

**CHARACTERIZATION AND MODELLING OF  
WATER USE BY AMARANTHUS AND PEARL MILLET**

by

**ZAID ADEKUNLE BELLO**

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**Supervisor: Professor Sue Walker**

**Bloemfontein**

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## **DECLARATION**

I declare that the dissertation hereby submitted by me for the degree of Doctor of Philosophy at the University of the Free State is my own independent work and has not previously been submitted by me at another university or faculty. I further more cede copyright of the dissertation in favour of the University of the Free State.

Zaid Adekunle Bello

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Signature

Date: January 2013

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Republic of South Africa

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## LIST OF SYMBOLS AND ABBREVIATIONS

A2	A2 emission scenario
ANOVA	Analysis of variance
APSIM	Agricultural Production Systems Simulator
ARC-GCI	Agricultural Research Council – Grain Crop Institute
ARC-ISCW	Agricultural Research Council – Institute of Soil, Climate and Weather
ARC-VOPI	Agricultural Research Council - Vegetable and Ornamental Plant Institute
AWS	Automatic weather station
B	Biomass
B1	B1 emission scenario
BBCH	Biologische Bundesanstalt, Bundessortenamt and Chemical industry
CC	Canopy cover
CERES	Crop Environment Resource System
CGR	Crop growth rate
CO <sub>2</sub>	Carbon dioxide
CROPWAT	Crop Water Requirements model of FAO
CSIRO	Commonwealth Scientific and Industrial Research Organization model
D	Deep percolation
d	Willmott index of agreement
DM	Dry mass
DUL	Drained upper limit of soil water
DSSAT	Decision Support Systems for Agrotechnology Transfer
DWAF	Department of Water Affairs and Forestry
$e_a$	Actual vapour pressure
$e_s$	Saturation vapour pressure
$e_s - e_a$	Saturation vapour pressure deficit
E	Soil evaporation
EC <sub>w</sub>	Electrical conductivity
ET	Evapotranspiration
ET <sub>o</sub>	Reference evapotranspiration
FAO	Food and Agriculture Organization
FM	Fresh mass
G	Soil heat flux density
GCI	Grain Crops Institute
GCM	Global Climate Model
GDD	Growing degree days
GS	Grain-filling stage stress
GY	Grain yield
H	Historical
HI	Harvest index
HI <sub>o</sub>	Reference harvest index
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
I	Irrigation
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
K <sub>sat</sub>	Hydraulic conductivity of soil
K <sub>c<sub>tr</sub></sub>	Coefficient for transpiration
L <sub>A</sub>	Leaf area
LAD	Leaf area duration
LAI	Leaf area index

LAN	Limestone ammonium nitrate
LAR	Leaf area ratio
LL	Lower limit of soil water
LSD	Least significant difference
$L_w$	Leaf mass
Mon	Monyaloti
MPI ECHAM 5	Max Planck Institute for Meteorology Global Climate Model
N	Nitrogen
NAR	Net assimilation rate
NB	Number of branches
NL	Number of leaves
NPK	Nitrogen Phosphorus and Potassium fertilizer
NRC	National Research Council, Washington D.C, U.S.A
Obs	Observed
P	Precipitation
PD	Planting dates
PH	Plant height
PWP	Plant wilting point of soil water
R	Runoff
$R^2$	Coefficient of determination
RGR	Relative growth rate
RGS	Reproductive and grain-filling stress
RMSE	Root mean square error
RS	Reproductive stage stress
RWC	Relative water content
$R_n$	Net radiation
SAS	Statistical Analysis System
Sim	Simulated
SLA	Specific leaf area
SPAC	Soil-Plant-Atmosphere-Continuum
SRES	Special report on emissions scenarios
SS	Stressed
SWC	Soil water content
T	Mean daily air temperature at 2 m height
T	Time
TAW	Total available water
$T_b$	Base temperature
$T_{max}$	Maximum temperature
$T_{min}$	Minimum temperature
TM	Turgid mass
TT	Thermal time
$u_2$	Wind speed at 2 m height
VS	Vegetative stage stress
UNFP	United Nations Population Fund
W	Total above ground dry mass
WP	Water productivity
WUE	Water use efficiency
$WUE_{bm}$	Water use efficiency (biomass)
$WUE_{gy}$	Water use efficiency (grain yield)
WW	Well-watered treatment
Y	Yield

$\Delta$	Slope vapour pressure curve
$\gamma$	psychrometric constant [kPa °C <sup>-1</sup> ]
$\Delta SW$	Change in soil water content

# **CHARACTERIZATION AND MODELLING OF WATER USE BY AMARANTHUS AND PEARL MILLET**

Zaid Adekunle Bello

Doctor of Philosophy in Agrometeorology, University of the Free State

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## **ABSTRACT**

Amaranthus (*Amaranthus spp*) and pearl millet (*Pennisetum glaucum* [L.] R. Br.) are drought tolerant crops with much potential that has not been well exploited as they can be cultivated under semi-arid climatic conditions. This study was carried out to characterize their water use and model their growth and yield in response to water. Experiments were carried out under a field line source sprinkler irrigation system for both crops for two seasons, as well as in a greenhouse with a pot experiment for amaranthus and in the lysimeter facility for pearl millet studies, each for one growth cycle. One genotype of amaranthus (*Amaranthus crentus* ex Arusha) and two lines of pearl millet (GCI 17, improved line and Monyaloti, local variety) were used in the trials with these crops in a semi-arid area near Bloemfontein, South Africa.

The influence of water application on growth of amaranthus was contrary to the expectation that fully irrigated plants will perform better than the plants receiving less water. Fully irrigated plants produced shorter plants with less leaves and branches. However, irrigation improved the plant height in both lines of the pearl millet. A large amount of irrigation resulted in taller plants for both lines while the shortest plants were found in the rainfed plots. Another millet crop parameter that was affected by irrigation was flower emergence. Flower emergence was earlier in irrigated plots of both lines of pearl millet and during the two seasons. In both lines of pearl millet, irrigation increased leaf area index and biomass accumulation during both seasons.

The two crops were able to exhibit the ability to tolerate water stress with different coping mechanisms and this influenced their water uptake and invariably also water use. Amaranthus was able to manage water stress in rainfed plots through the closure of stomata in the field and during the pot trials. Stomatal closure reduces water loss as a response to water deficit in the soil-crop-atmosphere continuum. Daily water use of amaranthus ranged from 1.2 to 6.5 mm day<sup>-1</sup> while the seasonal water use was 437 mm for

the first season and 482 mm for the second season. Higher water use in the second season was attributed to higher atmospheric evaporative demand recorded during the second amaranthus growing season compared to the first. It was observed that while water application can increase the production of amaranthus, it should also not be too much or it could have a detrimental effect on biomass production of the crop. This conclusion is due to the fact that the lowest irrigated plots produced higher fresh and dry mass of amaranthus during both seasons while production in the fully irrigated plots was low for the two seasons. The response of pearl millet to water deficit stress was to lower the leaf water potential (more negative) and also gradually decrease the leaf stomatal conductance.

Pearl millet demonstrated a response to the water stress condition by closing of the stomata as leaf water potential declined (towards more negative) so as to conserve water and prevent water loss. This minimized water loss through transpiration when the soil water available is limited. The crop adjusted to severe water stress conditions by maintaining a leaf water potential that keeps the leaf turgid in order to avoid wilting when the stomata closes so as to prevent excessive water loss. The daily evapotranspiration of the two lines of pearl millet for the two seasons were between 2 and 8 mm day<sup>-1</sup> for the first season and 1 and 6 mm day<sup>-1</sup> for the second season. The difference could also be attributed to a higher atmospheric evaporative demand in the first pearl millet growing season than the second season. Overall, the improved (GCI 17) and the local variety (Monyaloti) of pearl millet had water use of 309 and 414 mm in 2008/2009 season. The water use for the two lines was higher in the 2009/2010 season with GCI 17 having water use of 401 mm and Monyaloti 457 mm which was probably due to high availability of water. High soil water content coupled with a higher amount of rainfall in the second season than the first season could be the reason for difference of the water use of the two lines of pearl millet for the two seasons. However, the water use of the plants of the two lines of pearl millet from the rainfed plots and water stressed treatments showed that the crop was able to reduce water use under water stress conditions as a coping mechanism and hereby increase water use efficiency of the crop.

With the aid of the data from the field experiment, greenhouse and lysimeter trials, calibration and validation of AquaCrop crop model was performed successfully for both crops. Simulation of biomass production and cumulative evapotranspiration of both crops were performed adequately. The good performance in simulating these crop parameters were illustrated with a high index of agreement that was higher than 0.9 except for 2 cases of CC excluding the soil water comparisons. However, it was observed that more effort is needed to accurately simulate early canopy cover in amaranthus and also the soil water content and depletion patterns for both crops. Following successful validation, the model was also applied to predict the performance of both crops under a range of proposed planting dates and choice of varieties in pearl millet as possible adaptation strategies under two climate change scenarios. The model was able

to predict the production of the two crops under predicted climate change for the period between the year 2046 and 2065 and the most appropriate adaptation strategy as a recommendation is to delay planting for two months until the first half of January for both crops under the two future climate change scenarios (A2 and B1).

In conclusion, the two crops under investigation can adjust to water limited conditions but through different mechanisms. Amaranthus can avoid water stress through restricting growth, while the pearl millet crop escapes water stress through speedy completion of growth stages before the water stress condition sets in. It was also revealed that there are possibilities of cultivating these crops in central South Africa. However, more studies should be carried out on the effect of interaction of nutrient and irrigation on amaranthus production to reveal the reasons for the unexpected response of amaranthus to water application. Studies on root development of the two crops are hereby recommended to aid in accurate simulation of water balance of the two crops in the field situations. The calibration and validation of AquaCrop for these two crops can also be improved by using datasets of more varieties or genotypes of the crops and from other agro-ecological regions. In general, underutilised crops provide means of food security and source of income for farmers. Due to the fact that they are drought tolerant, they require minimum amount of input which is a desirable quality for low resource farmers and can be used as alternative crops in semi-arid areas.

# CHAPTER 1

## INTRODUCTION

### 1.1 INTRODUCTION AND MOTIVATION

The world population is projected to reach 7 billion in 2012, while the South African population is presently above 50 million (UNFP, 2011). Increasing population has thus put pressure on the world food production. However, in many developing countries, it is difficult for agricultural production to keep pace with the increased food demand due to the population growth. Therefore, there is a need to increase the food production of each country. Although, selected from a large agrobiodiversity of more than 7000 food species, the world depends on a very limited number of crops for basic diets of carbohydrates, proteins and fats (Mayes *et al.*, 2011; Wilson, 1992). The current world food supply is from about 30 plant species which is inadequate to meet the world's food and nutritional demands (Anon, 1996). About 50% of world food that dominates human consumption is mainly from a few cereals, namely wheat, rice, maize and barley (Ahmad & Javed, 2007; Collins & Hawtin, 1999) which have been widely and intensively cultivated for many years. However, there will be many challenges facing these staple crops in the near future. A diversification away from over-reliance on these staples is important in order to achieve an increase in food production (Mayes *et al.*, 2011). Also, the financial benefit of cultivating existing staple crops is no longer as good as it was due to fairly static producer prices coupled with rapidly rising input costs (Allemann, 2004). The search for alternative crops by farmers that cannot compete with established commercial farmers therefore calls for increasing need for new crops (Allemann, 2004). Apart from staple crops, there are other crops that are consumed by humans but their importance is peculiar to a particular region and has been forgotten or their potential has not been exploited very well (Ahmad & Javed, 2007). There have been many terms used to describe these less well-known crops such as underutilized species, neglected species or orphan crops, underexploited, underdeveloped species, abandoned, new, lost, underused, local, traditional, forgotten, alternative, niche and promising species (Padulosi *et al.*, 2003). For the purpose of this study, the underutilized crops/plants term is going to be used to address these crops.

The potential of underutilized crops to contribute to food security and alleviate poverty has not been fully exploited. Despite being a good source of food, they are under used or exploited for their contribution to human health (both nutritional and medicinal value), income generation and environmental services; however, underutilized crops still provide many advantages irrespective of their status and location (Anon, 1996; Bavec & Bavec 2006). Underutilized crops contribution to livelihoods involve occupying

important ecological niches, enhancing biodiversity, sustained production with low inputs, stabilization of ecosystems and creating new markets (Anon, 2009). One of the advantages provided by underutilized crops is the fact that they hold a great genetic diversity and they possess a vast heritage of indigenous knowledge (Padulosi *et al.* 1999; Frison *et al.*, 2000). Underutilized crops are indigenous or introduced and recognized as a traditional crop in a particular area/region. This means that they are native or adapted introduced plant species that form a complex part of the culture and diets of the people who grow them in a particular area (Mayes *et al.*, 2011). Although, they are locally abundant, when considered globally they are rare, their scientific information is scant and their current use is limited relative to their economic potential (Gruere *et al.*, 2008). Many indigenous crops also have the ability to resist plant diseases and to be produced without chemical pesticides (Bavec & Bavec, 2006). They also have the ability to adapt to a wider range of adverse environmental conditions such as drought, high temperature and soil with low nutrient status (van Wyk, 2011). It is well known that South Africa has a large and rich plant biodiversity (Cunningham *et al.*, 1992). There are a large number of indigenous plants with potential to provide food security and improved nutrition, job creation, and there is much opportunity for the farmers to use them as alternative crops (Allemann, 2004; van Wyk, 2011). Allemann (2004) reported that underutilized crops that are indigenous to South Africa have a wide range of uses such as herbs and spices, essential oils, fruits and nuts, industrial, and medicinal uses, floriculture, food and beverages. These indigenous crops cover the full range of oil crops, roots crops, ornamental plants, leafy vegetables, fruits and cereals.

Jansen van Rensburg *et al.* (2007) defined indigenous leafy vegetables as plant species which are either genuinely native to a particular region or which were introduced to that region long enough ago to have evolved through natural processes or farmer selection. However, indigenous leafy vegetables are obtained in South Africa by collecting from the wild and seldom by means of cultivation. Many are plants that emerge naturally when soils are disturbed and their green leaves are eaten fresh or cooked and eaten with porridge as a relish (van Wyk, 2011). However, due to lack of information on growth, management and usage of these crops, the marketing of this type of crop harvested from the wild or as weeds is limited to dried products (Vorster *et al.*, 2002; Hart & Vorster, 2006). The most popular indigenous leafy vegetable consumed on a wide scale in South Africa is amaranthus.

Amaranthus (*Amaranthus spp*) is an annual C4 plant that grows optimally under warm conditions (van den Heever & Coertze, 1996; Maboko, 1999; Schippers, 2000). In South Africa, amaranthus is rarely cultivated because of the belief that it easily grows naturally on any waste land but it has a potential to be developed and cultivated as a crop (Jansen van Rensburg *et al.*, 2007). The leaves of amaranthus have high protein, vitamin and mineral content (Makus & Davis, 1984). Amaranthus is considered a promising crop for marginal lands and semi-arid regions because of the nutritional benefits and ability to adapt to



adverse environmental conditions (Cunningham *et al.*, 1992; Allemann *et al.*, 1996). It can grow on a wide range of soils and can tolerate soil pH from 4.5 to 8.0 (Palada & Chang, 2003) and the amaranthus species are known to be tolerant to adverse climatic conditions (Grubben, 2004; Maundu & Grubben, 2004). However, prolonged dry spells will induce flowering and decrease leaf yield of the crop (Schippers, 2000; Palada & Chang, 2003). Amaranthus is also known to be moderately tolerant to salinity stress which can help the plant in semi-arid regions or on lands prone to soil salinity (Omami, 2005). One of the strategies used by the crop for salinity tolerance is more efficient use of water. Omami (2005) also found that salinity stress causes a change in the pattern of dry matter accumulation and partitioning to different parts of the plant which might be one of its salt tolerance strategies. Liu and Stutzel (2002) described different strategies employed by four genotypes of amaranthus to cope with drought stress using their pattern of soil water extraction. They found that one genotype extracted soil water fastest and grew faster while others had higher water use efficiency. Rapid leaf area development and high stomatal conductance, rapid root and shoot growth after germination are some of the features that ensure a crop uses available soil water efficiently (Liu & Stutzel, 2002). Though, amaranthus can cope with adverse conditions, application of water and soil organic or inorganic fertilizer will increase fresh and dry mass production (Akparobi, 2009).

Indigenous cereals usually possess the ability to survive poor soil nutrient status therefore; they can provide food and financial security to local farmers. As found in other parts of the world, staple crops such as maize, wheat, and rice have replaced indigenous cereals in South Africa. However, indigenous cereals, such as pearl millet possess potential for development and commercialisation of traditional food items that are based on these grains (van Wyk, 2011). It has been reported that there is a possibility of using indigenous cereals to produce malted beers and traditional food items so that tourists can experience the unique culinary traditions of South Africa (Fox, 1938; Ashton, 1939; Quin, 1959, Fox & Norwood Yound, 1982).

Pearl millet is an example of indigenous cereals found mainly in the northern and western part of South Africa. This crop was indigenised to this area due to many years of cultivation, as well as natural and farmer selection. However, now the production of pearl millet is limited to certain areas that are not considered as cereals producing areas in the country (Bichard, 2002). Pearl millet is an annual C4 plant that can grow on a wide variety of soils ranging from clay loams to deep sands but the best soil for its cultivation is a deep, well-drained soil. Pearl millet is easy to cultivate and can be grown in arid and semi-arid regions where water is often a limiting factor (Naeem *et al.*, 2007). However, it responds very favourably to slight improvements in growing conditions such as supplementary irrigation (Leisinger *et al.*, 1995). Pearl millet is called a “high-energy” cereal as it contains higher oil content and protein than

maize grains as well as having relatively higher vitamin A content than some of the cereals (ICRISAT, 2004; NRC, 1996). Pearl millet usually suffers less from pests and diseases than other staple grains such as maize, wheat and sorghum (NRC, 1996). Studies on drought tolerance strategies of pearl millet include that of de Rouw (2004) and de Rouw and Winkel (1998). They found that the best strategy to reduce risk is planting the crop at a period that will enable the sensitive stages of crop development to avoid the hazards of water stress that can occur during the water stress period of the season. In the case of early relief of water stress, recovery of leaf growth supports good grain filling by productive tillers in order to limit the yield losses of the main shoot of pearl millet (Winkel *et al.*, 1997).

