311: 172-178.

Ortega, J.F., de Juan, J.A., Tarjuelo, J.M. (2004). Evaluation of the water cost effect on water resource management: Application to typical crops in a semiarid region. Agr. Water Manage 66: 125-144.

Oweis, T., Hachum, A. (2006). Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. Agr. Water Manage. 80: 57-73.

Oweis, T., Pala, M., Ryan, J. (1998). Stabilizing rainfed wheat yields with supplemental irrigation and nitrogen in a Mediterranean climate. Agron. J. 90 5: 672-681.

Pereira, L.S., Oweis, T., Zairi, A. (2002). Irrigation Management under Water Scarcity. Agr. Water Manage. 57: 175-206.

Raes, D. (1995). Note on Irrigation Requirement. FAO, Rome, Italy. 24 p.

Raes, D. (2001). Water balance of a cropped soil, syllabus. K.U.Leuven, Leuven, Belgium. 79 p.

Raes, D. (2006). EToCalc version 2.1. Reference evapotranspiration calculator: instruction manual. FAO, Rome, Italy.

Raes, D., Geerts, S., Kipkorir, E., Wellens, J., Sahli, A. (2006a). Simulation of yield decline as a result of water stress with a robust soil water balance model. Agr. Water Manage. 81: 335-357.

Raes, D., Mallants, D., Song Z. (1996). Rainbow - a software package for analysing hydrologic data. In: Hydraulic Engineering Software VI. Blain, W.R. (ed.). Computational Mechanics Publications, Southampton, U.K.. 525-534.

Raes, D., Sithole, A., Makarau, A., Milford, J. (2004). Evaluation of first planting dates recommended by criteria currently used Zimbabwe. Agr. Forest Meteorol. 125: 177-185.

Raes, D., Steduto, P., Hsiao, T.C., Fereres, E. (2006b). Structure, algorithms and functionalities of AquaCrop. Proceedings of International Symposium on Water and Land Management for sustainable irrigated agriculture, April 4-8 2006, Cukurova University, Adana, Turkey. 13p.

Rijsberman, F.R., Manning, N. (2006). Beyond More Crop per Drop. Water Management for Food and the Environment. 4th World Water Forum, 16-22 March, 2006, Mexico. IWMI, Colombo, Sri Lanka. 18 p. Available online at http://www.iwmi.cgiar.org/ [last visited 03/04/07].

Ritchie, J. T. (1974). Evaluating irrigation needs for southeastern USA. In:. Proceedings of the Irrigation and Drainage Special Conference. ASCE, New York, USA. 262-273.

Sanchez-Diaz, M., Garcia, J.L., Antolin, M.C., Araus, J.L. (2002). Effects of soil drought and atmospheric humidity on yield, gas exchange, and stable carbon isotope composition of barley. Photosynthetica 40: 415-421.

Savin, R., Nicolas, M. E. (1996). Effects of short periods of drought and high temperature on grain growth and starch accumulation of two malting barley cultivars. Austr. J. Plant Physiol. 23: 201-210.

Saxton, K.E., Rawls, W.J. (2006). Soil water charateristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70: 1569-1578.

Schelling, K., Born, K., Weissteiner, C., Kühbauch, W. (2003). Relationships between yield and quality parameters of malting barley (Hordeum vulgare L.) and phenological and meteorological Data. J. Agron. Crop Sci. 189: 113-122.

Scott, B.J., Conyers, M.K., Poile, G.J., Cullis, B.R. (1997). Subsurface adidity and liming affect yield of cereals. Austr. J. Agr. Res. 48: 843-854.

SCS (US Soil Conservation Service) (1972). National Engineering Handbook, Hydrology section. 4 GPO, US Department of Agriculture, Washington DC, USA.

Sepaskhah, A.R., Ghahraman B. (2004). The effects of irrigation efficiency and uniformity coefficient on relative yield and profit for deficit irrigation. Biosyst. Eng. 87: 495-507.

Sinebo, W. (2005). Trade off between yield increase and yield stability in three decades of barley breeding in a tropical highland environment. Field Crop. Res. 92: 35-52.

SPSS Inc. (2004). SPSS 13.0 Computer Statistics Software: instruction manual. Chicago, USA.

Steduto, P. (1996). Water use efficiency. In: Sustainability of Irrigated Agriculture. Pereira, L.S., Feddes, R.A., Gilley, J.R., Lesaffre, B. (eds.) (2002). Kluwer Academic Publishers, Dordrecht. 193-209.

Steduto, P., Fereres, E., Hsiao, T.C., Raes, D. (2006). Yield Response to Water: The FAO revision framework and the crop-water producitivity model AquaCrop. Proceedings of International Symposium on Water and Land Management for sustainable irrigated agriculture, April 4-8 2006, Cukurova University, Adan, Turkey. 11 p.

Steduto, P., Hsiao, T.C., Fereres, E. (2007). On the conservative behavior of biomass water productivity. Irrig. Sci. 25: 189-207.

Swain, A. (1997). Ethiopia, the Sudan, and Egypt: The Nile River Dispute. J. Mod. Afr. Stud. 35: 675-694.

Swinnen, J., Maertens M. (2006). Problemen van de ontwikkelingslanden, syllabus. K.U.Leuven, Faculteit Economische en Toegepaste Economische Wetenschappen, Leuven, Belgium.

Tadesse, N. (2006). Surface Waters Potential of the Hantebet Basin, Tigray, Northern Ethiopia [online]. Agricultural Engineering International: CIGR Ejournal. Available at: http://cigr-ejournal.tamu.edu/submissions/volume8/LW%2005%20010%20Tadasse%20final %2016April2006.pdf [last visited 27/02/07].

TERRASTAT (2003). Terrastat. Land resource potential and constraints statistics at country and regional level [online]. FAO, Land and Water development division. Available at www.fao.org/ag/agl/agll/terrastat, last update 06/02/03, last visited 26/02/07].

Tesfaye, G., Haile, M., Gebremedhin, B., Pender, J., Yazew, E. (2000). Small-scale irrigation in Tigray: management and institutional considerations. In:Policies for sustainable land management in the highlands of Ethiopia: summary of papers and proceedings of a seminar held at ILRI, Addis Ababa, Ethiopia, 22-23 May 2000. ILRI Socio-economics and Policy Research Working Paper 30. Jabbar, M.A., Pender, J., Ehui, S.K. (eds.), (2003). ILRI, Nairobi, Kenya. 27-30. Available online at http://www.ilri.cgiar.org/Infoserv/webpub/ Fulldocs/WP30/small.htm#TopOfPage [last visited 26/03/07].