South Africa is a water scarce country with annual precipitation of around 500-600mm (Nieuwoudt *et al.*, 2004). Although, rainfall is not evenly distributed across the country, more than 50% of the South African fresh water is used for agricultural purposes (DWAF, 2004). Water availability is one of the major factors determining food production, with limited water usually signifying low food production. Low availability of water in the country calls for good management with respect to types of crops to be cultivated, irrigation management and environmental sustainability. The major environmental factor that directly or indirectly controls various physiological and metabolic processes and determines crop yield is water (Eiasu, 2009). As, there is a large variation in water availability from one geographic location to another, the choice of crops should be based on water available for crop production. Amaranthus and pearl millet, an indigenous leafy vegetable and cereal respectively, are suitable for cultivation in South Africa due to their drought adaptation attributes. Understanding crop response to water is imperative to improve crop water use efficiency and optimum crop growth and development. Increasing the water use efficiency requires an understanding of how crop production is related to such determining factors as transpiration and evaporative demand, water capture, water retention, and crop management (Haka, 2010). Therefore, there is a need to develop good strategies to promote efficient water use in semi-arid regions.

Crop modelling is one of the tools to develop and test possible management strategies for optimal water use efficiency. Crop models are described as computer simulation models developed in conjunction with advances in crop, environmental and computing sciences to assist in the efforts of agricultural sciences (Todorovic *et al.*, 2009; Singels *et al.*, 2010). They can also be defined as a simplified representation of a real system (Hillel, 1977; de Wit, 1982). A crop model can only be put into use after it has been calibrated for specific crops. Then calibrated crop models can assist as support tools for planning, decision making, yield predictions and evaluating the effects of climate change (Steduto *et al.*, 2009). Integration of knowledge and data across disciplines is another area in which crop models can be employed (Singels *et al.*, 2010). Another advantage of crop models is that they can save on lengthy and expensive field experiments, especially those with a high number of treatment combinations and thus the use of models

results in lower overall cost of such research (Whistler *et al.*, 1986). In addition, experiments could be pre-evaluated with a well-proven model which assists in refining the research questions and can lead to a better field study being done.

A crop model can be explained in terms of various algorithms describing growth from the perspective of carbon, radiation and water driven aspects (Todorovic *et al.*, 2009). Examples of carbon driven models are the Cropgro group of models (Boote *et al.*, 2002) and the Wageningen models (van Ittersum *et al.*, 2003). Carbon driven models operate in such a way that the higher level processes such as biomass accumulation, depend on the integration of lower level processes such as leaf photosynthesis and leaf development. In contrast, for radiation driven models, growth is calculated directly from intercepted radiation (Monteith, 1996). The carbon driven models are complex and usually require a large number of input parameters compared to radiation driven models that can be less complex requiring fewer parameters (Singels, 2009). CERES (Crop Environment Resource System) is an example of a radiation driven crop model and has the ability to integrate the effects of temporal and multiple stress interactions on crop growth processes under different environmental conditions (Ritchie & Otter, 1985; Ritchie *et al.*, 1985). Just like a typical radiation driven model, CERES is less complex and requires few parameters to operate compare to carbon driven models. Another type of models is a water driven model which simulates biomass production directly from crop water use (Tanner & Sinclair, 1983). For this type of model, biomass partitioning to different plant components is often influenced by water availability which confounds the relationship between mass of a given plant component and transpiration (Singels, 2009), as noted, total plant biomass is a function of transpiration and water productivity (WP). Water driven models are less complex than radiation driven models as they require few inputs of crop parameters (Steduto *et al.*, 2007; Steduto *et al.*, 2009). CropSyst (Stockle *et al.*, 2003) and the FAO's model – AquaCrop (Steduto *et al.*, 2009; Raes *et al.*, 2009) are examples of water driven models. AquaCrop is similar to the radiation driven models but different and advantageous due to the fact that AquaCrop normalizes WP parameter for climate (using both ETo and atmospheric CO<sub>2</sub>) thus giving it wider applicability in space and time (Steduto & Albrizio, 2005; Hsiao *et al.*, 2009; Steduto *et al.*, 2007).

AquaCrop is a water driven crop model that can be used for planning and decision making studies for underutilized crops. AquaCrop model focuses its simulation on attainable crop biomass and yield in response to water availability. The predecessor of the model, the FAO's irrigation and scheduling model CROPWAT (Smith, 1992), used the concept of phase-specific proportionality of relative yield to relative evapotranspiration in order to calculate yield response to water stress. However, one of the principles of the AquaCrop model lies in its capacity to separate evapotranspiration (ET) into crop transpiration (T) and soil evaporation (E). During crop establishment when ground cover is still very low, soil evaporation

can be quite a large proportion of evapotranspiration especially in arid zones. This is an advantage of the model as loss of water through the direct evaporation process is known to be high in semi-arid regions (Hensley & Bennie, 2003). AquaCrop estimates T and E based on a simple canopy growth and decline model and then treats final yield (Y) as a function of biomass (B) and harvest index (HI), thus allowing for the distinction of functional relationships between the environment and B, and between the environment and HI. It also segregates the crop responses to water stress into four separate components, namely, canopy growth, canopy senescence, transpiration and harvest index (Steduto *et al.*, 2009).

Though, there has been intensive work on crop modelling of staple crops such as wheat, maize and rice, not much has been done on indigenous leafy vegetables or cereals such as amaranthus and pearl millet. Crop growth and development are also imperative for effective calibration of crop models. Little is known about pearl millet response to irrigation from planting through to maturity as it is mostly grown under rain-fed conditions. There is also insufficient information on the cultivation of amaranthus and pearl millet under the South Africa climatic conditions, particularly considering their water use and water relations. Therefore, questions remain such as, how tolerant are they under South African weather conditions? What information on the water relations and water use characteristics of these crops exists? Can their water use efficiency be monitored and managed? Therefore, there was a need to study the water use characteristics of these two crops grown under field conditions in a semi-arid area near Bloemfontein.

Hypothesis of this study is that amaranthus avoids the effect of drought by restricting leaf growth in order to maximize its water use efficiency, while pearl millet can use water efficiently and hastens phenological development to survive under water stress conditions.

## **1.2 OBJECTIVES**

The main objective of this study is to characterize the water use of amaranthus (*Amaranthus cruentus* L. ex Arusha) and pearl millet (*Pennisetum glaucum* [L.] R. Br.) and to model the growth and yield of these two crops. The following specific objectives will be focused on:

- to monitor and compare the growth and development of both crops from planting to maturity under a range of water application conditions (Chapter 3);
- to determine water productivity of each crop (Chapter 4);
- to calibrate and validate the AquaCrop crop model for each crop with measured field and controlled environment data (Chapter 5); and
- to apply the AquaCrop model to predict and recommend adaptation strategies for amaranthus and pearl millet production under climate change in a semi-arid region of South Africa (Chapter 6).

## CHAPTER 2

### MATERIALS AND METHODS

#### 2.1 FIELD TRIALS

##### 2.1.1 Experimental site

The field research was conducted on the Department of Soil, Crop and Climate Sciences Experimental Farm, Kenilworth, located at latitude of 29.02°S and longitude 26.15°E and altitude of 1354 m. This is 20km North West of the University of the Free State main campus, Bloemfontein. The mean annual temperature is 15.9°C, with an average maximum of 30.8°C during January and 16.8°C during July and an average minimum temperature of 15.3°C during January and -2.0°C in July. The mean annual rainfall is  $\pm$  559 mm and the maximum is received in February with  $\pm$  111 mm precipitation. It has characteristics associated with high evaporative demand as is the case of other semi-arid areas where relatively low and erratic type of rainfall is expected. The soil of the experimental field is loamy aridic ustorthents (*Amalia family*), slightly acidic with the pH range of 5.1–6.5, 3 m down the profile (Woyessa, 2002). The morphological properties of the soil are reddish brown in colour with a fine sandy loam texture having low clay content (8-14% clay & 2-4% silt) in the first one meter of the profile (Soil Classification Working Group, 1991). The soil is suitable for agricultural cultivation in this semi-arid region because it drains freely while the plinthic horizon reserves water within the lower part of the profile which is within range of plant roots (Bennie *et al.*, 1994).

##### 2.1.2 Treatments and plot layouts

The study was carried out over two summer growing seasons during 2008/2009 and 2009/2010. The plot size for the two crops in total was 90 X 60 m<sup>2</sup>. The field was ploughed and rotovated before planting. Irrigation was supplied by a line source sprinkler system (Fig. 2.1a) and the plots were laid out in a split plot design as described by Hanks *et al.* (1980) with four replications. The treatments include five levels of water application, from full irrigation (W5, plots closest to the line source) to rainfed plots (W1, plots furthest from line source).

- W5 – Full irrigation
- W4 – Adequate Irrigation
- W3 – Moderate irrigation
- W2 – Least irrigation
- W1 – Rainfed

The rainfed plots were twice the size of the irrigated plots to avoid effects of border and lateral movement of water. Rain gauges were used to measure the amount of irrigation water applied from the irrigation sprinklers of the line source sprinkler system. This enabled quantification of water availability per treatment in reference to the fully irrigated plots (Table 2.1). Irrigation was done during windless conditions mostly at night. Irrigation water was supplied when the soil water fell below 70% of the drained upper limit (DUL) in the fully irrigated plots (W5). Water for irrigation with an average electrical conductivity of  $EC_w$  67.7 mS/m was obtained from a borehole on the experimental farm. Access tubes were installed at the centre of each of the amaranthus plots and at the centre of two replicates per treatment per variety of pearl millet for monitoring soil water content (Figures 2.1 and 2.2).

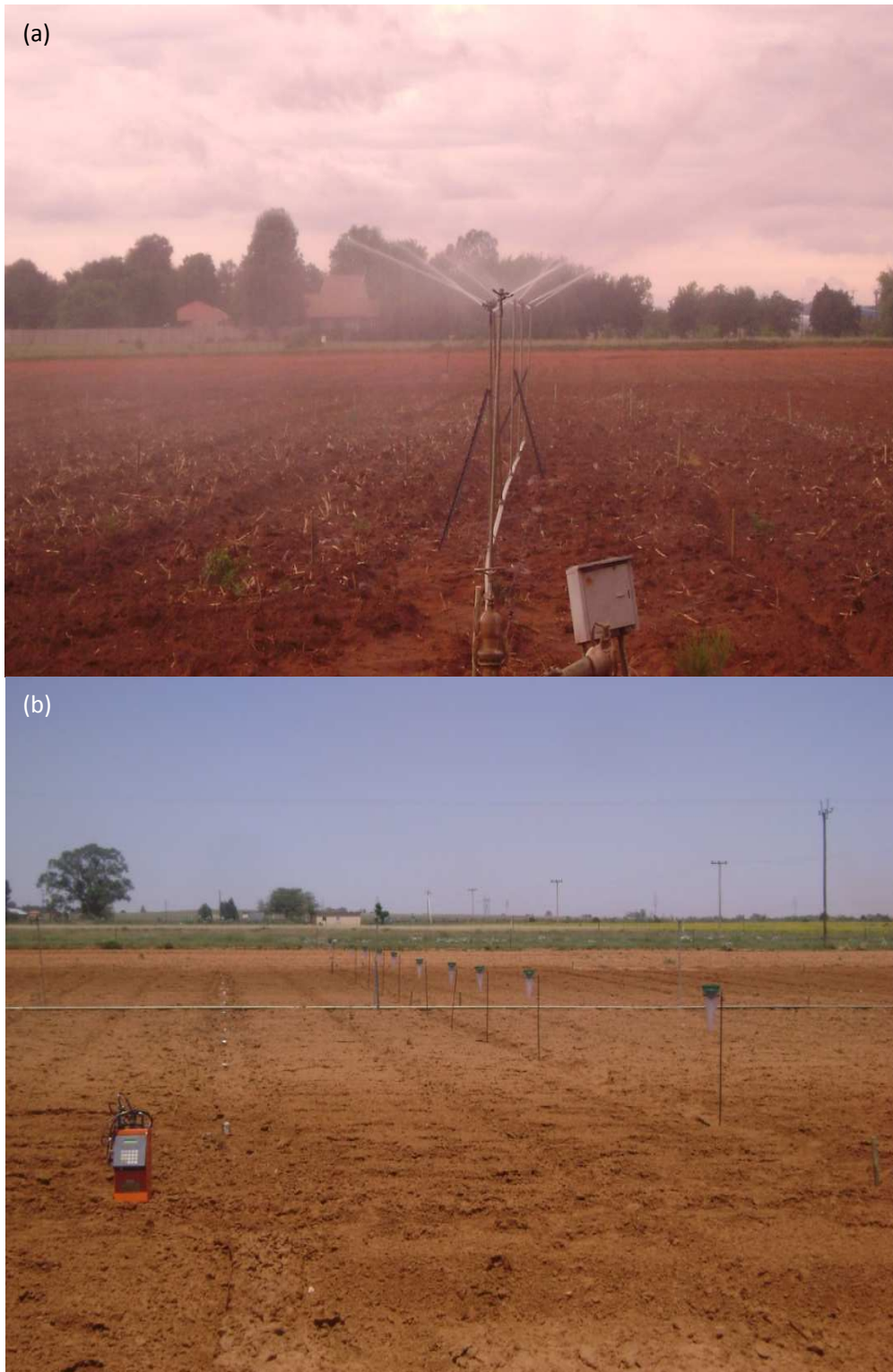
**Table 2.1** Relative application of water from line source sprinkler per treatment for the two seasons

Treatments	Distance from the line source (m)	Relative application of water
W5 (Full irrigation)	1.50	1.00±0.00
W4	4.50	0.73±0.07
W3	7.50	0.57±0.10
W2	10.50	0.39±0.10
W1 (Rainfed)	16.50	0.00±0.00

## 2.2 AGRONOMIC PRACTICES FOR FIELD TRIALS

### 2.2.1 Amaranthus

The genotype of amaranthus provided by the Agricultural Research Council Vegetable and Ornamental Plant Institute (ARC-VOPI, Roodeplaat) is *Amaranthus crentus* ex Arusha. Amaranthus plots had a total size of 23 m X 36 m and the plot for each treatment was 11 m X 3 m. Amaranthus seedlings were raised in the greenhouse sown in trays before transplanting into the field when they were between 4 and 5 cm high (Fig 2.5). The recommended planting date for amaranthus in the Bloemfontein area is between October and November (van den Heever & Coertze, 1996).



**Figure 2.1** (a) Line source sprinkler irrigation system and (b) the rain gauges for measuring irrigation water application per treatment and the neutron probe for measuring soil water content.

The 2:3:4 (30) NPK fertilizer was broadcast at a rate of 300 kg ha<sup>-1</sup> before transplanting. Transplanting took place on 30-31 December for 2008/2009 season while it was done on 11 November for 2009/2010 season. Transplanting was delayed in the first season because of difficulty of obtaining the seed which caused the delay in raising seedlings. The spacing used for cultivation was 100 cm between rows and 30 cm within row. Plants were monitored and irrigated until establishment was achieved four days after transplanting. Topdressing with 50 kg of LAN was done 45 days after transplanting. Weed control was done manually when required.

### **2.2.2 Pearl millet**

The two lines of pearl millet cultivated were provided by the Agricultural Research Council Grain Crop Institute (ARC-GCI, Potchefstroom) being the improved line, GCI 17 and local variety, Monyaloti. The planting date for millet in Free State area is between mid-November and early December. Planting was done on 28 November 2008 during the 2008/2009 season while a replanting was necessary on 16 December, 2009 for the second season (2009/10), because of uneven emergence of plants during the first planting (30 November, 2009). The total size of the whole field was 30 m X 36 m in which plot size for each treatment was 3 m wide and each row was 7 m long. The two lines were cultivated at recommended row spacing of 90 cm between rows and within row spacing of 20 cm (ARC-GCI). Fertilizer at the rate of 40 kg N ha<sup>-1</sup>, 20 kg P ha<sup>-1</sup> and 20 kg K ha<sup>-1</sup> was broadcast during each season and rotovated into the soil before sowing. Seeds were treated with metalaxyl to protect against downy mildew and sown at a depth of approximately 2-3 cm. There is no herbicide listed for pearl millet therefore, weeding were done manually as required.

## **2.3 DATA COLLECTION**

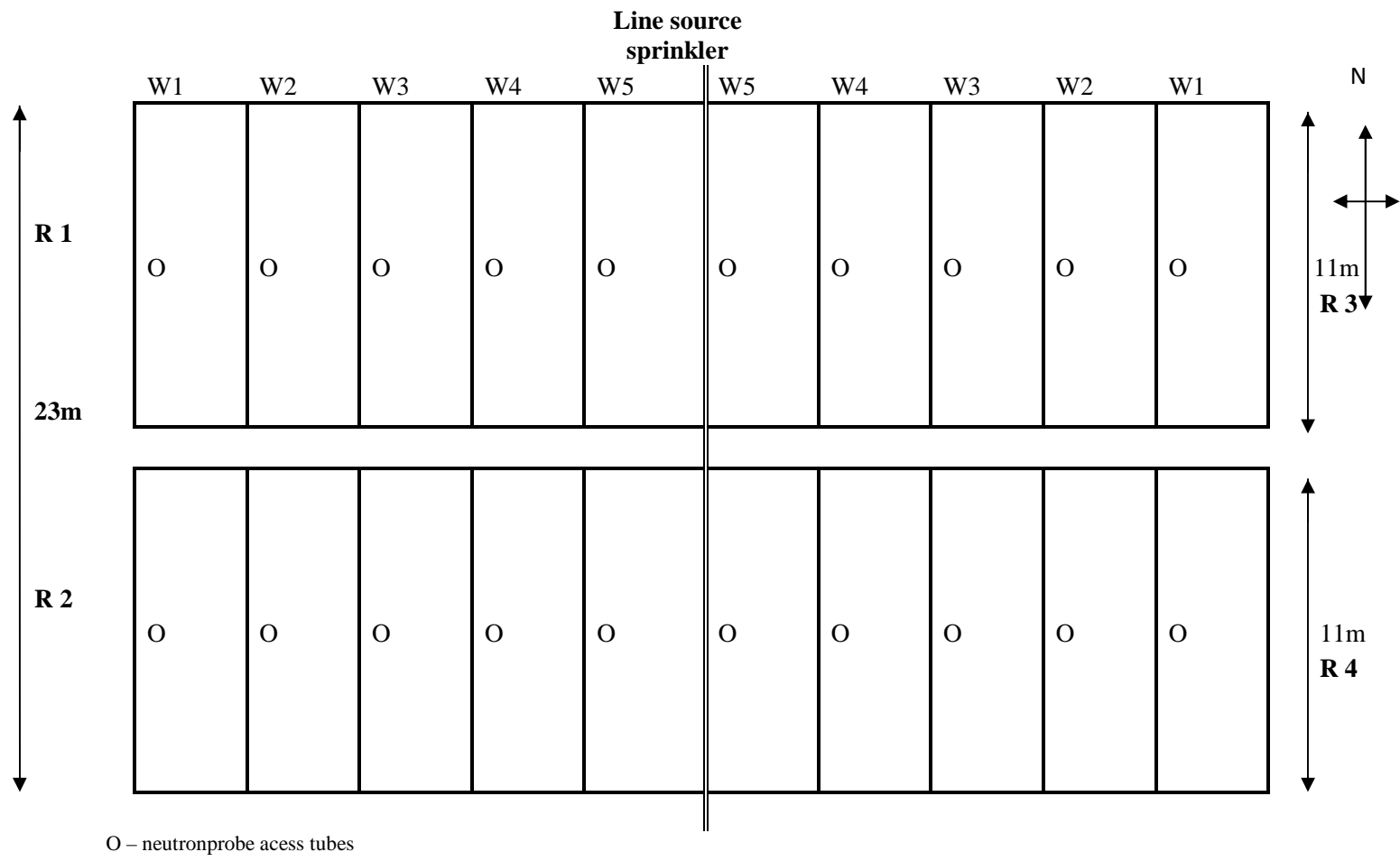
### **2.3.1 Weather**

Daily weather data monitored by the automatic weather station at the research site include:

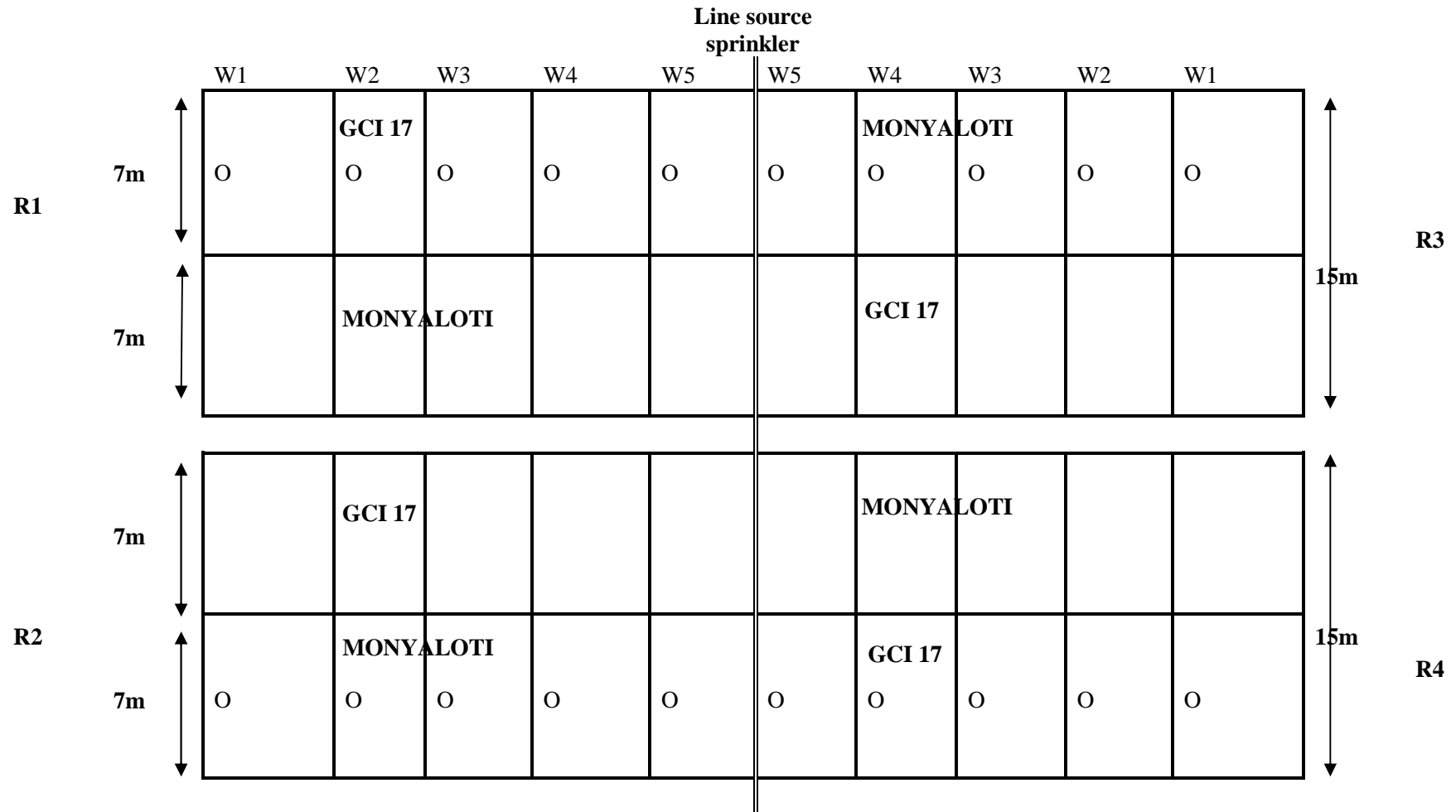
- Maximum and minimum air temperature (°C),
- Solar radiation (MJ m<sup>-2</sup>),
- Wind speed (m s<sup>-1</sup>),
- Rainfall (mm) and
- Relative humidity (%).

These parameters were measured at regular intervals, means were calculated and hourly values were recorded and stored daily by the automatic weather station. The automatic weather station was provided and managed by Agricultural Research Council – Institute of Soil, Climate and Water (ARC-ISCW).





**Figure 2.2** Layout of the line source system for amaranthus plots.



O – neutronprobeaccess tubes

**Figure 2.3** Layout of the line source system for pearl millet experiment.



**Figure 2.4** Trays of amaranthus seedlings in glasshouse of the Department of Soil, Crop and Climate Sciences, UFS before transplanting (2009/2010 season).

Mean temperature was calculated from maximum and minimum temperature using the equation

$$T = \frac{T_{\max} + T_{\min}}{2} \dots \dots \dots \text{Equation 2.1}$$

where  $T_{\max}$  - daily maximum temperature(°C)  
 $T_{\min}$  - daily minimum temperature(°C)

Reference evapotranspiration ( $ET_o$ ) was calculated from the observed weather data by the automatic weather station (Allen *et al.*, 1998) using equation 2.2:

$$ET_o = \frac{0.408 \Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \dots \dots \dots \text{Equation 2.2}$$

where  $ET_o$  - reference evapotranspiration [ $\text{mm day}^{-1}$ ],  
 $R_n$  - net radiation [ $\text{MJ m}^{-2} \text{day}^{-1}$ ],  
 $G$  - soil heat flux density [ $\text{MJ m}^{-2} \text{day}^{-1}$ ],  
 $T$  - mean daily air temperature at 2 m height [ $^{\circ}\text{C}$ ],  
 $u_2$  - wind speed at 2 m height [ $\text{m s}^{-1}$ ],  
 $e_s$  - saturation vapour pressure [kPa],  
 $e_a$  - actual vapour pressure [kPa],  
 $e_s - e_a$  - saturation vapour pressure deficit [kPa],

$\Delta$  - slope vapour pressure curve [kPa °C<sup>-1</sup>],

$\gamma$  - psychrometric constant [kPa °C<sup>-1</sup>].

### 2.3.2 Soil water monitoring

The field soil water content was monitored weekly with the aid of neutron moisture meter, Campbell Pacific Neutron Water Meter, Model 503DR. Access tubes 2m long made of aluminium were installed at the centre of each treatment plot to enable measurement at six levels (30cm intervals) down to 1.8 m depth. The drained upper limit (DUL) of the Bainsvlei soil of the experimental field was calculated to be 0.264 mm mm<sup>-1</sup> or 475 mm for the profile of 1800 mm. Plant lower limit (LL) for the soil is 0.083 mm mm<sup>-1</sup> or 151 mm for the whole profile (Chimungu, 2009). The total water use (both daily and seasonal) was estimated by the water balance equation:

$$ET = P + I - \Delta SW - D - R \dots \dots \dots \text{Equation 2.3}$$

where

ET - evapotranspiration (mm)

P - precipitation (mm)

I - irrigation (mm)

D - deep percolation (mm)

R - runoff (mm)

$\Delta SW$  - change in soil water content (mm) as measured weekly by neutron moisture meter.

D - Deep percolation and R - runoff are assumed to be negligible.

### 2.3.3 Crop phenology and crop growth parameters

Growth analyses carried out include leaf area index, leaf mass, total aboveground biomass, yield and harvest index. Plants were sampled at the soil surface from each replicate per treatment, and recorded as plants per stand. Destructive sampling was performed to obtain leaf area per plant and total aboveground biomass. Leaves were removed from the plants and leaf area was measured with the aid of LI3000 leaf area meter (LI-COR Inc., Lincoln, Nebraska, USA), every week during the vegetative and reproductive stages of the crop. Total aboveground biomass was calculated from the sum of biomass of leaves and stems of the plant. Plants parts (leaves and stems) were oven dried at 65°C for 36-48 hours to determine dry mass every week. All the destructive samplings were done randomly to avoid effects due to growth variation or sampling error from the plots. Individual specific plants in each replicate plot of each treatment were marked for weekly observations of plant height, number of leaves and number of branches per plant for the two crops. In pearl millet, flower emergence was monitored by counting plants with heads until a constant number were reached. At maturity, total aboveground biomass was determined for the two lines of pearl millet, number of stems with heads per hill was counted and plant height was measured.

Harvesting of amaranthus plants started 14 days after transplanting to determine the fresh and dry mass. This was continued every week until senescence set in. To simulate commercial production, 30 days after transplanting, plants were harvested at 30 cm above ground. This was repeated on the same plants at the same height at 14 day intervals. This leaf harvest was assumed to be the edible portion of the plant and their fresh and dry mass was recorded for both seasons.

#### **2.3.4 Crop physiology**

For the measurement of plant water status, leaf water potential was measured with a pressure chamber, PMS-600 model (PMS Instrument Company) and stomatal conductance with a leaf porometer (Decagon Devices, Inc.). Leaf water potential was only monitored for pearl millet plants due to technical reasons. Five leaves that were fully expanded and fully exposed were sampled per treatment. The measurements were carried out at midday on sunny days under cloudless conditions. During the leaf water potential measurements, transparent plastics were used to cover the leaf before cutting to minimize loss of water through transpiration. Mounting of detached leaves were done within minimum amount of time (30 seconds) to avoid water loss from the point of incision of the leaves. Pressure was applied slowly until water film started to appear from the point of incision protruding from the pressure chamber lid. A magnifying glass was used to view and determine the point in time when water appears on the incision and the pressure reading was taken immediately. Stomatal conductance measurements were also taken around midday between 12:00 and 14:00 hour. Five fully expanded and fully exposed leaves per treatment were sampled for these measurements. All leaves were sampled randomly and at the same upper level on the stem of the plant.

#### **2.3.5 Yield and yield components**

##### **2.3.5.1 Amaranthus**

Total aboveground biomass at weekly interval was regarded as the yield considering amaranthus as a leafy vegetable crop. Yield was reported in fresh and dry mass for the weekly harvest. Each cutting during the serial harvesting techniques was also reported as edible portion of yield.

##### **2.3.5.2 Pearl millet**

The harvest of pearl millet was from 1 m<sup>2</sup> of each treatment plot. Pearl millet plants were harvested for final yield when the seed moisture content had dropped below 15%. Yield components considered were head number per unit area and total grain mass as grain yield per unit land area.

### **2.4 POT AND LYSIMETER EXPERIMENTS**

Pot and lysimeter experiments were carried out purposely for precision measurement of some parameters of the two crops to collect information necessary for calibration of the AquaCrop crop model. The major parameters under investigation were water productivity (WP), crop growth and

development and harvest index (HI) of each crop. A pot trial was done for amaranthus, while the pearl millet study was carried out on lysimeters.

#### **2.4.1 Amaranthus pot trial**

The pot experiment was carried out in the greenhouse of the Department of Soil, Crop and Climate Sciences located at the main campus of the University of the Free State, Bloemfontein during the 2010/2011 summer season. The same genotype of amaranthus (*Amaranthus crentus* ex Arusha) was used for the investigation. The pot dimensions were 36 cm in diameter and 28 cm high with a volume of 28.5 L. The pots were filled with top soil from the experimental site where field trials had been conducted. The soil was oven dried at 105°C for 24 hours to determine the initial water content of the soil. All the pots were filled and then saturated with water and left to drain, and weighed daily until a constant mass was observed and recorded. Differences between the dried soil mass and drained soil mass were taken as the water content at full water holding capacity. NPK (2:3:4 (30)) fertilizer was applied at the rate of 300 kg ha<sup>-1</sup> before transplanting of seedlings. The pots were covered with quartz gravel to minimize soil surface evaporation and two pots were left bare to serve as reference for determining the evaporation rate. It was observed that the evaporation was small compared to plant transpiration. Therefore, evaporation was considered negligible and all water loss considered as transpiration.

Seeds were sown in trays to raise seedlings and one seedling per pot was transplanted after three weeks to the pots when the seedlings were between 4 and 5 cm high. Transplanting was done during the late afternoon to avoid transplant shock. Irrigation was done immediately after transplanting to enhance good root and soil contact. The temperature of the greenhouse was regulated to 30°C during the day and 16°C at night. Pots were divided into two groups of 10 pots per treatment; well-watered and water-stressed (Figure 2.5). Well-watered pots were weighed three times a week and then water added to refill to full water holding capacity as the difference in mass. Following the weighing, the stressed pots were not rewatered to full water holding capacity until the water depletion was below 30%. All pots were weighed irrespective of the treatment at around 17:00 hour and then rearranged within the treatments after weighing to maintain random distribution in the greenhouse.

Data collected included daily transpiration, weekly biomass (fresh mass and dry mass), stomata conductance and leaf relative water content. Four plants per treatment were harvested for biomass on a weekly basis. The stomatal conductance of four fully expanded and exposed leaves per treatment (one leaf per plant) was measured twice a week at midday between 12:00 and 14:00 hours. Relative water content (RWC) was measured by destructive sampling four fully exposed and fully expanded leaves per treatment. A small portion taken from the middle of each leaf was weighed to determine

the mass of the cut portion immediately after sampling (FM). These portions of leaves were floated in distilled water to rehydrate to full turgidity and then weighed to determine the turgid mass (TM). The



**Figure 2.5** (a) Pots with amaranthus plants at 3 days and (b) 30 days after transplant in the greenhouse of the Department of Soil, Crop and Climate Sciences, University of the Free State.



rehydrated portions were oven dried at 65°C to constant mass to determine dry mass (DM). The RWC was calculated as:

$$\text{RWC} = ((\text{FM} - \text{DM})/(\text{TM} - \text{DM})) \times 100 \dots \text{Equation 2.5}$$

#### 2.4.2 Pearl lysimeter trial

The drainage lysimeter unit is located at the Department of Soil, Crop and Climate Sciences Experimental Farm, Kenilworth, near Bloemfontein. It was constructed in 1999 to investigate the contribution of root accessible water tables towards the irrigation requirements of crops (Ehlers *et al*, 2003). The unit has 30 round plastic drainage lysimeters of which 18 were used for this study. Each lysimeter is 1.8m in diameter and 2m deep and they are buried in two parallel rows. One row contains a Clovelly soil and the other row, Bainsvlei soil. Each horizon of both soils was removed separately and packed in the same order into the lysimeters to reconstruct that specific soil. The drained upper limits (DUL) for the soils were 0.236 mm mm<sup>-1</sup> or 425 mm for the Clovelly soil profile of 1800 mm and 0.260 mm mm<sup>-1</sup> or 468 mm for Bainsvlei soil profile of 1800mm. The lower limit (LL) was calculated to be 0.047 mm mm<sup>-1</sup> or 85 mm for Clovelly profile and 0.083 mm mm<sup>-1</sup> or 151 for Bainsvlei profile of 1800 mm (Haka, 2010). The particle size distribution for the two soils is illustrated in Table 2.2. Each lysimeter is equipped with two neutron probe access tubes to a depth of 1900 mm. A drip irrigation system, with dripper lines installed at the surface of the soil of each lysimeter with equally spaced drippers for uniform application and redistribution of water, allows water to be applied manually using 20 litres containers connected to dripper lines. Soil water was monitored twice a week at 30 cm intervals down to 1800 mm depth with the aid of neutron moisture meter, Campbell Pacific Neutron Water Meter, Model 503DR. A rain shelter was used to exclude rain from the facility during the study period.

Preparation of the facility started with manual tillage and addition of two bags of compost to the top soil of each tank of the lysimeter unit. The two lines of pearl millet, GCI 17 and local variety Monyaloti, the same as those cultivated in the field trials were used for the lysimeter trial. Fertilizer was applied before sowing at a rate of 40 kg N ha<sup>-1</sup>, 20 kg P ha<sup>-1</sup> and 20 kg K ha<sup>-1</sup> by scattering. Each lysimeter was planted with 15 plants as the stand per tank at the spacing of 90 cm between rows and 20 cm within rows (Fig 2.6). Weeding was done manually as required. The soil surface of each lysimeter was covered with quartz gravel to eliminate soil evaporation after the emergence of plants. Irrigation treatments were applied such that water was withheld at the beginning of different growth stages of the crop to impose water stress and they are:



- WW - well-watered treatment
- VS - vegetative stage stress
- RS - reproductive stage stress
- GS - grain-filling stage stress
- RGS - reproductive and grain-filling stress.

**Table 2.2** Particle size distribution of each soil for the different depths in the lysimeters  
(Ehlers *et al.*, 2003)

Soil	Soil depth (mm)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Silt (%)	Clay (%)
Clovelly	0–300	1.3	10.7	79	4	5
	300–600	1.4	25.6	65	3	5
	600–900	1.4	25.6	65	3	5
	900–1200	1.4	25.6	65	3	5
	1200–1500	1.4	25.6	65	3	5
	1500–1800	1.4	25.6	65	3	5
Bainsvlei	0–300	0.3	6.4	83.3	2	8
	300–600	0.2	4.1	77.8	4	14
	600–900	0.1	3.5	78.4	4	14
	900–1200	0.1	5.7	76.2	4	14
	1200–1500	0.1	5.1	70.8	4	20
	1500–1800	0.2	5.2	70.7	4	20

Soil water content was kept between approximately 20-40% depletion of plant available water content. Each lysimeter was irrigated weekly to replenish soil water deficit while irrigation was withheld for lysimeters under the stress treatments. Each lysimeter was replenished back to field capacity at the end of each growth stage stress treatment.

Data collected weekly included leaf water potential, stomatal conductance, flower emergence, and radiation interception. Total aboveground biomass and yield were measured at the end of the study and related to the transpiration used by the crop. Transpiration (T) was calculated using equation 2.6:

$$T = P + I - \Delta SW - D - R - E \dots\dots\dots\text{Equation 2.6}$$

Rainfall (P) was zero as rainfall was excluded with the aid of rain shelter throughout the study period. Drainage (D) and runoff (R) were zero because the water table was kept constant at a 1.2m from the soil surface and spillage from the surface of the tank was prevented by the rims of the lysimeter. Soil evaporation (E) was negligible due to the quartz gravel that was used to cover each lysimeter.