Tesfaye, K., Walker, S. (2004). Matching of crop and environment for optimal water use: the case of Ethiopia. Phys. Chem. Earth 29: 1061-1067.

Tollens, E. (2004). Het Voedselvraagstuk. In: Voedsel voor 9 miljard mensen. Perspectieven op landbouw en wereldvoedselvoorziening. Schoonheydt, R., Waelkens, S (eds.). Lannoo Campus, Leuven, Belgium. 192 p.

UNDP (2006). Human Development Report 2006. UNDP, New York, USA. 423 p. Available online at http://hdr.undp.org/hdr2006/ [last visited 02/04/07].

UNESCO (2004). World Water Assessment Program. National Water Development Report for Ethiopia (Final). Addis Abeba, Ethiopia, December 2004. 273 p. Available online at http://unesdoc.unesco.org/images/0014/001459/145926E.pdf [last visited 27/02/07].

UN-Water (2006). Coping with Water Scarcity. A strategic issue and priority for system-wide action. UN-Water, New York, USA. 12 p. Available online at ftp://ftp.fao.org/agl/aglw/docs/waterscarcity.pdf [last visited 02/04/07].

Vanoosterom, E.J., Acevedo, E. (1992). Adaptation of barley (Hordeum vulgare L.) to harsh Mediterranean environments. I. Morphological traits. Euphytica 62: 1-14.

Vavilov, N.I. (1951). The origin, variation, immunity and breeding of cultivated plants, Chronica Botanica 13: 1-366.

Vörösmarty C.J., Green, P., Salisbury J., Lammers, R.B. (2000). Global water resources: vulnerability from climate change and population growth. Science 289: 284-288.

Zhang, H., Oweis, T. (1999). Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. Agr. Water Manage 38: 195-211.

Zwart, S.J., Bastiaanssen, W.G.M. (2004). Review of measure crop water productivity values for irrigated wheat, rice, cotton and maize. Agr. Water Manage 69: 115-133.

Appendix I

Comparison of crop features for tef, maize, barley and faba bean

Table I.1: Comparison between four major food crops in Ethiopia (Source: Hailu *et al.*, 2001)

Criterium	**Crop**			
	Tef	**Maize**	**Barley**	**Faba bean**
Yield	3.46	3.37	**3.94**	2.70
Food quality	**4.89**	3.39	3.38	2.87
Drought tolerance	**3.99**	3.32	3.70	2.79
Labour requirement	3.03	3.73	3.55	**4.42**
Performance on poor soil	3.54	2.59	**3.55**	3.47
Duration to maturity	3.18	4.21	**4.87**	3.44
Contribution to soil fertility	2.56	3.64	3.37	**4.76**
Residue importance	**4.96**	3.23	3.67	2.00
Tillage requirement	2.81	3.87	2.96	**4.77**
Storability	**4.36**	2.52	2.59	2.08
Grand mean	**3.72**	3.34	3.53	3.30
Overall rank	**1**	3	2	4

Appendix II

Applied irrigation doses

Table II.1: Applied irrigation doses - barley

Date	Days after sowing	Phenological stage	Irrigation depth [mm]	Treatment T1	T2	T3	T4
12/09/2006	65	Heading	15.87	x			
15/09/2006	68	Heading	15.87	x			
18/09/2006	71	Flowering	15.87	x		x	x
21/09/2006	74	Flowering	15.87	x		x	x
24/09/2006	77	Flowering	15.87	x		x	x
27/09/2006	80	Grainfilling	15.87	x			x
30/09/2006	83	Grainfilling	16.10	x			x
03/10/2006	86	Grainfilling	16.10	x			x
06/10/2006	89	Grainfilling	16.10	x			x
10/10/2006	93	Ripening	8.59	x			
12/10/2006	95	Ripening	10.74	x			
15/10/2006	98	Ripening	7.51	x			

Table II.2: Applied irrigation doses - tef

Date	Days after sowing	Phenological stage	Irrigation depth [mm]	Treatment T1	T2	T3	T4
12/09/2006	37	Booting	10.74	x			
14/09/2006	39	Booting	10.74	x			
16/09/2006	41	Booting	10.74	x			
18/09/2006	43	Heading	10.74	x			
20/09/2006	45	Heading	10.74	x			
22/09/2006	47	Heading	10.74	x			
24/09/2006	49	Flowering	10.74	x		x	x
26/09/2006	51	Flowering	10.74	x		x	x
28/09/2006	53	Flowering	10.74	x		x	x
30/09/2006	55	Flowering	10.74	x		x	x
2/10/2006	57	Flowering	10.74	x		x	x
4/10/2006	59	Flowering	10.74	x		x	x
6/10/2006	61	Grainfilling	10.74	x			x
8/10/2006	63	Grainfilling	10.74	x			x
11/10/2006	66	Grainfilling	10.74	x			x
14/10/2006	69	Grainfilling	10.74	x			x
16/10/2006	71	Grainfilling	10.74	x			x
18/10/2006	73	Grainfilling	10.74	x			x
20/10/2006	75	Grainfilling	10.74	x			x
22/10/2006	77	Grainfilling	10.74	x			x
24/10/2006	79	Grainfilling	10.74	x			x
26/10/2006	81	Grainfilling	10.74	x			x
28/10/2006	83	Grainfilling	10.74	x			x
30/10/2006	85	Grainfilling	10.74	x			x
1/11/2006	87	Grainfilling	10.74	x			x
3/11/2006	89	Grainfilling	10.74	x			x
5/11/2006	91	Grainfilling	10.74	x			x
7/11/2006	93	Ripening	10.74	x			
9/11/2006	95	Ripening	9.66	x			
11/11/2006	97	Ripening	9.66	x			
13/11/2006	99	Ripening	8.59	x			
15/11/2006	101	Ripening	7.51	x			
17/11/2006	103	Ripening	6.44	x			
19/11/2006	105	Ripening	5.37	x			
21/11/2006	107	Ripening	5.37	x			

Appendix III

Observed vs. simulated water content in the root zone

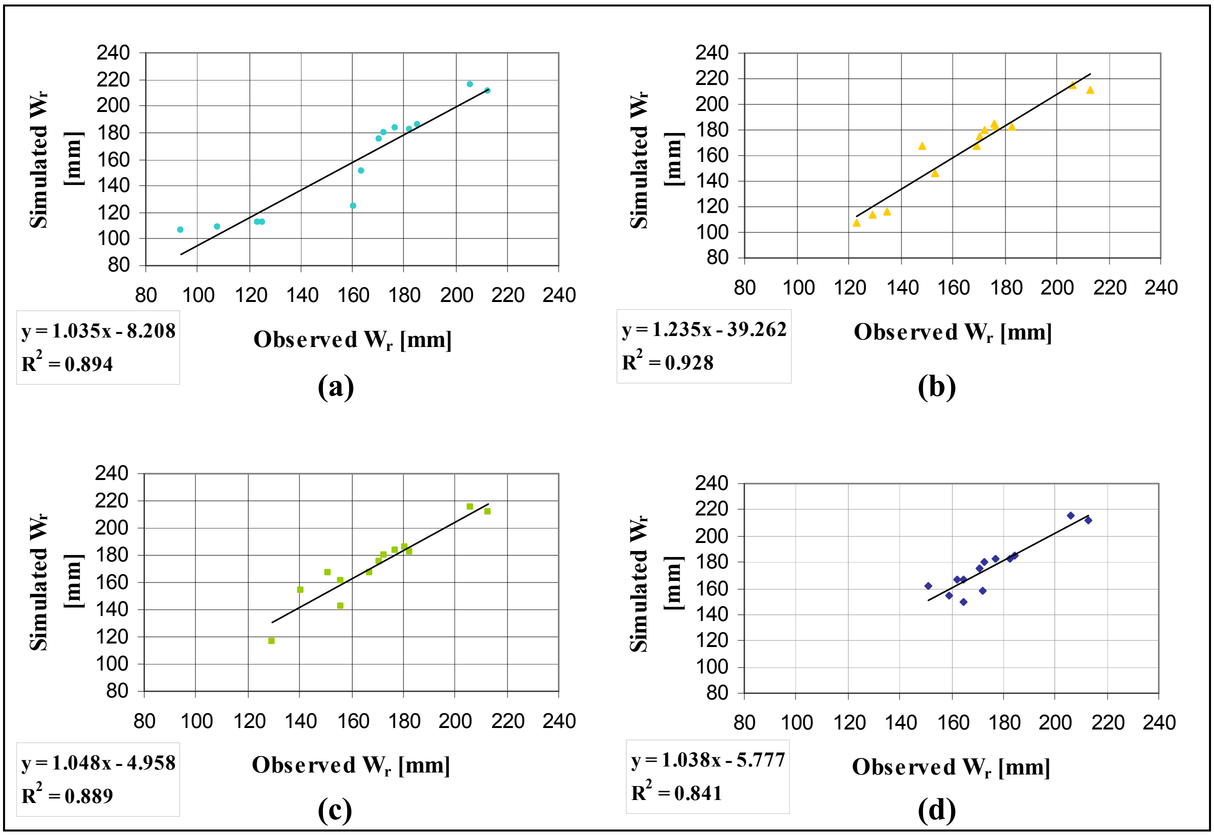


Figure III.1: Observed vs. simulated water content in the root zone (W_r) for different irrigation treatments - barley: (a) Rainfed - (b) Irrigation only in flowering - (c) Irrigation only in flowering and grainfilling - (d) Full irrigation.

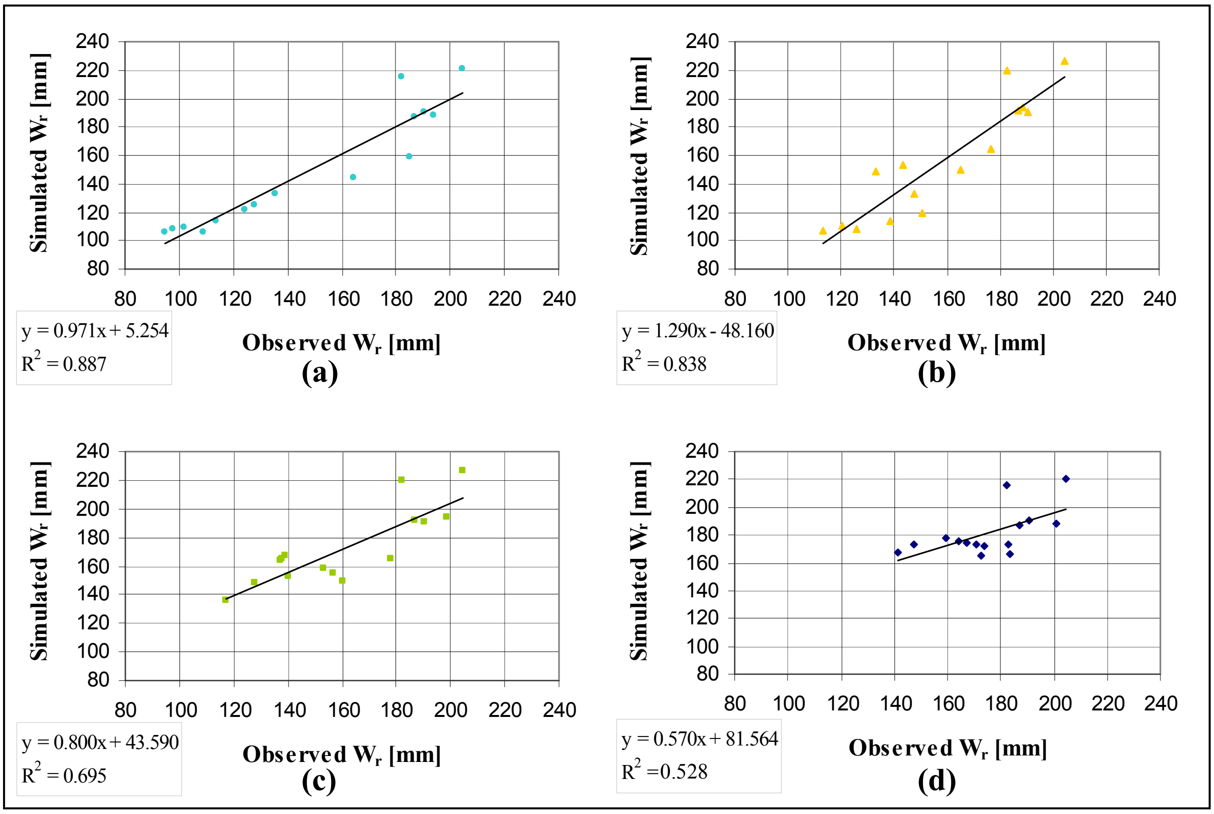


Figure III.2: Observed vs. simulated water content in the root zone (W_r) for different irrigation treatments - tef: (a) Rainfed - (b) Irrigation only in flowering - (c) Irrigation only in flowering and grainfilling - (d) Full irrigation.