**Figure 2.6** (a) Pearl millet cultivated in the two rows of drainage lysimeters under the moveable rain shelter (b) view of top of lysimeter tank with surface covered with quartz gravel illustrating two neutron probes pipes per tank and pearl millet stand.

## 2.5 MODELLING PARAMETERS AND INPUT

Climate, crop, management (irrigation and field management) and soil files were created for the model to be able to calibrate, validate and simulate the two crops response to water using the AquaCrop model. Ten years of daily weather data from the automatic weather station at the study site, courtesy of ARC-ISCW, including maximum and minimum temperatures, relative humidity, rainfall and wind speed as required by the model was used to create the climate file (Raes *et al.*, 2009; Steduto *et al.*, 2009). Crop files were created using information observed from pot trials, the lysimeter study and the agronomic practices as carried out during the field experiments for each crop. The field management option in the model was operated at the non-limiting soil fertility level, without surface

mulches and no surface runoff. A soil file was created using information from the past studies of the profile description of the soil at the research site (Chimungu, 2009) and it was assumed that there were no restrictive soil layers (see more details in Chapter 5).

## **2.6 STATISTICAL ANALYSIS**

Data collected were statistically analyzed by an analysis of variance for split plot design based on the description by Hanks *et al.* (1980) for the line source sprinkler system. This was done with the aid of Statistical Analysis System (SAS) program 9.2 package for Windows V8 (Statistical Analysis System Institute Inc, 1999-2010). Pots and lysimeter trials were also analysed with the aid of SAS 9.2 program. Means were compared using the least significant difference (LSD) test at a probability level of 5% using the Duncan Multiple Range tests. Validation of the model calibration and model performance was evaluated with the aid of statistical indices such as coefficient of determination ( $R^2$ ), root mean square (RMSE), and index of agreement (d) (Willmott, 1982).

## CHAPTER 3

### GROWTH AND DEVELOPMENT OF AMARANTHUS AND PEARL MILLET

#### 3.1 INTRODUCTION

A good understanding of the growth and accurate identification of crop developmental stages are essential for sound management decisions and improved crop productivity. Growth can be described as the irreversible changes with time, mainly in size, often in form and occasionally in number (Hunt, 1982). It can also be defined as the progressive development of an organism. Murthy (2003) also defines growth as the irreversible increase in size and volume and adds that it is the consequence of differentiation of plant cells and distribution of biomass. Developmental stages of crops involve the crop's whole life cycle (Tilton & Hollinger, 1982). Knowledge of crop developmental stages can be used for management decisions such as planting dates, fertilisation, pest and diseases control, weeding and irrigation. However, the type of crop under investigation has to be taken into consideration. Crop growth is influenced by both genetic and environmental factors. Environmental factors influencing crop growth include radiation, temperature, nutrients and water. The productivity of plants within a community depends on growth parameters such as plant height, number of leaves, number of tillers, and number of branches hence the importance of these parameters to realise potential yields (Singh *et al.*, 2001). Crop growth is usually reported as dry mass, height, length and/or diameter of leaf, stem or root. Ejieji and Adeniran (2010) used growth parameters such as fresh and dry mass, and plant height to explain amaranthus response to different levels of water application and fertiliser. A study on irrigation effects on roots and shoots of pearl millet reveals that irrigation influenced root length to be longer and a higher yield was observed due to the production of more tillers in irrigated plots compare to plants from rainfed plots (Gregory & Squire, 1979). Therefore, there is a need to establish an easy means to appreciate and analyse growth and development of crops.

Growth analysis is a standard technique for studying plant growth and productivity (Chanda *et al.*, 1987). Plant growth analysis can be used as an explanatory, holistic and integrative approach to interpret plant form and function (Hunt, 1990). This technique has been used to study plant development and factors that influence crop yields (Gardner *et al.*, 1985). It uses simple primary data in the form of mass, areas, volumes and numbers of plant components to investigate processes involving the whole plant (Evans, 1972; Causton & Venus, 1981; Hunt, 1990). With information on growth rates of amaranthus, the optimum period for agronomic processes can be estimated (Horak & Loughin, 2000). Growth analysis has been used to explain relationships such as sink source relationship in different crops. Tekalign and Hammes (2005) reported that fruit development reduced leaf area index, tuber growth and partitioning coefficient in four different cultivars of potato. Understanding the growth and development of a crop will help to determine water use and water

relations of the crop. In crop modelling, the growth and developmental pattern of the particular crop is important for calibration and yield prediction (Waggoner, 1977). The objective of this chapter is to report the growth and development of amaranthus and pearl millet from planting to maturity under different levels of water application. This paper will also use growth analysis to relate growth rate to the water use of each crop and compare the two crops based on these relationships.

## 3.2 MATERIALS AND METHODS

### 3.2.1 Field description

The study was carried out at the Department of Soil, Crop and Climate Sciences Experimental Farm, Kenilworth, located at latitude 29.02°S, longitude 26.15°E and at an altitude of 1354 m. A description of the experimental site, treatments and plot layouts, experimental design and agronomic practices employed in the experiments (2008/2009 and 2009/2010) are given in detail in Chapter 2.

### 3.2.2 Phenological stages

Different growth stages were identified and recorded using the observations from the field studies during the two growing seasons for the two crops. Classification of developmental stages of amaranthus was done according to the *Biologische Bundesanstalt, Bundessortenamt and Chemical Industry* (BBCH) system of coding phenological growth stages of plants. The BBCH scale is a system designed for uniform coding of stages of development of mono- and dicotyledonous plant species that are phenologically similar (Meier *et al.*, 2009). For this field study, the whole life cycle of amaranthus was classified into early, mid- and late vegetative stages as the planting method was transplanting and the seed production was not considered. The vegetative stage was sub-divided according to the extended BBCH scale (Hack *et al.*, 1992) with reference to the BBCH stage 40, the development of harvestable vegetative plant parts or vegetatively propagated organs. In this instance, number of leaves was considered as the harvestable plant part. However, phenological stages of pearl millets were classified into vegetative, flowering and grain filling stages using the data from the field observations. Thermal time (TT) is used to predict or analyse the length of different stages of crop growth and development, such as flowering or time to maturity (Bonhomme, 2000; Robertson, 1973). It is reported as growing degree days (GDD) with unit of °C d. TT was calculated for both crops using equation 3.1. Base temperature ( $T_b$ ) was taken to be 7°C for amaranthus and 8°C for pearl millet as these values are the recommended input values for AquaCrop model (Berti *et al.*, 1996; Garcia-Huidobro *et al.*, 1982).

$$TT = \left[ \sum \left( \frac{T_{max} + T_{min}}{2} \right) - T_b \right] \cdot \Delta t \dots\dots\dots \text{Equation 3.1}$$

For each of the crops, one plant per replicate of each treatment was marked for observations such as plant height, number of leaves and number of branches (only in amaranthus). In addition, number of tillers (only in pearl millet) per stand was recorded every week. In pearl millet, flower emergence was monitored by counting main shoot with heads until a constant number was reached.

### 3.2.3 Measurements for growth analysis

Plant sampling was carried out weekly during both seasons. One plant and its tillers per plot of each replication was cut at ground surface level and separated into leaves, stems and flowers during the vegetative and reproductive stages of the two crops. Leaves separated from the whole plant were measured every week with a LI3000 leaf area meter (LI-COR Inc., Lincoln, Nebraska, USA). Plant parts (leaves and shoots) were oven dried at 65°C for 36-48 hours to determine dry mass every week. The total above ground biomass was calculated as the sum of biomass of separated parts (stems, leaves and flowers). Leaf area and dry mass observed were used to calculate growth rate parameters.

### 3.2.4 Procedure for calculation of growth analysis and their significances

The following equations were applied to calculate the standard growth analysis parameters:

Leaf area index (LAI) = leaf area per plant X plant population

Leaf area ratio (LAR) =  $L_A/W$  (Hunt, 1990) ( $m^2 g^{-1}$ )

Specific leaf area (SLA) =  $L_A/L_W$  (Hunt, 1990) ( $m^2 g^{-1}$ )

Leaf area duration (LAD) =  $(LAI_2 + LAI_1) (t_2 - t_1)/2$  (Gardner *et al.*, 1985) (days)

Relative growth rate (RGR) =  $[(\ln W_2 - \ln W_1) / (t_2 - t_1)]$  (Gardner *et al.*, 1985) ( $mg g^{-1} day^{-1}$ )

Net assimilation rate (NAR) =  $[(W_2 - W_1) / (t_2 - t_1)] [(\ln L_{A2} - \ln L_{A1}) / (L_{A2} - L_{A1})]$  (Gardner *et al.*, 1985) ( $mg g^{-1} day^{-1}$ )

Crop growth rate (CGR) = LAI X NAR ( $g m^{-2} field area day^{-1}$ )

where  $L_{A1}$  and  $L_{A2}$  are leaf areas at time 2 ( $t_1$ ) and time 1 ( $t_2$ ) respectively while  $L_W$  is leaf mass.  $W_2$  and  $W_1$  are total above ground dry mass at  $t_2$  and  $t_1$  respectively. LAI, LAR and SLA were calculated instantaneously to determine growth at a single point in time. However, RGR, NAR and CGR were calculated using mean values as they were derived in comparing the performance of the crop plant over stated time intervals.

#### 3.2.4.1 Significance of growth analysis parameters

The leaf area index (LAI) is defined as the leaf area per unit area of land (Watson, 1947). The leaf area index represents the complete layers of leaves displayed by the crop as an average cover of the entire crop. Radiation interception and its conversion to carbohydrates and other usable materials in crop production explain the interest in LAI. The canopy of a crop can be expressed in terms of LAI and/or as a function of radiation intercepted by the crop (Jones & Kiniry, 1986). Among the growth rate parameters is leaf area ratio (LAR), which is the ratio of photosynthesising tissue to respiring

material or total plant biomass (Hunt, 1982). In other words, LAR is usually considered to be the ratio between the total leaf area and the total aboveground dry mass per plant. It compares the available factory for assimilate production which is then translocated to other parts of the plant for development of new leaves and other plant parts (Evans, 1972). Leaf area expansion trends can also be illustrated with LAR. Specific leaf area (SLA) as a growth rate parameter measures leafiness or leaf density or an expression of the relative thickness of leaves (Evans, 1972). SLA is sensitive to environmental change and prone to ontogenetic drift (Hunt, 1990).

Leaf area duration (LAD) represents the persistence of leaf exposed for radiation interception during crop growth (Gardner *et al.*, 1985). It measures the total potential for assimilation that the crop possesses (Watson, 1947). LAD takes into account the area under the LAI versus the time curve. LAD as a growth analysis parameter is concerned with not only how many leaves develop but also the ability of the crop to produce and maintain leaf area during a growing season (Evans, 1972; Hunt, 1990). This parameter expresses the relationship between biomass production and the leaf area during the growth period of a crop.

The following growth analysis parameters are termed efficiency indices (Evans, 1972; Hunt, 1990). Relative growth rate (RGR) is an efficiency index of biomass production. It is defined as the increase in plant material per unit of material per unit of time (Hunt, 1990). This shows the effectiveness of a crop in dry mass production per unit of dry mass of the crop per unit of time. Net assimilation rate (NAR) is also an efficiency index but of the photosynthetic system. NAR is defined as the net gain in assimilate per unit of leaf area per unit of time (Gardner *et al.*, 1985). This growth analysis parameter shows the effect of increasing competition for nutrients as well as other factors such as age and size increase. The crop growth rate (CGR) is an efficiency index that considers land area in producing plant biomass. CGR is defined as the rate of dry mass produced per plant stand per unit of land area (Hunt, 1990). Typically linear relationships exist between LAI and CGR (Rowden *et al.*, 1981).

#### 3.2.4.2 Approaches to growth analysis

Approaches to crop growth analysis include classical and functional approaches. The classical approach of crop growth analysis is the simplest approach as it deals with the mean values derived from the observed data of at least two harvests (Hunt, 1979). This approach is straightforward to describe the plant growth trend. The functional approach is concerned with the instantaneous values that could be derived from the equation of fitted polynomials to observed growth data (Hunt, 1979; Parsons & Hunt, 1981; Poorter, 1989a). The functional approach uses a regression procedure to adjust for deviations in the data from the overall trend. It depicts a clearer picture of the reality of plant growth when a series of observational data is disturbed by random errors (Parsons & Hunt, 1981). The functional approach integrates statistical analyses and provides a good perception of ontogenetic drift.

Another advantage of the functional approach is that it enhances understanding of a process that is complex to explain (Hunt, 1982). Therefore, a functional approach is used to discuss variability that cannot be explained simply under the classical approach.

### **3.2.5 Statistical analysis**

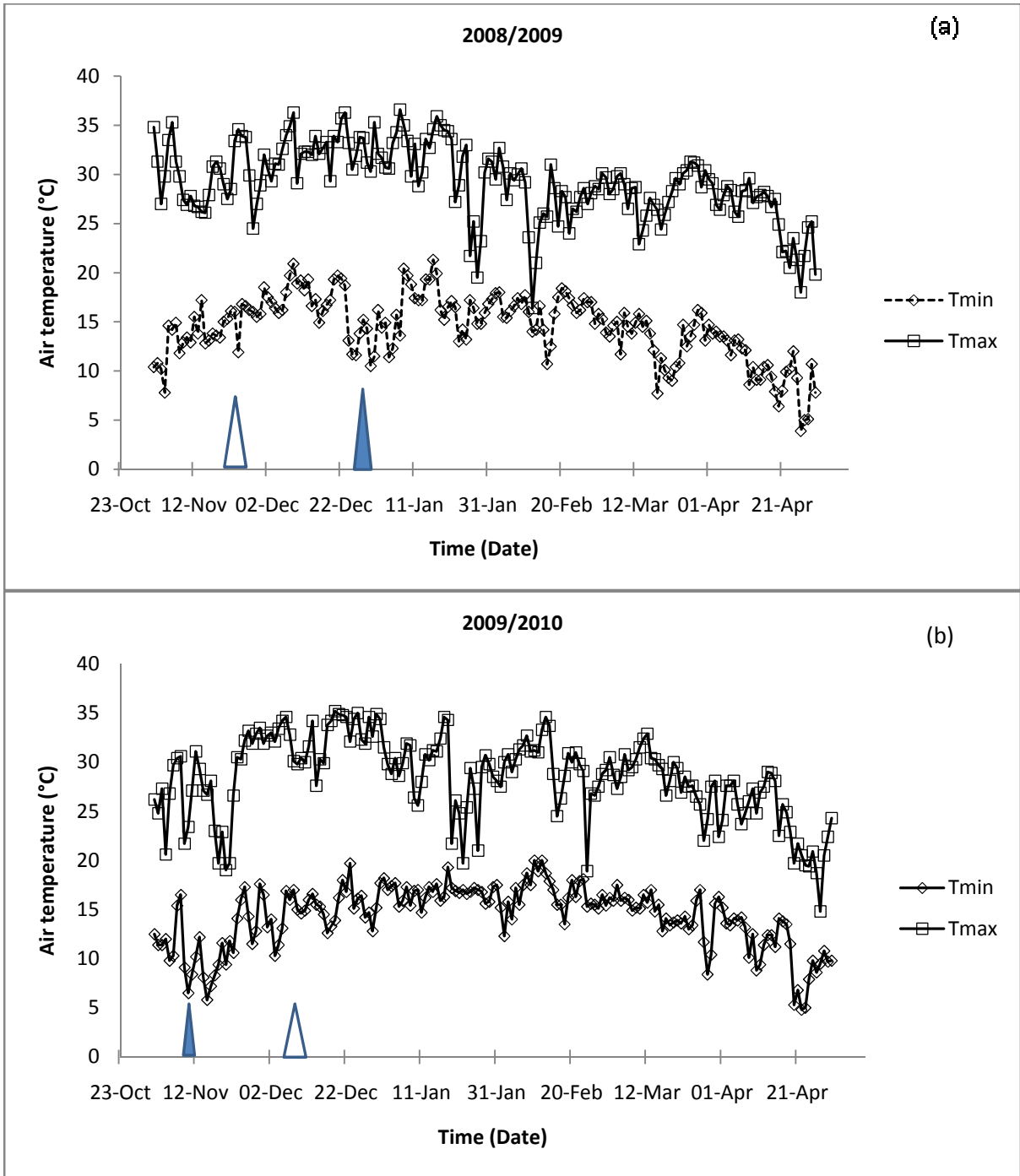
Statistical analyses were done with the Statistical Analysis System (SAS) program 9.2 package for Windows V8 (Statistical Analysis System Institute Inc, 1999-2010). Means were compared by least significant difference (LSD) test at a probability level of 5% using the Duncan Multiple Range test.