Appendix IV

Crop parameters as input for AquaCrop

Table IV.1: Crop parameters as input in AquaCrop - barley

Parameter	Value
CC_0 [%]	1.40
Max. CC [%]	81
CGC [%·day^{-1}]	0.16
Full canopy [days after sowing]	57
Flowering period [days after sowing]	60 - 75
Kc coefficient [-]	1.15
Rooting depth in initial and mid-stage [m]	0.3 - 0.5
Soil water depletion factor (p) for stress related to leaf expansion growth [-]	0.30 - 0.60
Soil water depletion factor (p) for stress related to stomatal closure [-]	0.55 - 1.00
Soil water depletion factor (p) for stress related to early canopy senescence[-]	0.85 - 1.00
Crop water productivity [g·m^{-2}]	14.0
Harvest index [%]	23

Table IV.2: Crop parameters as input in AquaCrop - tef

Parameter	**Value**
CC_0 [%]	1.20
Max. CC [%]	68
CGC [%·day^{-1}]	0.11
Full canopy [days after sowing]	80
Flowering period [days after sowing]	49 - 59
Kc coefficient [-]	0.85
Rooting depth in initial and mid-stage [m]	0.2 - 0.5
Soil water depletion factor (p) for stress related to leaf expansion growth [-]	0.22 - 0.80
Soil water depletion factor (p) for stress related to stomatal closure [-]	0.22 - 1.00
Soil water depletion factor (p) for stress related to early canopy senescence[-]	0.98 - 1.00
Crop water productivity [g·m^{-2}]	28.0
Harvest index [%]	8

Appendix V

Observed vs. simulated canopy cover

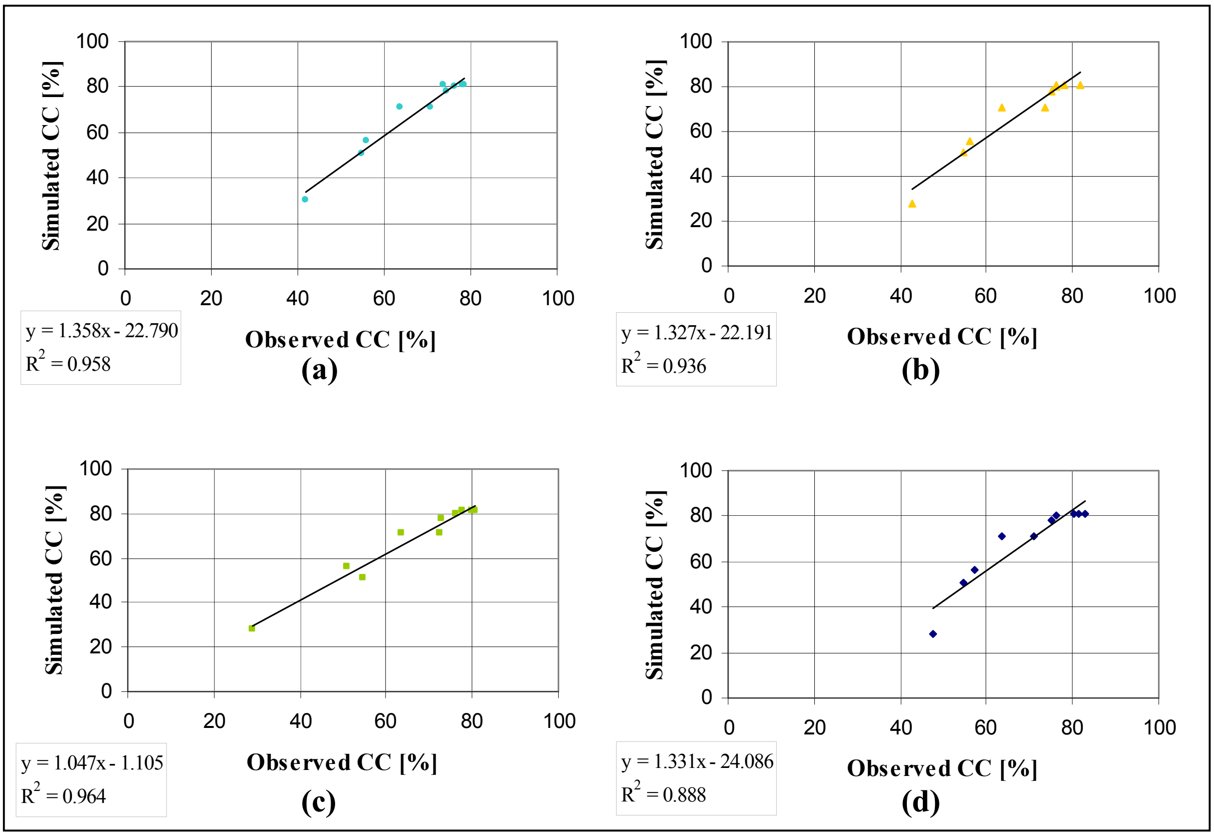


Figure V.1: Observed vs. simulated canopy cover for different irrigation treatments - barley: (a) Rainfed - (b) Irrigation only in flowering - (c) Irrigation only in flowering and grainfilling - (d) Full irrigation.

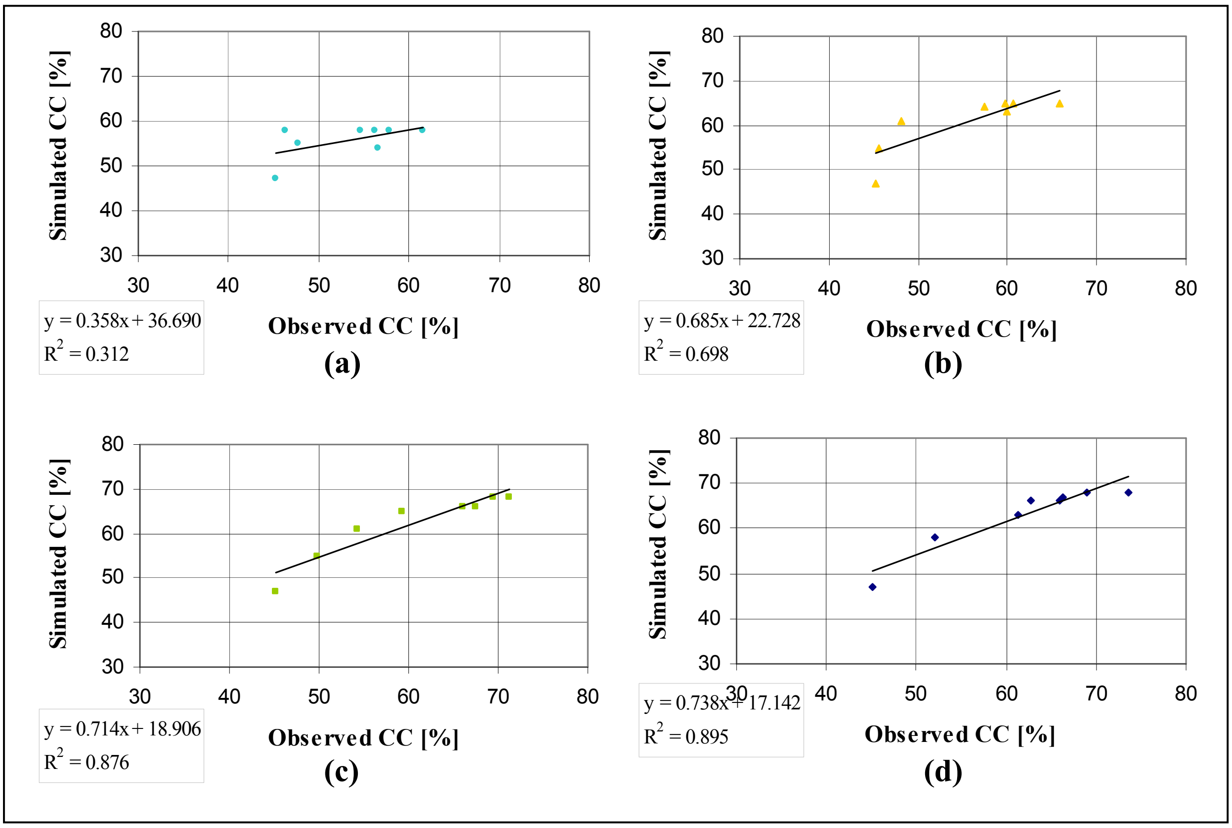


Figure V.2: Observed vs. simulated canopy cover for different irrigation treatments - tef: (a) Rainfed - (b) Irrigation only in flowering - (c) Irrigation only in flowering and grainfilling - (d) Full irrigation.

Summary in Dutch - Nederlandstalige samenvatting

Inleiding

Water is een van de belangrijkste natuurlijke hulpbronnen op aarde. Niet duurzaam gebruik en een toenemende bevolkingsdruk maken water vandaag ook een schaarse bron, waarmee zorgvuldig moet omgesprongen worden. Oorzaken voor het tekort aan water zijn veelvuldig en divers. Enkel een krachtdadige en wetenschappelijk onderbouwde aanpak van het schaarsteprobleem kunnen een antwoord bieden op het huidige water- en voedselveiligheidsvraagstuk.

Deze studie verdiept zich in strategieën voor duurzaam watergebruik. Meer specifiek wordt het concept *waterproductiviteit* bestudeerd en dit in de context van landbouw in (semi-) aride gebieden, waar regenval onregelmatig en onbetrouwbaar is. De bevolking in deze regio's is voor hun dagelijks bestaan vaak aangewezen op regengevoede landbouw. De slogan «more crop per drop» vertegenwoordigt het doel van het waterproductiviteitsonderzoek: nagaan hoe de biomassaproductie van een plant gemaximaliseerd kan worden per eenheid toegediend water (regen of irrigatie).

Gerst en tef, typische landbouwgewassen in de hooglanden van Tigray (Ethiopië) leenden zich perfect voor deze studie. Een veldexperiment werd opgezet op de campus van de Universiteit van Mekelle (13.30 °N, 39.29 °O). Experimentele resultaten van veld- en laboratoriumwerk dienen als toets voor de ijking van het waterproductiviteitmodel AquaCrop.

De doelstelling van dit eindwerk houdt in:

- de **bepaling van de waterproductiviteit van gerst en tef** , evenals
- het maken van **schattingen van de oogst van gerst en tef in jaren met verschillende neerslagpatronen**.

Na degelijke ijking en validatie van AquaCrop zal het in de toekomst mogelijk zijn om flexibele en eenvoudige richtlijnen uit te schrijven voor boeren in de (semi-)aride regio met als oogmerk de verbetering van de productiviteit van gerst en tef bij wisselende weerkarakteristieken.

Waterproductiviteit: ontvouwing van het concept

Waterschaarste is een wereldwijd probleem en ligt aan de bron van de noodzaak voor de ontwikkeling en verbetering van duurzame technologieën inzake waterbeheer. In de landbouw vormt het begrip *waterproductiviteit* een sleutelbegrip in deze strategie. Waterproductiviteit, uitgedrukt in kg·m^{-3} wordt gedefinieerd als de verhouding:

$$\frac{\textbf{totale hoeveelheid droge biomassa, geproduceerd door gewas, geschikt om te verkopen}}{\textbf{totale hoeveelheid water, afkomstig van verschillende bronnen, opgenomen door gewas}}$$

Steduto *et al.* (2007) gaan dieper in op de definitie van water productiviteit en formuleren deze als:

$$\frac{\textbf{totale hoeveelheid droge biomassa geproduceerd door gewas}}{\textbf{totale hoeveelheid water getranspireerd door gewas}}$$

Deze relatie benadrukt de afhankelijkheid van waterproductiviteit van de evaporatieve eis van de atmosfeer. Wanneer gecorrigeerd wordt voor deze klimaatafhankelijke variabele, wijzen Steduto *et al*. (2007) op het constant karakter van waterproductiviteit. Waterproductiviteit zou bovendien niet enkel onveranderlijk zijn voor één gewas, maar ook voor een groep van gewassen (C_3 tegenover C_4 planten) (zie figuur 2.2).