## **3.3 RESULTS AND DISCUSSION**

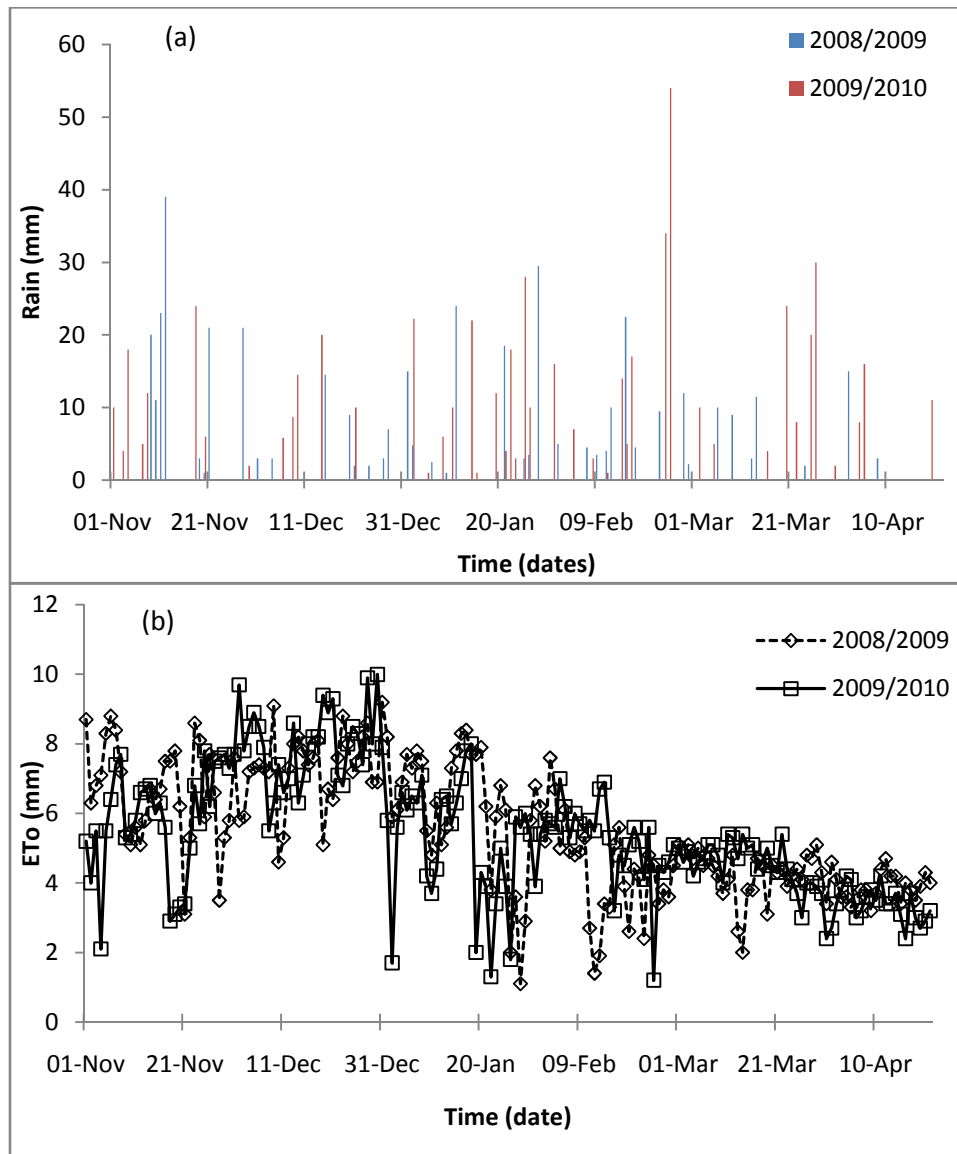
### **3.3.1 Weather conditions**

The automatic weather station installed and managed by the ARC-ISCW on the experimental site was the source of the weather variables. Figure 3.1 shows that the patterns of minimum and maximum air temperatures for the two seasons (2008/2009 & 2009/2010) were similar. The minimum and maximum temperatures ranged from 3.9°C to 21.3°C and 16.4°C to 36.6°C for the first season and 4.8°C to 20.0°C and 14.8°C to 35.2°C for the second season. These two seasons were considered to be warmer than long-term climatic conditions of Bloemfontein (SAWS, 2002). The conditions were suitable for cultivation of amaranthus and pearl millet as they are both adapted to high temperatures, semi-arid and arid conditions. Rainfall distribution for the two seasons indicated that the 2009/2010 season was wetter (575 mm) than the 2008/2009 season (415 mm) (Figure 3.2). Amaranth was transplanted on 30 December for the 2008/2009 season while it was transplanted on 11 November for the 2009/2010 season. In the first season (2008/2009), pearl millet was planted on the 28 November while it was done on 16 December during the second season (2009/2010). Apart from the months of November and December, the rest of the 2009/2010 season had more rainfall than the 2008/2009 season. Both seasons received rain events of more than 30 mm per day, which was once in November for the 2008/2009 season and twice in February for the 2009/2010 season. In the 2008/2009 season, the transplanting and sowing dates of amaranthus and pearl millet coincided with the incidence of rainfalls. In 2009/2010, there was no rain at the transplanting of amaranthus and sowing of pearl millet, making crop establishment a challenge in terms of management. Reference evapotranspiration (ET<sub>o</sub>) for the two seasons shows decline with months after the peak was in January (Figure 3.2). However, at transplanting/planting for both crops and the two seasons, the ET<sub>o</sub> for the month of December was higher in the 2009/2010 season compared to the 2008/2009 season. The ET<sub>o</sub> for amaranthus growing season was higher during the 2009/2010 season than that of the two lines of pearl millet for the same growing season.





**Figure 3.1** Daily minimum ( $T_{\min}$ ) and maximum air temperature ( $T_{\max}$ ) at the experimental site, Kenilworth, Bloemfontein for the two cropping seasons (a) 2008/2009 (b) 2009/2010. Blocked and unblocked arrows represent transplanting/planting dates for amaranthus and pearl millet respectively.



**Figure 3.2** (a) Daily rainfall and (b) reference evapotranspiration (ETo) at the experimental site, Kenilworth, Bloemfontein for the two cropping seasons (2008/2009 & 2009/2010).

### 3.3.2 Phenological stages

#### 3.3.2.1 Amaranthus

Differences in the growing degree days for the two seasons reflect the influence of planting dates (Table 3.1). Each stage of the crop development required more thermal time during the second season (2009/2010) than the first (2008/2009) as transplanting was done on the 30 December during the first season and in mid-November during the second season. This might also be due to the fact that seasonal ETo is also higher in the 2009/2010 than the 2008/2009. Therefore, it will take each growth stage of amaranthus longer time to complete in the 2009/2010 season than in 2008/2009 season. The highest TT recorded during the 2008/2009 season (800 °C d) was found in the plants from the W5 plots while the highest in the 2009/2010 season was in the plants from the W3 plots (1300 °C d). However, plants from the rainfed (W1) plots accumulated the lowest TT (641 °C d) during the

2008/2009 season while plants from the W2 plots accumulated the least (1012 °C d) in 2009/2010 season. The two treatments (W2 and W1) had the lowest amount of water applied compared to the rest of the treatments. This might be an indication that less irrigation might be beneficial to amaranthus rather than large amounts of irrigation water or the treatments with less water might grow faster to escape water stress. Thermal time accumulation for the early vegetative stage in all the treatments for each season was more than 50% of the total accumulated TT for each of the treatments. This shows that understanding crop response to temperature helps to predict developmental process and yield (Atkinson & Porter, 1996).

**Table 3.1** Thermal time (°C d) accumulated for the different growth stages of amaranthus for the two seasons (2008/2009 & 2009/2010)

2008/2009 season				
Treatments	Early vegetative	Mid-vegetative	Late vegetative	Total
W5	569c	81a	150d	800c
W4	552bc	160c	72b	784bc
W3	569c	114b	72b	755b
W2	552bc	82a	97c	731b
W1	465a	114b	62a	641a
2009/2010 season				
Treatments	Early vegetative	Mid-vegetative	Late vegetative	Total
W5	797c	139a	107a	1043b
W4	780b	156b	345.b	1281c
W3	764a	189c	348b	1300c
W2	733a	137a	142a	1012a
W1	799c	153b	333b	1284c

Early vegetative 30% of the final size of the harvestable plant parts; Mid-vegetative 50% of the final size of the harvestable plant parts; Late vegetative 70% of the final size of the harvestable plant parts. Values in the same column not sharing the same letter differ significantly at LSD (P=0.05).

Growth parameters are discussed by year because of the significant differences between the seasons (Table 3.2). Irrespective of the treatments, when compared at the same time for the number of leaves per plant, plant height and number of branches per plant, amaranthus performed better in the first season compare to the second season for all the parameters (Figure 3.3). However, in 2008/2009, there was a significant difference between the treatments with the least irrigated plots (W2) producing the highest number of leaves per plant (Fig. 3.3a). At 60 days after transplanting, W2 also produced the highest number of leaves in 2009/2010 (Fig. 3.3b). Though, the number of leaves per plant was significantly different for the two years but overall, the treatments were not different statistically (Table 3.2). Perhaps, larger samples could have been taken however, in a line source sprinkler system, this is not possible due to small width of the treatments plots. As individual plants in a field experiment often vary to a great extent, resulting in large “noise”, one may not expect the differences

to be significant. Despite this, they will nevertheless be discussed. Across all the treatments, the 2009/2010 season had lower number of leaves per plant than that of 2008/2009 at 35 days after transplanting. The W2 plots also produced the tallest plants in 2008/2009, with the height of 138cm (Figure 3.3c). The height of the W2 plants only reached 85 cm in 2009/2010, although they were not significantly different from the W3 plants (87 cm), the tallest for that season. The shortest plants were found in the W1 plots during the 2008/2009 season at a height of 91 cm 52 days after transplanting. They were taller than the tallest plants found in the W3 plots during the 2009/2010 season at a height of 87 cm 56 days after transplanting. The relationship between crop growth and the environment is not a simple one, as the plant somehow integrates the environment it experiences. Therefore an integrative process should also be used during the analysis. The largest number of branches per plant in the 2008/2009 season was found in plots that had received the least irrigation (W2) while the lowest number of branches per plant was found in the plots maintained near DUL (W5). In the 2009/2010 season, rainfed plots produced plants with the highest number of branches per plant, while fully irrigated plots were among the plots with the least number of branches per plant. The fully irrigated plots produced plants with the least number of branches per plant in the both 2008/2009 and 2009/2010 seasons with 25 and 21 branches. This seems to indicate that there is a trend that under conditions with a good water supply, the plants will produce fewer branches, and the opposite, under water deficit stress where the plants tend to initiate and produce more branches. Crop establishment was a challenge during the transplanting which might have imposed stress on the crop. Plants exhibiting short plant height, low number of leaves and branches in 2009/2010 season might have experienced a water stress condition during this time.

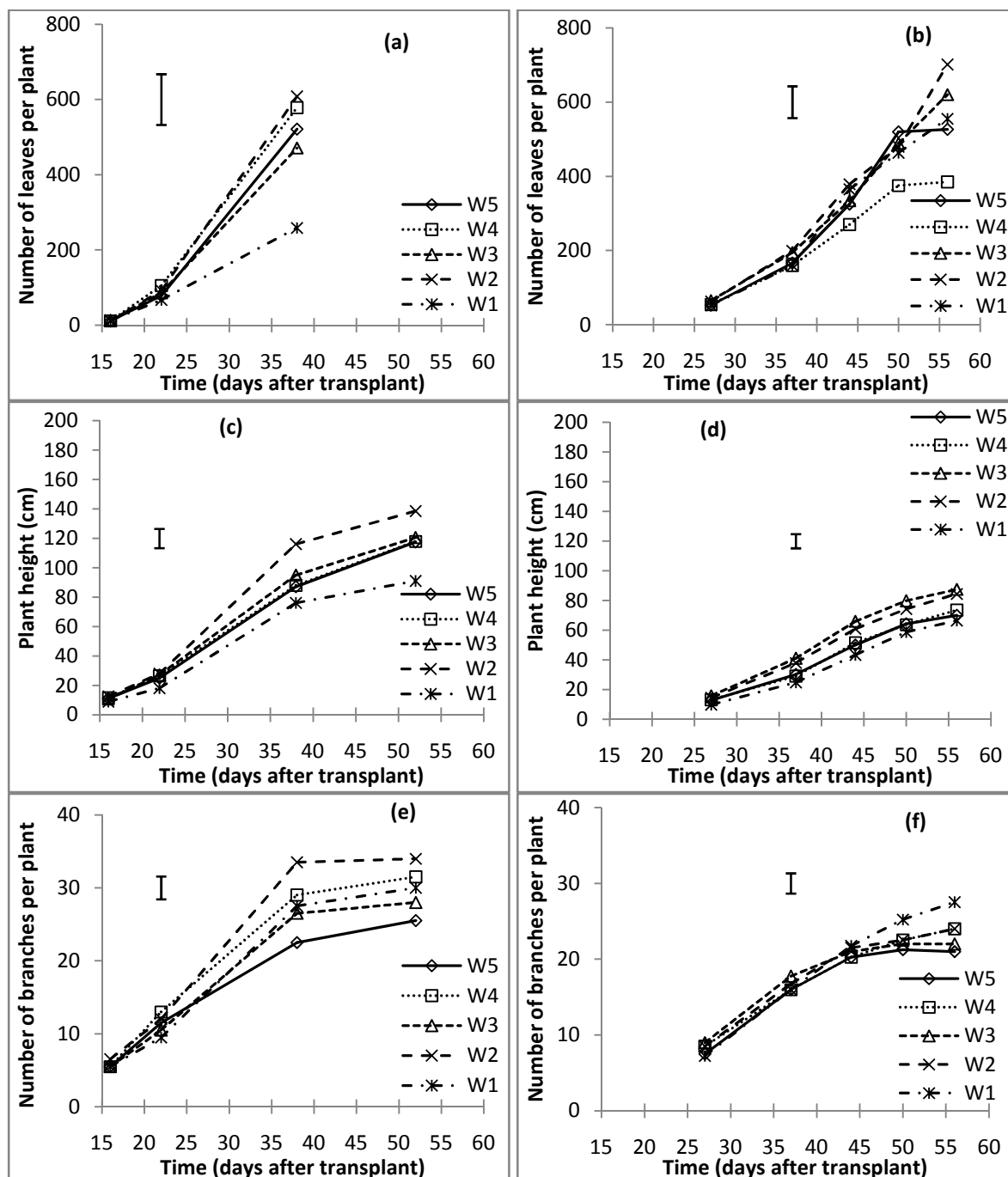
**Table 3.2** Mean sum of squares from the analysis of variance (ANOVA) of the amaranthus growth parameters

	DF	Mean squares		
		NL	PH	NB
Year	1	84740.71*	8262.11*	967.26**
Treatments	4	7107.98 (ns)	1120.48**	14.54 (ns)

NL = Number of leaves per plant; PH = Plant height; NB = Number of branches per plant; DF = degrees of Freedom  
 \*Significant at  $p < 0.05$ ; \*\* Significant at  $p < 0.01$ ; ns = not significant

Omami (2005) reported that amaranthus developed avoidance mechanism in response to water stress by reducing water that was loss through transpiration with senescence of leaves and reduction of leaf stomatal conductance. This mechanism was also observed in quinoa which is in the same family as amaranthus. Quinoa may avoid water stress through development of a deep, dense root system and through reduction in leaf area by senescence of leaves (Jacobsen *et al.*, 2003). However, water and nutrient application improves growth and development of amaranthus. In a study carried out by Okunade *et al.* (2009), irrigation significantly increased plant height of okra and amaranthus at different stages of development. Regarding the effect of nutrients on amaranthus growth and

development, Ayodele (2002) reported an increase in vegetative growth (plant height and number of leaves) with the application of inorganic fertilizer to amaranthus compared to a control treatment with zero application of fertilizer. Similarly, Akanbi and Togun (2002) and Omolayo *et al.* (2011) reported that plant height, number of leaves and leaf area of amaranthus increased with the application of organic manure and compost. However, these aspects were not included in this study.



**Figure 3.3** (a-2008/2009, b-2009/2010) Number of leaves per plant, (c-2008/2009, d-2009/2010) plant height and (e-2008/2009, f-2009/2010) number of branches of amaranthus as affected by water treatment.

### 3.3.2.2 Pearl millet

Growth stages were classified into three namely: 'Vegetative' stage - which starts from emergence to flowering; 'Flowering' - which starts with the emergence of flowers and terminates when 50% of the plant population of a plot have emerged flowers; and 'Grain filling' starts immediately after the fertilization of the flowers and ends at maturity. This is the period at which assimilates produced are mainly for grain formation. The accumulated thermal time for Monyaloti was higher than that of GCI 17 during both seasons (Table 3.3). Higher accumulated thermal time may be explained by the longer growth duration of Monyaloti compared to GCI 17. However, both lines of pearl millet accumulated more thermal time during the 2008/2009 season as they were planted 2 weeks earlier. Plants from the rainfed plots of the two lines of pearl millet accumulated the highest TT during the vegetative stage for both seasons. It was observed that accumulated TT for all the treatments during the flowering stage was higher in GCI 17 plots for the 2008/2009 season than that of Monyaloti for the same season. The reverse was the case for the second season. The lowest TT recorded for the flowering stage for both lines of pearl millet across both seasons was found for the GCI 17 rainfed plot with only 76°C d during the 2008/2009 season. This could be a drought escape coping mechanism for the crop against water stress. The Mabhaudhi (2012) and Farooq *et al.* (2009) reviews stated that crops with drought escape mechanism normally complete their growth cycle before water stress becomes terminal. Plants are expected to spend a fixed amount of thermal time for a particular developmental stage as well as the whole life cycle (Olivier & Annandale, 1998). The concepts of thermal time and temperature have been used extensively to explain growth and development in pearl millet (Craufurd & Bidinger, 1988). Investigation by Singh *et al.* (1998) also supports the findings of this study that more thermal time is spent to reach the reproductive stage than for other phenological stages. Kamkar *et al.* (2006) investigated germination of three species of millet in relation to cardinal temperature. They reported that germination rate of different species of millet increased with the increase in temperature up to 35°C. Craufurd and Bidinger (1988), using 10°C as base temperature for pearl millet found the range of thermal time for the duration of the vegetative phase to be between 360 and 500°C d. This is much lower than the values found in this study, probably due to different origin of lines, as like sorghum there is a wide spectrum of genetic material. The lowest accumulated thermal time during the vegetative stage of both lines of pearl millet and across all treatments was 710°C d which is higher than that reported by Craufurd and Bidinger (1988).

The water treatments did not have significant effect on the number of leaves per main shoot of the two lines of pearl millet (Figure 3.4). In the GCI 17 plots, the W5 produced the highest and the W1 plots the lowest number of leaves throughout the season. However, Monyaloti had a larger number of leaves at the end of the season, irrespective of the treatments. Leaves on tillers may contribute to the increase in leaf area per plant per stand in the plots of both lines. The plant height was also not significantly different according to the treatments (Figure 3.4).