Het onveranderlijk karakter van gewassen betekent een barrière voor de verbetering van de productiviteit van water dat getranspireerd wordt door planten. Toch kan de lange keten die loopt van het toedienen van water in de vorm van regen of irrigatie tot aan de uiteindelijke gewasopbrengst positief beïnvloed worden door in te spelen op andere factoren (Steduto *et al.*, 2007). Oog voor de graad van gewasgevoeligheid in verschillende ontwikkelingsstadia is hier van groot belang. Planten kennen immers groeiperiodes die gevoeliger zijn voor stressfactoren dan andere. De bloeiperiode en de periode waarin de granen zich vormen, worden aangenomen als de meest precaire periodes in de gewasgroei. Watertekort in deze periodes staat dan ook een goed oogstresultaat in de weg. Anderzijds zijn planten bestand tegen een milde vorm van waterstress, aangenomen dat de periodes waarin watertekort optreedt niet samenvallen met gevoelige fenologische stadia. Planten die over te weinig water beschikken om in al hun behoeften te voorzien, hebben een lagere opbrengst. De mate waarin de opbrengst afneemt ten opzichte van de potentiële opbrengst is in grote mate afhankelijk van de periode waarin watertekort optreedt. Doorenbos and Kassam (1979) stellen dat het mogelijk en voordelig is om de waterproductiviteit van gewassen wezenlijk te verhogen door de planten slechts van een beperkte hoeveelheid water te voorzien, op voorwaarde dat de afname in oogstopbrengst kleiner is dan de vermindering in transpiratie die er mee gepaard gaat. In deze studie werden de onderzochte planten onderworpen aan verschillende niveaus van waterbeschikbaarheid om na te gaan wat de impact hiervan is op waterproductiviteit en gewasontwikkeling.

Studiegebied: Tigrayhoogvlakte in Ethiopië

Het onderzoek van deze studie concentreert zich in de Tigray-hoogvlakten van Ethiopië. Ethiopië ligt omsloten door buurlanden in de Hoorn van Afrika (zie figuur 2.3). Landbouw draagt de economie van het land, maar de sector is erg afhankelijk van onbetrouwbare en onregelmatige neerslag. Droogtes betekenen een catastrofe voor meer dan 80 % van de bevolking die tewerk gesteld is in de agrarische sector. Hongersnood is een dagelijks gegeven voor een groot deel van de bijna 75 miljoen tellende bevolking.

In de meest noordelijke provincie Tigray (12°15’ N - 14°50’ N, 36°27’ E - 39°59’ E) wordt het nationale beeld nog uitvergroot (zie figuur 2.4). De regio, die 3,3 miljoen inwoners telt, is de meest voedselonzekere van Ethiopië. De groei van het bruto nationaal product blijft onder het nationaal gemiddelde, en ligt beneden de jaarlijkse bevolkingsaanwas. Het dient nogmaals beklemtoond dat de onregelmatigheid en onbetrouwbaarheid van de neerslag het klimaat in Ethiopië kenmerken. De neerslag vertoont een bimodaal patroon: 80 % van de regen valt in het belangrijkste regenseizoen van juni tot midden september (zie figuur 2.6). Jaarlijks valt er tussen 450 en 980 mm neerslag. Landbouw staat in voor het levensonderhoud van de meest inwoners van Tigray. De landbouwbedrijfjes zijn kleinschalig en verbouwen graan- en peulgewassen. Oogsten zijn laag door een gebrek aan mechanisatie, meststoffen en andere productiemiddelen.

Ondanks terugkerende droogtes draagt Ethiopië terecht de bijnaam «Watertoren van Afrika». In Tigray vormt de Tekeze rivier de belangrijkste permanente bron aan water. Enorme hoeveelheden water gaan echter verloren als run-off of via grensoverschrijdende rivieren. De aanwezigheid van watervoorraden biedt echter reeds perspectieven om deze op een duurzame manier aan te wenden.

Studiegewassen: gerst en tef

Gerst

Gerst, *Hordeum vulgare L.* (zie figuur 2.8), is een éénjarig C_3-graangewas dat een gewashoogte tussen 0,5 en 1 m bereikt. De plant groeit vrij goed in marginale gebieden (ondiepe bodems, koude, onvruchtbaarheid, steile hellingen) waar andere graansoorten niet overleven. Uit onderzoeken is gebleken dat gerst hoge waarden voor waterproductiviteit vertoont in vergelijking met andere graangewassen (Sepaskhah and Ghahraman, 2004).

In Tigray wordt gerst al meer dan 5 000 jaar verbouwd en ook vandaag is het een van de belangrijkste voedselgewassen. De gemiddelde oogst in de periode 1996-2006 bedroeg 1,13 miljoen ton graan verbouwd op bijna 1 miljoen ha. De productiviteit is laag in vergelijking met productiviteitscijfers die in Europa worden opgetekend en bedraagt slechts 1,14 $ton{\cdot}ha^{-1}$ (zie figuur 2.10). Gerst groeit voornamelijk tijdens het belangrijkste groeiseizoen en wordt gezaaid tussen eind mei en eind juli. Oogsten gebeurt op de traditionele manier met een sikkel vanaf midden september tot begin oktober. Graan van gerst fungeert als voedselbron voor de lokale bevolking, het stro als dierenvoeder. De granen worden tevens verwerkt in lokale dranken.

Tef

Tef (zie figuur 2.11) is een kruidachtig, éénjarig C_4-graangewas, en een zeer populair voedselgewas in Ethiopië, de bakermat van de plant. De plant heeft een fragiel uitzicht en bereikt een maximale hoogte die varieert tussen 0,3 en 1,2 m. Tef stelt weinig eisen aan waterbeschikbaarheid: de plant kan overleven met een jaarlijkse minimum neerslag van 300 $mm{\cdot}jaar^{-1}$. De plant is waarschijnlijk goed bestand tegen zowel watertekort als -overschot, maar deze eigenschappen zijn nog weinig beschreven in wetenschappelijke literatuur.

Tef verbouwen in Tigray vereist zware arbeid: de minuscule afmetingen van het zaaizaad vragen goed doorploegde velden alvorens het zaaien van start kan gaan. De zaaidatum valt later dan van de meeste andere gewassen om te snelle groei tijdens het regenseizoen te vermijden waardoor de planten zouden kunnen platvallen. De oogst gebeurt 2 tot 3 maanden later op de traditionele manier met een sikkel. In Ethiopië worden naar schatting elk jaar bijna 2 miljoen ha tef verbouwd. Totale oogstcijfers komen met een productiviteit van amper 0,98 $ton{\cdot}ha^{-1}$ uit op een productie van 1,98 miljoen ton graan per jaar. De lage productiviteit kan gezien worden als één van de grootste nadelen van het gewas dat het basisvoedsel is van bijna 70 miljoen mensen. Een typisch Ethiopisch tefgerecht is «ndjera», een platte pannenkoek die gecombineerd wordt met peulvruchten. Tef draagt in belangrijke mate bij aan de voedingswaarde van het dagelijkse dieet dankzij een gebalanceerd geheel van verschillende aminozuren, ijzer en calcium.

Experimenteel veldwerk

Een veldexperiment werd ontworpen om de respons van gerst en tef op verschillende niveaus van waterstress na te gaan. Beide gewassen werden ingezaaid op twee aparte velden, ingedeeld volgens een *randomized complete block design* met 4 herhalingen (R) en 4 behandelingen (T) (zie figuur 3.1). De verschillende behandelingen hielden in:

- T1: geen waterstress (volledige irrigatie na afloop van het regenseizoen)
- T2: mogelijke waterstress in alle gewasstadia (regengevoed)
- T3: geen waterstress tijdens bloemenzetting (irrigatie tijdens bloemzetting)
- T4: geen waterstress tijdens bloemzetting en graanvorming (irrigatie tijdens bloemzetting en graanvorming)

Exacte gegevens over de hoeveelheid water toegediend zijn samengevat in appendix II.

Klimaatgegevens

Klimaatgegevens werden verzameld in het weerstation op de campus van de Universiteit van Mekelle. Resultaten zijn samengevat in tabel 3.5 en figuren 3.4 en 3.5. Opvallend is het verschil tussen de maanden juli en augustus enerzijds, en september, oktober en november anderzijds. De eerste twee maanden van het groeiseizoen zijn gekenmerkt door veel neerslag en een hoge relatieve vochtigheid, terwijl uren zonneschijn, temperatuur, evapotranspiratie en windsnelheid laag liggen. Het einde van het groeiseizoen vertoont het tegenovergestelde patroon.

Bodemgegevens

Met behulp van de pedotransferfuncties van Saxton en Rawls (2006) kon de bodem van de onderzoeksvelden na textuurbepaling (ISO 11277, 1998) geclassificeerd worden als Klei-Leem in het geval van gerst, als Lemige Klei voor tef (geclassificeerd volgens het WRB-systeem als Vertisols (FAO/ISRIC/IUSS, 2001)). Theoretische waarden voor θ_{SAT}, θ_{FC}, θ_{WP}, K_{sat} en ρ_b voor beide bodems zijn samengevat in tabellen 3.6 en 3.7 respectievelijk.

De hydraulische conductiviteit van de vooraf gesatureerde bodems werd bepaald door middel van een combinatie van de dubbele-ring methode en de Porchetmethode. Resultaten zijn weergegeven in tabellen 3.8 en 3.9 en figuur 3.6. De bepaling bracht een grote heterogeniteit (ondergrondse scheuren) van de bodems aan het licht. Deze vaststelling was belangrijk gezien het de waterbeschikbaarheid voor planten aanzienlijk beïnvloedt. De aanwezigheid van een ondoordringbare harde laag in de ondergrond van het gerstveld, die eveneens consequenties heeft voor de waterbeschikbaarheid, werd vastgesteld en de diepte ervan werd schematisch in kaart gebracht (zie figuur 3.7).

Experimenteel bepaalde gegevens over de bulkdensiteit en waterretentiecapaciteit van de bodems zijn samengevat in tabellen 3.10 en 3.11 enerzijds, en in tabel 3.12 en figuur 3.8 anderzijds. Empirische en theoretische waarden zijn van dezelfde orde.

Op wekelijkse basis werd het bodemwatergehalte opgemeten via de gravimetrische methode. De evolutie van dit watergehalte wordt gepresenteerd in figuren 3.9 en 3.10.

Gewasgegevens

Gerst werd gezaaid op 10 juli; tef pas later in het regenseizoen, op 7 augustus, geheel volgens de lokale landbouwgewoontes. In tabel 3.15 worden alle ontwikkelingsstadia van beide gewassen weergegeven. Doorheen de ontwikkeling van de planten werden verschillende gewasparameters op wekelijkse basis opgevolgd. De opstelling van beide proefvelden liet toe betrouwbare parametergemiddelden te berekenen voor verschillende niveaus van waterstress (verschillende behandelingen). Een statistische analyse, uitgevoerd met SPSS 13.0 software (SPSS, 2004), maakte het mogelijk om de prestaties van gewassen onder verschillende graden van water stress te vergelijken. De statistische tests bestonden uit een *univariate analyse* van de variantie (algemeen lineair model), aangevuld met *post hoc* veelvuldige vergelijkingen voor gemiddelden op verschillende significantieniveaus, namelijk 0,1* en 0,05**.

Gerst

De bepaling van verschillende gewasparameters (planthoogte, verse en droge biomassa, LAI, gewasbedekkingsgraad, totale oogst, massa van 1000 granen, oogst per eenheid van water toegediend) voor gerst onthulde dat weinig tot geen significante verschillen konden ontwaard worden tussen planten die verschillende niveaus van waterstress ondervonden. Uit experimenten bleek dat planten die met meer waterstress te kampen hadden niet significant slechter presteerden dan planten zonder waterstress. Enkel wat betreft oogstopbrengst - zowel totale oogst als oogstkwaliteit (massa van 1000 granen) - scoorden regengevoede planten significant lager dan planten met minder waterstress. Verschillen bleven evenwel klein. Het is daarom niet duidelijk of de meeropbrengsten die verkregen konden worden door planten te irrigeren na het regenseizoen ook daadwerkelijk loonden. De oorzaak van de minieme verschillen tussen planten die verschillende niveaus van waterstress ondervonden, was te wijten aan het feit dat gerst reeds vroeg in het regenseizoen gezaaid werd, waardoor de tijdsspanne waarin alle planten dezelfde behandeling kregen (zelfde hoeveelheid regenwater) zeer uitgebreid was. Daarenboven was ook de goede kwaliteit van het regenseizoen in 2006 medeverantwoordelijk voor de geringe significante verschillen. Resultaten van de analyse van de gewasparameters zijn samengevat in tabellen 3.16 tot en met 3.27 en in figuren 3.11 tot en met 3.25.