**Table 3.3** Thermal time accumulated (°C d) for the different growth stages for the two lines of pearl millet (a) 2008/09 and (b) 2009/2010

a)

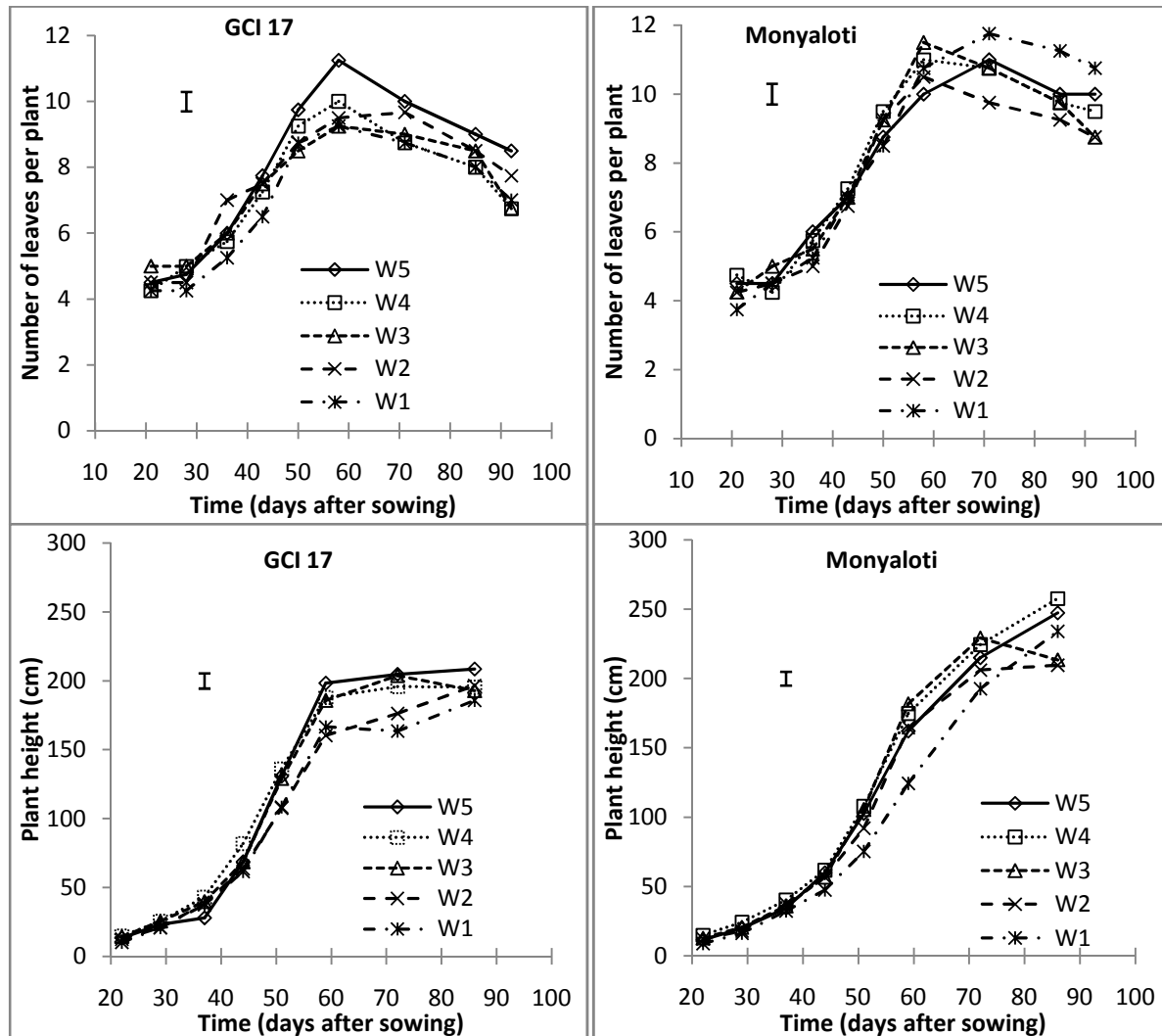
Treatments	GCI 17				Monyaloti				
	Vegetative	Flowering	Grain filling	Total	Treatments	Vegetative	Flowering	Grain filling	Total
W5	710a	277.6b	567c	1555a	W5	944a	125a	677c	1745b
W4	710a	277.6b	567c	1555a	W4	944a	125a	677c	1745b
W3	710a	277.6b	567c	1555a	W3	944a	125a	677c	1745b
W2	725a	310.1c	551b	1586b	W2	955a	114a	518b	1586a
W1	1036b	76a	521a	1633c	W1	1036b	259b	451a	1745b

b)

Treatments	GCI 17				Monyaloti				
	Vegetative	Flowering	Grain filling	Total	Treatments	Vegetative	Flowering	Grain filling	Total
W5	717a	71a	760c	1548a	W5	731b	268c	762b	1761b
W4	717a	86b	744b	1548a	W4	717a	227a	777c	1721a
W3	717a	86b	744b	1548a	W3	731b	268c	762b	1761b
W2	717a	208c	622a	1548a	W2	731b	158a	832d	1721a
W1	731b	196c	622a	1548a	W1	744b	253b	724a	1721a

Values in the same column not sharing the same letter differ significantly at LSD (P=0.05).

There was a steady increase in height for all the treatments up until 60 days after sowing in the GCI 17 plots after which the height was at the peak level. Increase in height did not stop in the Monyaloti plots until after 86 days after sowing (Figure 3.4).

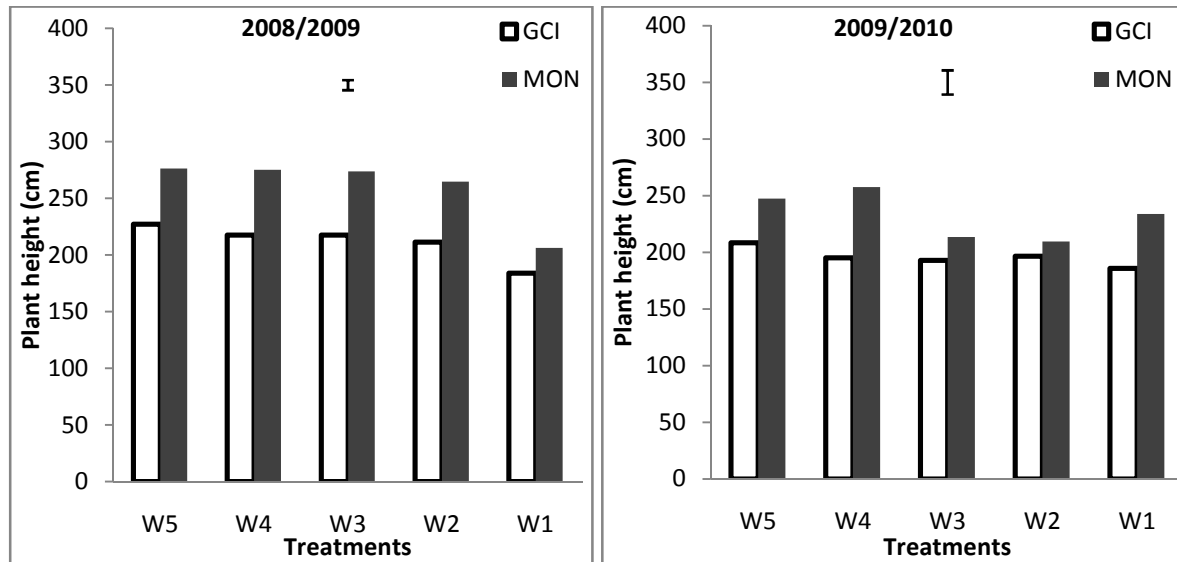


**Figure 3.4** Number of leaves per main shoot and plant height of pearl millet as affected by water treatment during 2009/2010 season.

For both seasons, the two lines had significantly different final plant heights (Figure 3.5). The local variety is taller than the improved line of pearl millet, irrespective of treatment and season. The difference in height between the two lines could be associated with the genetic component of the lines. Treatments significantly affected the two lines of pearl millets during both seasons. In the 2008/2009 season, for both lines of pearl millet, the rainfed plots (W1) produced the shortest plants while there was no difference in the height of other water treatments. In 2009/2010, none of the treatments had any significant effect on the GCI 17 but there was a significant difference within the treatments for Monyaloti. The treatments of W5 and W4 produced the tallest plants in 2009/2010 in the Monyaloti plots while those in the W3 and W2 were the shortest (Figure 3.5). This shows that



irrigation improves plant height irrespective of the lines of pearl millet. Maas *et al.* (2007) observed positive correlation between plant height and grain yield of pearl millet. Therefore, as irrigation increases plant height and invariably increasing grain yield of pearl millet.



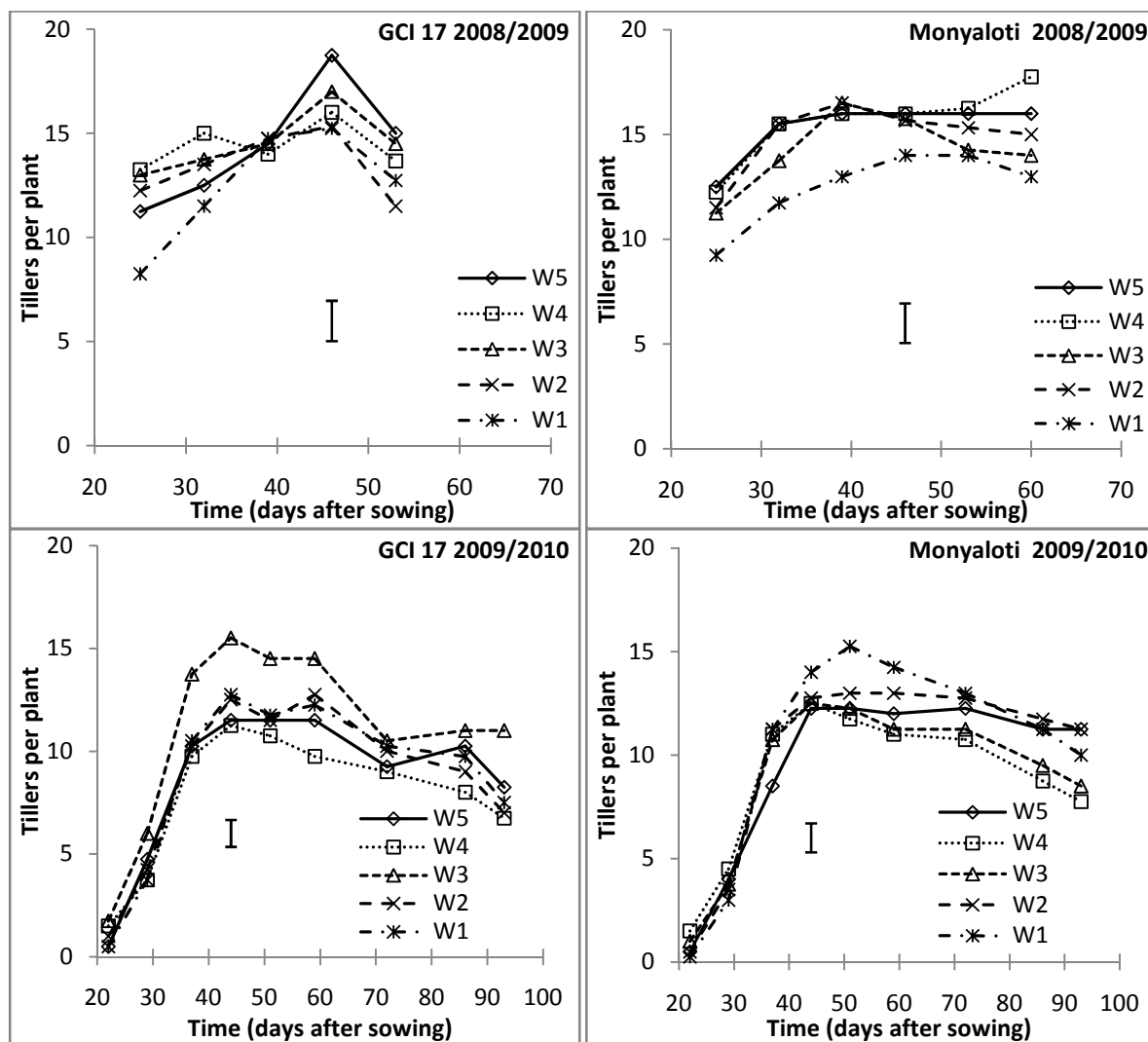
**Figure 3.5** Final plant height of the two lines of pearl millet as affected by water treatment for the two seasons (2008/2009 & 2009/2010).

During the 2008/2009 season, there was no significant effect of water treatments on the number of tillers per plant in the GCI 17 plots (Figure 3.6). Although, the rainfed (W1) produced the lowest number of tillers per plant at 25 days after sowing, it was not significantly different from other treatments at 53 days after sowing. However, Monyaloti responded with significant differences at different water levels in the same season (Figure 3.6). The W1 plots had the lowest number of tillers per plant from 25 days till 53 days after sowing. The highest number of tillers per plant for the two lines during the 2008/2009 season was 18, found in the plots of W5 (53 days after sowing) and in W4 (60 days after sowing) for the GCI 17 and Monyaloti lines respectively, this shows that when given adequate water, both pearl millet lines can produce a favourable number of fruiting stems with potential for higher grain production. Production of tillers in the GCI 17 line was significantly affected by water treatments in the 2009/2010 season (Figure 3.6). Plants from the W3 plots produced the most tillers per plant throughout the 2009/2010 season; however, there was no significant effect of the treatments on tillers per plant in Monyaloti plots during the 2009/2010 season. The peak of number of tillers produced per plant in 2009/2010 season was 15, found in the W3 and W1 plots of the GCI 17 and Monyaloti lines. The number of tillers per plant on 93 days after sowing for the two lines of pearl millet during the 2009/2010 season was between 7 and 11. High number of tillers per plant observed in W5 and W4 treatments during the 2008/2009 season illustrates the beneficial effect of irrigation on pearl millet. During the 2009/2010 season that was regarded as a wetter season, the W3 treatments (moderate irrigation) performs better than the other irrigated treatments due to the fact

that the crop the crop is adversely affected by excess water. Yamauchi *et al.* (1994) also found that pearl millet among other crops (sorghum, maize, wheat and barley) is sensitive to excessive soil water.

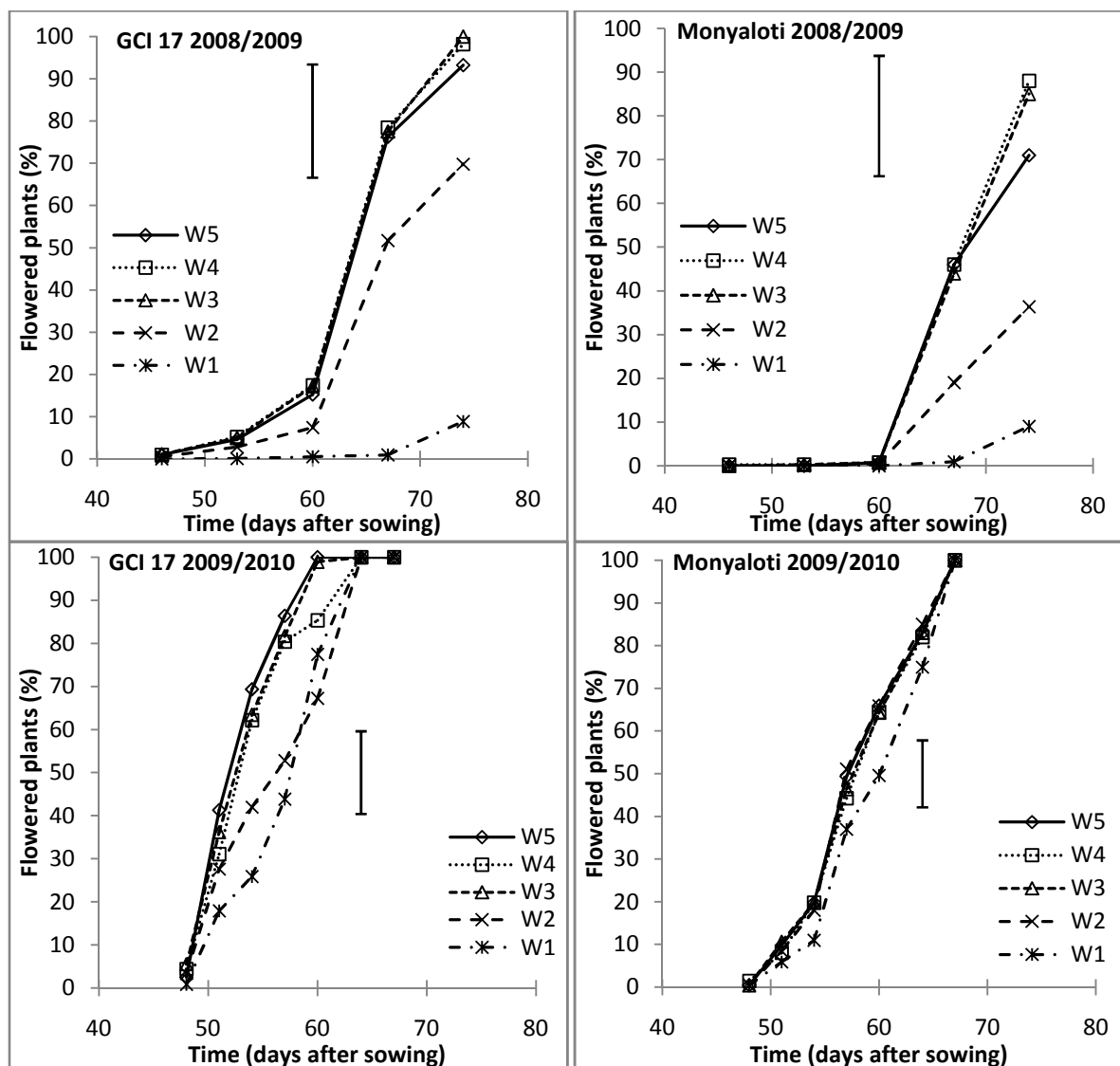
There were significant differences in flower emergence of the two lines of pearl millet between the both seasons (Figure 3.7). During the 2008/2009 season, flower heads emergence was completed earlier on the adequately watered plots of W5, W4 and W3, than in the water stressed plots of W2 and the rainfed (W1), which only attained very low number of heads per tiller. Though, during the first season, flowering measurement was not carried out till all the treatments achieved 100% flowering, but the flowering was delayed in rainfed plots than the irrigated plots. This shows that irrigation hastened and enhanced flowering in pearl millet. For the GCI 17 plots in the 2009/2010 season, the same trend as 2008/2009 was found with flowers stalks of the plants in the W5, W4 and W3 plots emerging faster than those of the W2 and W1 plants, however, all water treatments achieved 100% flower emergence, although the W5 and W4 of GCI 17 achieved it about 10d earlier, all the treatments achieved it around the same time (67 d) in Monyaloti plots. The rainfed plots consistently had the slowest flower emergence rate in the Monyaloti plots during the 2009/2010 season. The flower emergence was faster and completion was earlier in the 2009/2010 season than the 2008/2009 season. Irrespective of irrigation, plants in the Monyaloti plots were slower to flower than GCI 17 plants, which was reflected in the longer growing season discussed earlier. This could be a form of drought tolerance mechanism in Monyaloti.

The findings on irrigation effects on the number of leaves per plant correspond with Gregory and Squire (1979) who also found that irrigation have no influence on final number of leaves per plant of pearl millet in India. They reported the highest number of leaves per plant to be 12. However, contrary to irrigation treatments, photoperiod extension increased the number of leaves on the main axis of pearl millet also in India (Carberry & Campbell, 1985). In an experiment carried out in United States, it was observed that planting date had an influence on pearl millet height as a longer photoperiod produced taller plants (Maas *et al.*, 2007). Plant height can be used to evaluate yield in pearl millet as Faridullah *et al.* (2010) and Wilson *et al.* (2008) found a positive correlation between dry mass yield, grain yield and plant height in pearl millet. Therefore, tillers produced by pearl millet contribute to the yield of the crop. Gregory and Squire (1979) found that irrigated pearl millet produced higher yield than rainfed because more tillers survived to produce grain in the irrigated plots. This result supports the findings from the Kenilworth site.



**Figure 3.6** Tillers per plant of pearl millet as affected by water treatment during 2008/2009 and 2009/2010 seasons.

Low plant density can increase both tiller production and the number of tillers with heads at maturity (Carberry & Campbell, 1985; Carberry *et al.*, 1985). Under a range of population densities, different numbers of productive tillers were recorded for pearl millet grown under natural photoperiod conditions of 13.5 hours in India (Carberry & Campbell, 1985). van Oosterom *et al.* (2003) observed a correlation between number of leaves on the main shoot and tillers per plant in pearl millet. High numbers of tillers per plant were produced in varieties of pearl millet with higher number of leaves. The findings of Mahalakshmi and Bidinger (1985a) were in agreement with the result of this study as they also found a delay in flowering of pearl millet due to water stress. The reproductive stage has been identified as the most sensitive to water stress of the phenological stages in grain crops (Saini & Westgate, 1999). Water stress at this phenological phase of pearl millet lead to a reduction in yield (Mahalakshmi & Bidinger, 1985b).

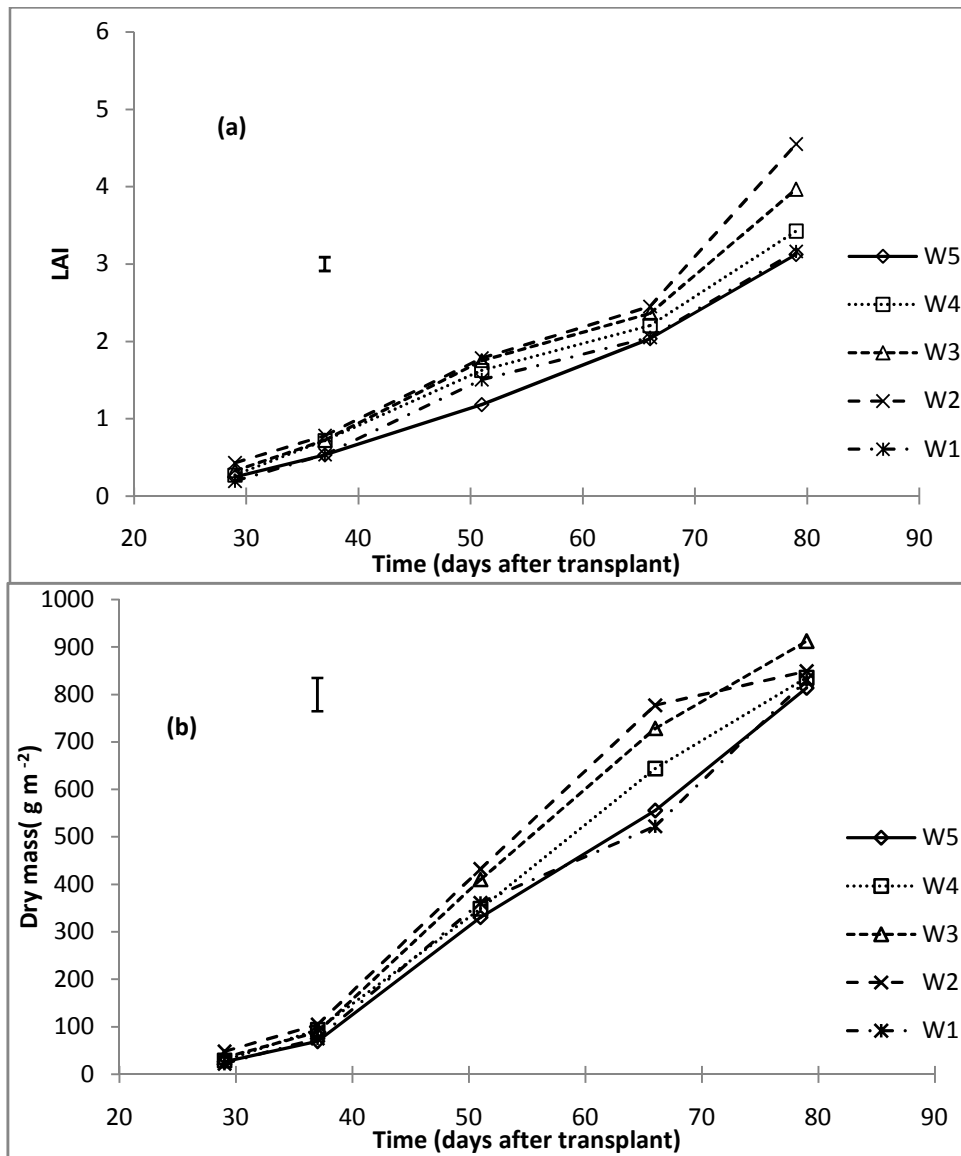


**Figure 3.7** Flowering percentage of the two lines of pearl millet as affected by water treatment for the two seasons (2008/2009 & 2009/2010).

### 3.3.3 Growth analysis

#### 3.3.3.1 Amaranthus (2009/2010)

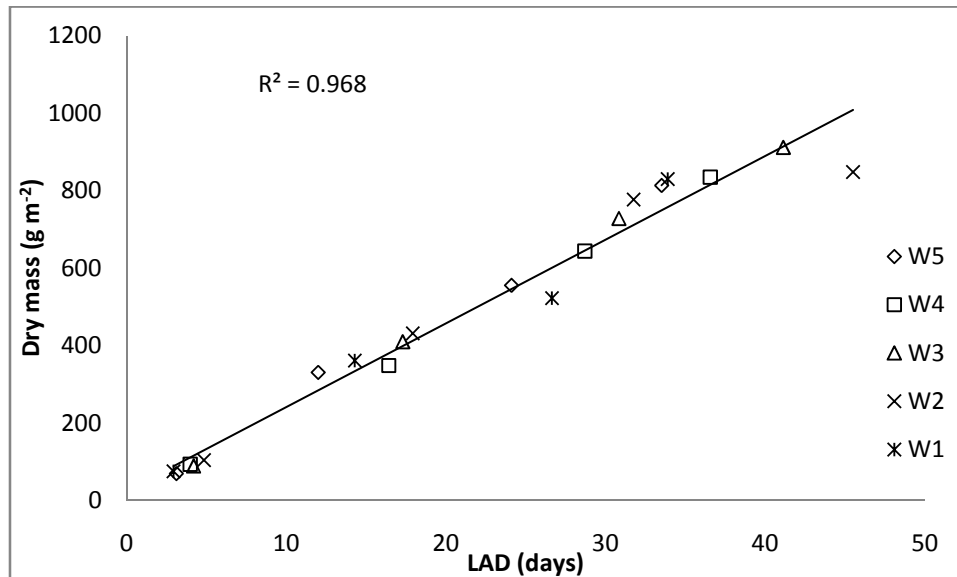
Growth analysis for amaranthus will only be discussed for 2009/2010 season as leaf area was not measured in the 2008/2009 season. Leaf area is an important component of the listed growth analysis parameters. There was a significant difference between the leaf area indices (LAI) of all the treatments. The LAI for all the treatments increased steadily with time. At the end of the measurements, on day 79 after transplant, (measurement stopped due to technical reason), W2 had the highest LAI, while W5 and the rainfed (W1) plants recorded the lowest (Figure 3.8). This implies that one could expect that by the end of the season (at final harvest) a larger canopy would be produced in the plots receiving the lowest irrigation application (W2).



**Figure 3.8** Leaf area index (LAI) and dry mass produced as affected by water treatment in amaranthus plot (2009/2010).

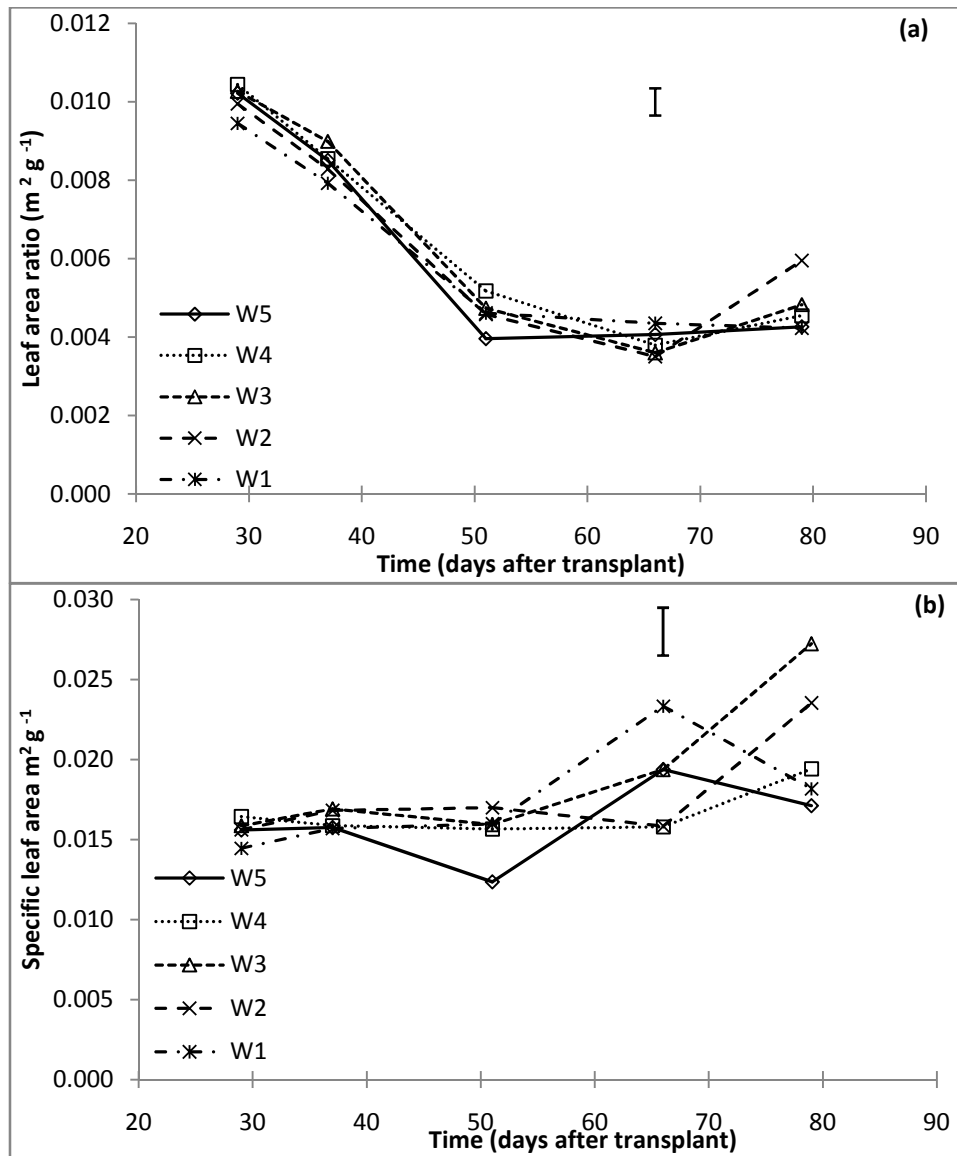
Results of LAI are contrary to the expectation of this study that more water available should help the crop to grow more leaves and increase its LAI. This observation might be due to the sensitivity of the crop to excessive water. Excessive water might impose stress due to lack of aeration for the roots zone because soil pore spaces were continually filled with water. Dry mass of amaranthus was significantly affected by water treatment (Figure 3.8). W2 and W3 were not significantly different but W2 steadily produced the highest biomass until 66 days after transplanting. Then, W3 produced the highest biomass at 79 days after transplanting. Plants from the W5 and W1 plots were not significantly different but produced the lowest biomass by 79 days after transplanting. There was a linear relationship between the leaf area duration (LAD) and biomass production of amaranthus (Figure 3.9). Plants from the W3 plots produced more than 900 g m<sup>-2</sup> of dry mass with LAD of 41 days while it took plants from the W2 plots 32 days of LAD to produce only 777 g m<sup>-2</sup>. LAD is a function of LAI

which represents the availability of a factory to convert intercepted photosynthetically active radiation to sugars and finally to biomass. The longer a canopy stays green and functioning with active photosynthesis, the more time is available for the production of biomass.



**Figure 3.9** Relationship between leaf area duration (LAD) and above ground dry mass of amaranthus as affected by water treatment (2009/2010).

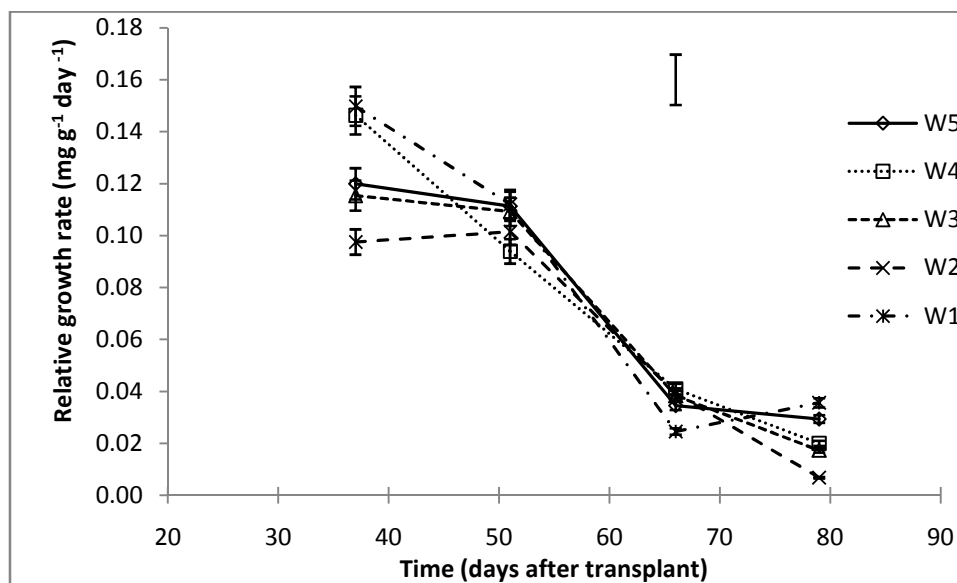
The LAR of amaranthus was not significantly influenced by the treatments at anytime throughout the season (Figure 3.10). The highest LAR was about 0.008 and 0.10 m<sup>2</sup> g<sup>-1</sup> during the early stage of the crop, while it was lower than 0.004 m<sup>2</sup> g<sup>-1</sup> at the end of the season. This would indicate that there was no variation in the productivity of the leaves on the water stressed plants compared to those kept close to DUL (i.e. adequate water). So this can infer that the water stress was not so severe as to influence or alter the structure of the leaves growing under stress conditions. This can be a sign of the resilience or tolerance of the amaranthus to water stress, that leaves have not undergone major changes in structural make-up. Irrespective of the treatments, specific leaf area (SLA) of the crop was also not significantly different (Figure 3.10). However, rainfed (W1) plants exhibited a large increase in SLA from 0.0143 m<sup>2</sup> g<sup>-1</sup> at 51 days after transplanting to 0.0210 m<sup>2</sup> g<sup>-1</sup> 66 days after transplanting while W3 increased from 0.0175 m<sup>2</sup> g<sup>-1</sup> at 66 days after transplanting to 0.0245 m<sup>2</sup> g<sup>-1</sup> 79 days after transplanting. Therefore, there was higher increase in SLA in rainfed crop than the irrigated crops. This confirms that SLA of crop is affected by the environment and with the age of a crop the thickness of the leaf decreases.



**Figure 3.10** Leaf area ratio (LAR) (a) and specific leaf area (SLA) (b) of amaranthus as affected by water treatment (2009/2010).

The relative growth rate (RGR) is the increase of total above ground dry mass per plant (Hunt, 1990). Gardner *et al.* (1985) also described relative growth rate as an indication of the effectiveness of a plant at producing new material per unit mass of the current plant size. This data shows a typical decline in RGR with time through the growing season. At 33 days after transplanting, the W1 and W4 plots significantly produced plants with the highest RGR than plants from the plots of W2 (Figure 3.11). The plants from the plots of W2 at the same time had the lowest RGR. So one could say that the rainfed treatment (W1) and W4 were the quickest to utilise their initial leaf area immediately after transplanting, however, soon the RGR from leaf weight evened out across the treatments and the advantage was lost. Close to the end of the season, W1 plants still produced new mass with an average of  $0.04 \text{ mg g}^{-1} \text{ day}^{-1}$  while the W2 plants had the lowest efficiency with RGR of  $0.007 \text{ mg g}^{-1} \text{ day}^{-1}$ .

There were significant differences in the rate of dry matter accumulation per unit leaf area across the treatments (Figure 3.12). The W5 plots produced plants with the highest increase in NAR, from  $4.35 \text{ g m}^{-2} \text{ day}^{-1}$  to  $6.88 \text{ g m}^{-2} \text{ day}^{-1}$  between 37 and 51 days after transplanting. After 51 days after transplanting, a sharp decline in NAR occurred till the end of the measurements in all the treatments as is expected and in keeping with the general pattern of growth of annuals. However, an increase was found in W1 plots between 66 and 79 days after transplanting. This observation confirms the direct relationship between the RGR and NAR (Poorter & Remkes, 1990). The RGR increase for the same period of time that NAR increase for the same treatment, W1 (see Figure 3.11). Increase in NAR may shows that more biomass was produced per unit leaf area within this period of time in rainfed plots (Konings, 1989; Poorter, 1989b).