Tef

Wanneer de focus naar tef wordt verlegd, valt het op dat er meer significante verschillen konden vastgesteld worden voor gewasparameters. Dit was een logisch gevolg van het feit dat tef pas later in het regenseizoen gezaaid werd, zoals het de gewoonte is in Tigray, waardoor de lengte van de periode waarin planten dezelfde hoeveelheid (regen)water ontvingen, aanzienlijk verminderde. Gewassen die enkel in stressgevoelige ontwikkelingsstadia een supplement water toegediend kregen, scoorden beter op het vlak van oogstcijfers (zowel kwaliteit en hoeveelheid van de oogst, als oogst per eenheid van water). Toch was het te vroeg om definitieve conclusies te trekken over de mogelijkheid om water productiviteit te verhogen door waterstress in gevoelige gewasstadia te milderen. Meer uitgebreid onderzoek op lange termijn is nodig. Resultaten van de analyse van de gewasparameters zijn samengevat in tabellen 3.16 tot en met 3.27 en in figuren 3.11 tot en met 3.25. Uit de geanalyseerde gegevens bleek dat de afhankelijkheid van planten van een goed regenseizoen afneemt wanneer gewassen later in het groeiseizoen gezaaid worden.

In tegenstelling tot voor gerst, bleven de gemiddelde waarden van de gewasparameters voor tef veelal onder het nationaal gemiddelde. De beperkte groei van de tefplanten was waarschijnlijk te wijten aan de hoge plantdichtheid en daarmee samenhangend nutriëntentekort, veroorzaakt door de specifieke breedwerpige zaaiwijze van tef.

IJking en validatie van het waterproductiviteitmodel AquaCrop

Het waterproductiviteitmodel AquaCrop (Raes *et al.*, 2006; Steduto *et al.*, 2006) is een simulatiemodel dat een minimum aan invoergegevens (over klimaat, gewas, bodem, managementactiviteiten en de interactie tussen deze vier componenten) vereist om de oogstrespons van planten op water te simuleren. Gegevens uit veldexperimenten kunnen aangewend worden als invoerdata voor het model (zie tabel 4.1). AquaCrop is vervolgens in staat om de ingevoerde parameters om te zetten en op die manier:

- een inschatting te maken van de waterstress die planten ervaren in regengevoede omstandigheden
- een oogstrespons op water te bepalen
- de waterproductiviteit van gewassen te beoordelen
- irrigatiestrategieën te ontwerpen en te evalueren

Gerst

De simulatie van de bodemwaterbalans vereiste een aanpassing van het bodemvochtgehalte bij veldcapaciteit (FC) en bij verwelkingspunt (WP). Deze bijstelling was gerechtvaardigd aangezien de wekelijkse metingen van het bodemvochtgehalte erop wezen dat de experimentele bepaling van θ_{FC} en θ_{WP} een overschatting inhield. Wanneer vervolgens de gesimuleerde bodemwaterbalans vergeleken werd met de experimenteel bepaalde balans bleken beide grote overeenstemming te vertonen. Figuur 4.1, tabel 4.4 en appendix III geven blijk van de degelijke simulatie van het model.

Het ijken van de gewasontwikkeling resulteerde eveneens in een sterke overeenkomst tussen simulatie en realiteit. Figuur 4.2, tabel 4.5 en appendix IV ondersteunen deze stelling.

De bepaling van de waterproductiviteit als helling van de relatie tussen de droge bovengrondse biomassa en de cumulatieve verhouding tussen transpiratie en evapotranspiratie bevestigde de hypothese van Steduto *et al.* (2007) dat waterproductiviteit een onveranderlijk karakter heeft en voor C_3 planten zoals gerst waarden vertoont tussen 13,0 en 15,0 $g{\cdot}m^{-2}$ (zie figuren 4.3 en 4.4). In de toekomst kan het nuttig zijn om ook het constant karakter van de waterproductiviteit van gerstplanten die onderworpen zijn aan relatief zware waterstress nader te onderzoeken.

Tef

Voor tef werd eveneens getracht AquaCrop te ijken en te valideren. Een vergelijking tussen de gesimuleerde en experimenteel bepaalde bodemwaterbalans en gewasontwikkelingscurve, leerde dat de ijking niet tot de gewenste validatie van het model kon leiden (zie figuren 4.6 en 4.7, tabel 4.9 en appendices V en VI). Relevante informatie over cruciale gewasparameters van tef kon niet worden verzameld op het veld of in de literatuur en liet hiaten achter in de gegevens die nodig waren om AquaCrop te valideren. De bepaling van de waterproductiviteit als helling van de relatie tussen de droge bovengrondse biomassa en de cumulatieve verhouding tussen transpiratie en evapotranspiratie bleef hoogst onnauwkeurig aangezien transpiratiegegevens vastgelegd werden door een ontoereikend model. Gedegen onderzoek in de toekomst is noodzakelijk voor een waardevolle ijking van AquaCrop voor het specifieke gewas tef.

Simulatieresultaten voor droge, normale en natte jaren

Met een goed geijkt en gevalideerd model is het mogelijk om de bodemwaterbalans, de gewasontwikkeling en de oogstopbrengst voor verschillende types van jaren te voorspellen. Aangezien enkel voor gerst de validatie van AquaCrop als geslaagd verondersteld kon worden, konden voorlopig geen voorspellingen voor tef worden gedaan.

Invoergegevens bestonden uit bodem- en gewasparameters zoals vastgelegd tijdens de modelijking aangevuld met meteorologische gegevens voor 16 jaren tussen 1984 en 2003. Door middel van een frequentieanalyse werden alle onderzochte jaren geclassificeerd als droge, normale of natte jaren op basis van de totale neerslag in het regenseizoen (zie tabel 4.12). De aanvang van het groeiseizoen voor elk van deze jaren moest geschat worden door een combinatie van twee arbitraire criteria: ‘regenval in decade overschrijdt 0,5 ET_0’ (FAO-criterium) en ‘regenval is minstens 40 mm in 15 dagen’ (Raes *et al.*, 2004).

Wanneer de voorspelde gewasopbrengsten werden vergeleken met de classificatie van de jaren, werd duidelijk dat in het algemeen droge jaren voor minder oogst zorgen, terwijl oogstverschillen in normale of natte jaren nauwelijks opmerkbaar zijn. Uitzonderingen waren aanwezig en wezen op het feit dat naast totale neerslag ook de neerslagdistributie in het regenseizoen een belangrijke invloed heeft op de uiteindelijke oogstresultaten.