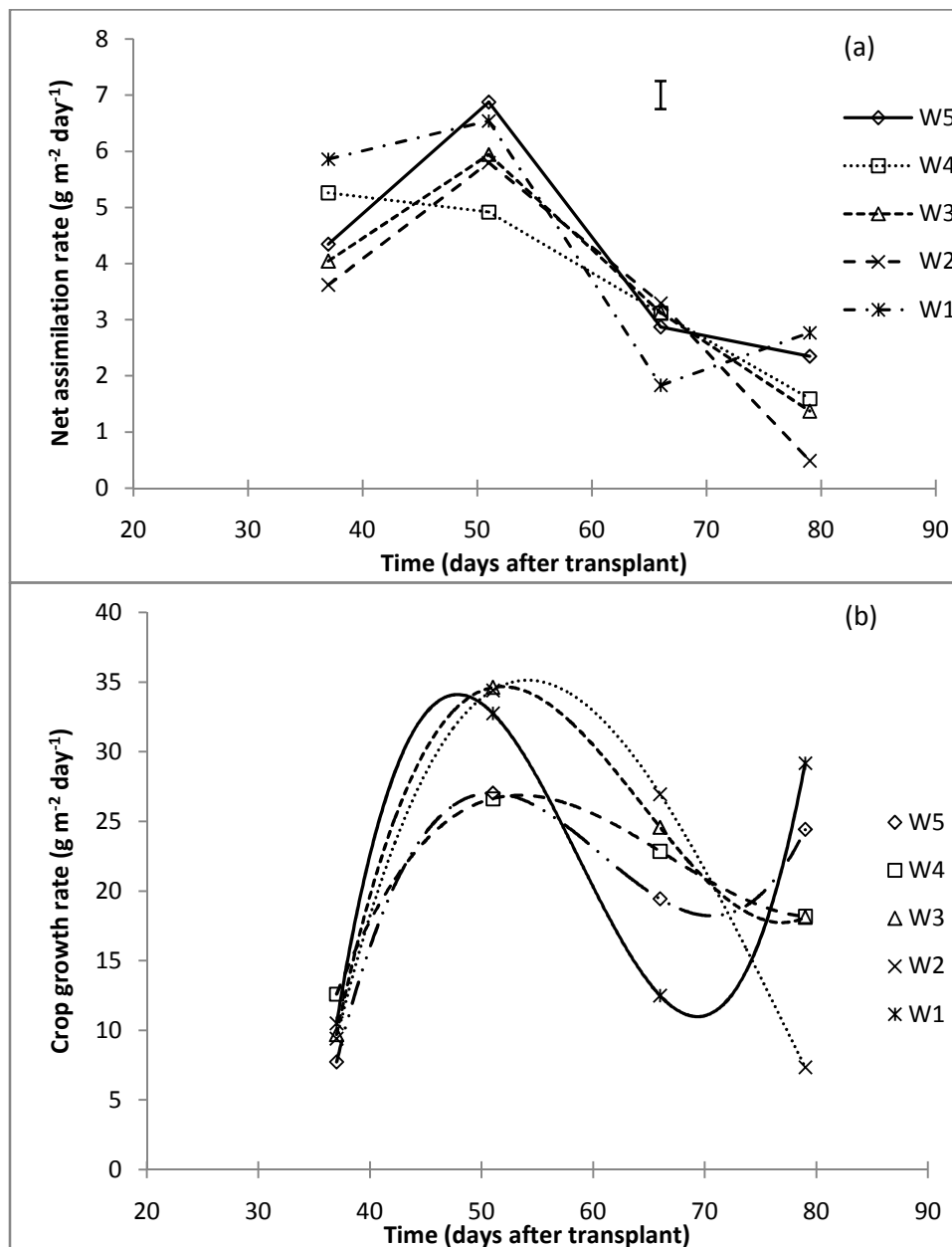


**Figure 3.11** Relative growth rate (RGR) of amaranthus as affected by water treatment (2009/2010).

The functional approach is used to describe the crop growth rate (CGR) of amaranthus as affected by water treatments in this study. The trend found for NAR and RGR was also found in CGR (Figure 3.12). The peak of increase in CGR for all the treatments was reached at around 51 and 55 days after transplanting and thereafter CGR shows a sharp decline. The highest CGR were from the plots of W1, W2 and W3 while W4 and W5 had the lowest growth rate around the peak. This is a reflection of influence of LAI on CGR. The results reveal that photosynthate produced is proportional to leaf area of the crop (Law-Ogbomo & Ajayi, 2009). Growth analysis gives good means of interpreting crop response to environment and management in terms of structural development and productivity. The growth parameter that is most sensitive to water stress is leaf growth (Hsiao, 1993). Lower leaf area per plant was observed in two genotypes of amaranthus subjected to water and salinity stresses (Omami & Hammes, 2006). The observations from this study also show that there was a significance difference between the water treatments but not in the expected directional trend. Interpretation of



linear relationship between leaf area duration (LAD) and biomass accumulation (Fig. 3.9) has to do with low accumulation of biomass under conditions of lower leaf area duration (Hsiao, 1993). This is true in this study, the longer the canopy stays green, the more biomass can be accumulated. Under favourable conditions, the rate of increase in dry mass of plant is related to the photosynthetic activity of the leaves (Evans, 1972). Since LAR is a measure of the productivity of leaves, it shows that more biomass is produced per unit of leaf area. The decline in LAR found during this study was also observed during the study of four amaranthus genotypes under optimum condition which reveals that crop biomass increased at faster rate than leaf area (Horak & Loughin, 2000).



**Figure 3.12** (a) Net assimilation rate (NAR) and (b) Crop growth rate (CGR) of amaranthus as affected by water treatment (2009/2010).

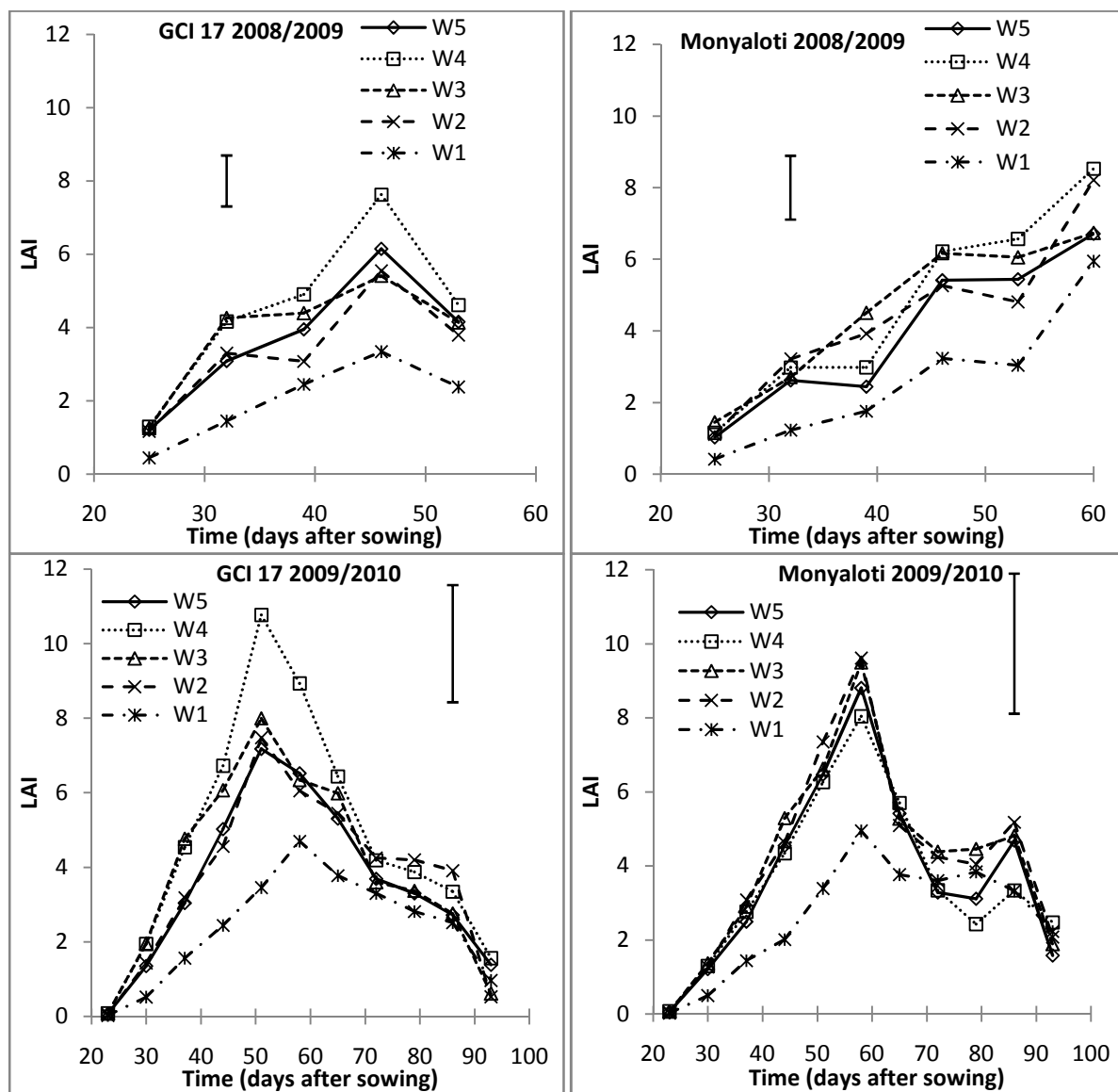
Specific leaf area (SLA) gives some indication of the thickness of leaves or of the internal structure and amount of lignin or other constituents. In an experiment exploring the effect of salinity on growth and development of amaranthus, a decrease in SLA with increase in salinity stress was reported (Omami, 2005). Low SLA means thicker leaves and exhibiting low SLA was suspected to be a coping mechanism for this crop under stress. In other leafy crops, cabbage, lettuce and spinach, higher SLA was recorded in the plots of crops cultivated under cover with higher temperature than in open air (Gimenez *et al.*, 2002). In this experiment, the increase in SLA provided more surface area for photosynthesis which might be the reason for increase in biomass accumulated in rainfed crop. There was a decrease (after 50 days after transplanting) in NAR in all the treatments which may be due to age of the leaf and partitioning of assimilates to non-photosynthetic parts of the plant (Evans, 1972). The decrease in RGR in all treatments can be related to the effects of change in biomass as the crop grows and approaches the reproductive stage (Evan, 1972). RGR decreases with decrease in amount of nitrate supplied to amaranthus (Hunt *et al.*, 1985). Increase in CGR in all the treatments was expected because of the increase in their LAI with time. Law-Ogbomo and Ajayi (2009) found increase in CGR with increase in planting densities and application of poultry manure. The increase in CGR of amaranthus from 70 days after transplanting may be due to the ability of amaranthus to regrow new leaves and branches when water becomes available. Amaranthus can undergo temporary wilting and revive after rainfall as a means of coping or drought tolerance (Myers, 1996).

#### 3.3.3.2 Pearl millet

Growth rates are reported for the two lines and both seasons. Leaf area index (LAI) was significantly different within the season, for the two lines of pearl millet and the water treatments (Figure 3.13). During the 2008/2009 and 2009/2010 seasons, the plants of GCI 17 in W4 plots had the highest LAI of 7.6 and 10.8 respectively. Meanwhile, rainfed (W1) plants had the lowest LAI irrespective of season and line of the crop. In all these instances, the LAI for W1 plants was never higher than 5, showing a severe effect of lack of available water on the leaf growth. The maximum LAI was attained between the 50 and 60 days after sowing for the two lines of pearl millet, signifying the peak of canopy cover. The LAI for the crop was significantly higher in the 2009/2010 season than the previous one, which can be attributed to higher rainfall received during that season.

Biomass production is an important parameter in growth analysis. Biomass production was significantly affected by water treatments in pearl millet plots (Figure 3.14). The trend found in biomass production was similar to that of LAI. At the end of the measurements, both lines of pearl millet in W4 plots produced the highest biomass for the two seasons, while W1 plants produced the lowest biomass for the two lines in both seasons. In the second season, 93 days after sowing, Monyaloti had produced more biomass than the GCI 17 in the W5, W4 and W3 plots with differences of 131, 470 and 443 g m<sup>-2</sup> respectively (Fig. 3.14). Therefore, the rate of biomass accumulation in

Monyaloti was faster than in GCI 17. The relationship between leaf area duration (LAD) and biomass produced revealed a linear relationship between the two parameters with a good fit (Figure 3.15). The longer leaf area was exposed to photosynthetic radiation, the higher the biomass produced by both lines of pearl millet during both seasons (Figure 3.15). There was significant difference in LAR between the two seasons (Figure 3.16). The peak of LAR in GCI 17 during the 2008/2009 season was  $0.003\text{m}^2 \text{g}^{-1}$  while it was  $0.009\text{m}^2 \text{g}^{-1}$  in the 2009/2010 season (Figure 3.16). Higher LAR during the 2009/2010 season might be attributed to the fact that more water was received through rainfall which enhanced the growth of the crop. There was a sharp decline in LAR for all the treatments in both seasons. The decline started 30 days after sowing with the highest LAR found in Monyaloti plots of W3 in both seasons and lines.



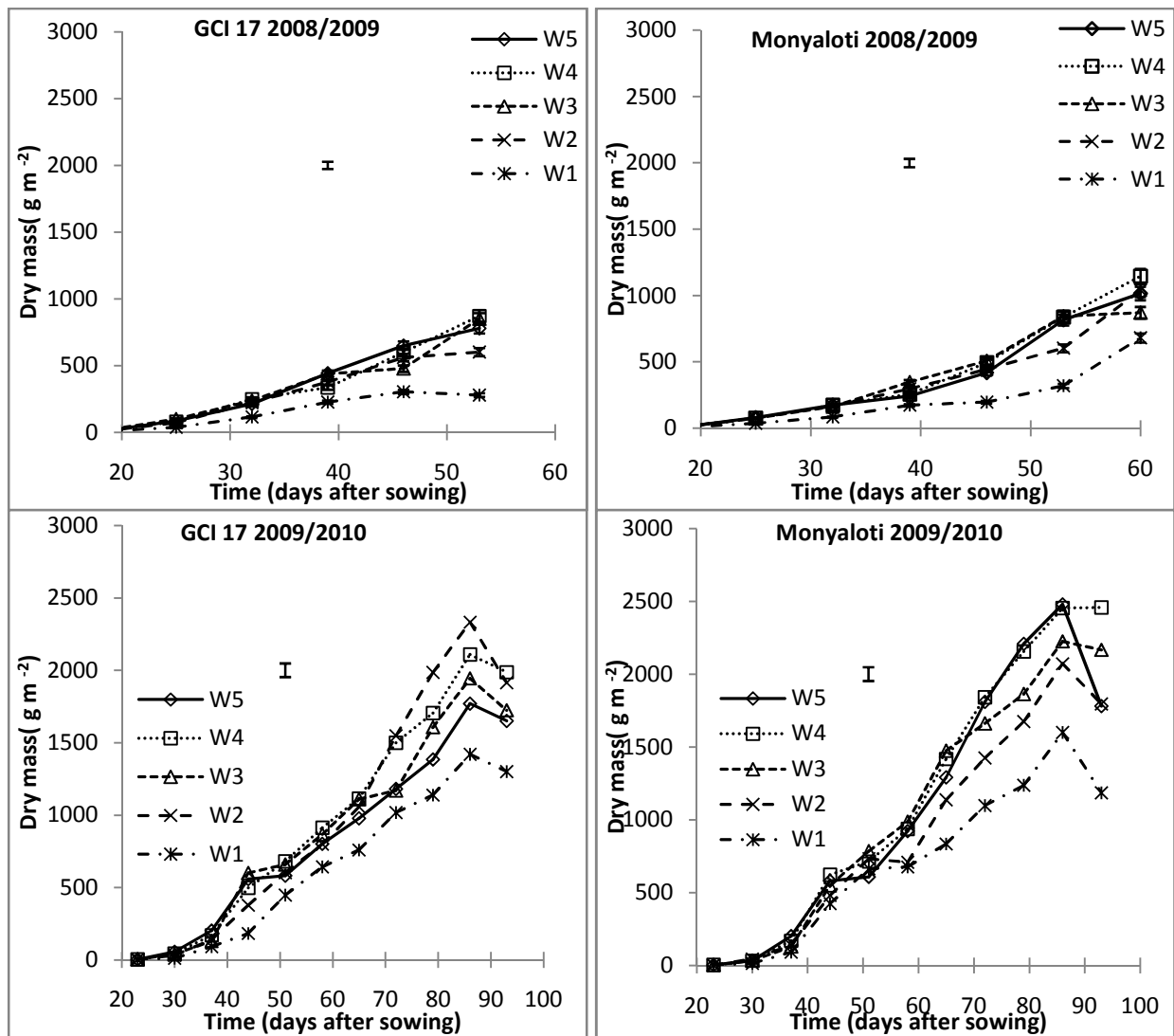
**Figure 3.13** Leaf area index (LAI) as affected by water treatment in pearl millet plots (2008/2009 & 2009/2010).

In the absence of measurement of leaf dry mass for the two lines of pearl millet during the first season, specific leaf area (SLA) is only reported for the second season. SLA measures the thickness of leaves of a crop (Hunt, 1990) such that the lower the SLA, the thicker the leaves. SLA was significantly different within the treatments at the beginning of the season (Figure 3.17). The same trend was followed for SLA for both lines of pearl millet. The W3 had the highest SLA of  $0.140\text{m}^2\text{g}^{-1}$  in GCI 17 plots and  $0.082\text{m}^2\text{g}^{-1}$  in Monyaloti plots and the lowest was in the W1 plots of GCI 17 with  $0.041\text{m}^2\text{g}^{-1}$  and Monyaloti with  $0.038\text{m}^2\text{g}^{-1}$ . This shows that the W3 had the thinnest leaves and that the W1 leaves were less robust and thick. The thickness of leaves in the rainfed plots might be a means of conserving moisture in the leaves and reduce transpiration during water stress incidence. The relative growth rate (RGR) declined with time after 25 days after sowing during the two seasons and for both lines of pearl millet (Figure 3.18). Irrespective of the treatments, the two lines of pearl millet did not differ significantly in RGR. The RGR reached the lowest value at 45 days after sowing during the first season and 50 days after sowing in the second season in the two lines, so showed similar trend relative to the initial canopy sizes.

The NAR and CGR for the 2008/2009 season exhibited large variation due to small number of sampling harvest and times during the season. Therefore, only the 2009/2010 season data will be presented for NAR and CGR. For clearer change in growth, the functional approach will also be used to present the effect of the treatments on these two parameters. Except for the W1 treatment, Figure 3.19 illustrated the decline in the NAR for the two lines of pearl millet until about 50-60 days after sowing after which the NAR tended to increase. This shows the trend of NAR with plant age. At 30 days after sowing, the highest NAR in improved line, GCI 17 was found in the plots of W5 with  $93\text{g m}^{-2}\text{day}^{-1}$  while that of local variety, Monyaloti was in the plots of W2 with  $92\text{g m}^{-2}\text{day}^{-1}$ , so it is at a similar level, but observed in a different treatment showing that Monyaloti probably was better adapted to water stress situations. The CGR of the two lines of pearl millet increased steadily in all the treatments during the 2009/2010 season till 44 days after sowing (Figure 3.20). In the GCI 17 plots, the W5 treatments had the highest CGR 44 days after sowing while the W1 treatment had the least. The same trend was found in Monyaloti plots. However, the W2 treatment had the highest CGR at 86 days after sowing in the plots of the two lines of pearl millet, again giving an indication of it being more suitable to drought conditions.

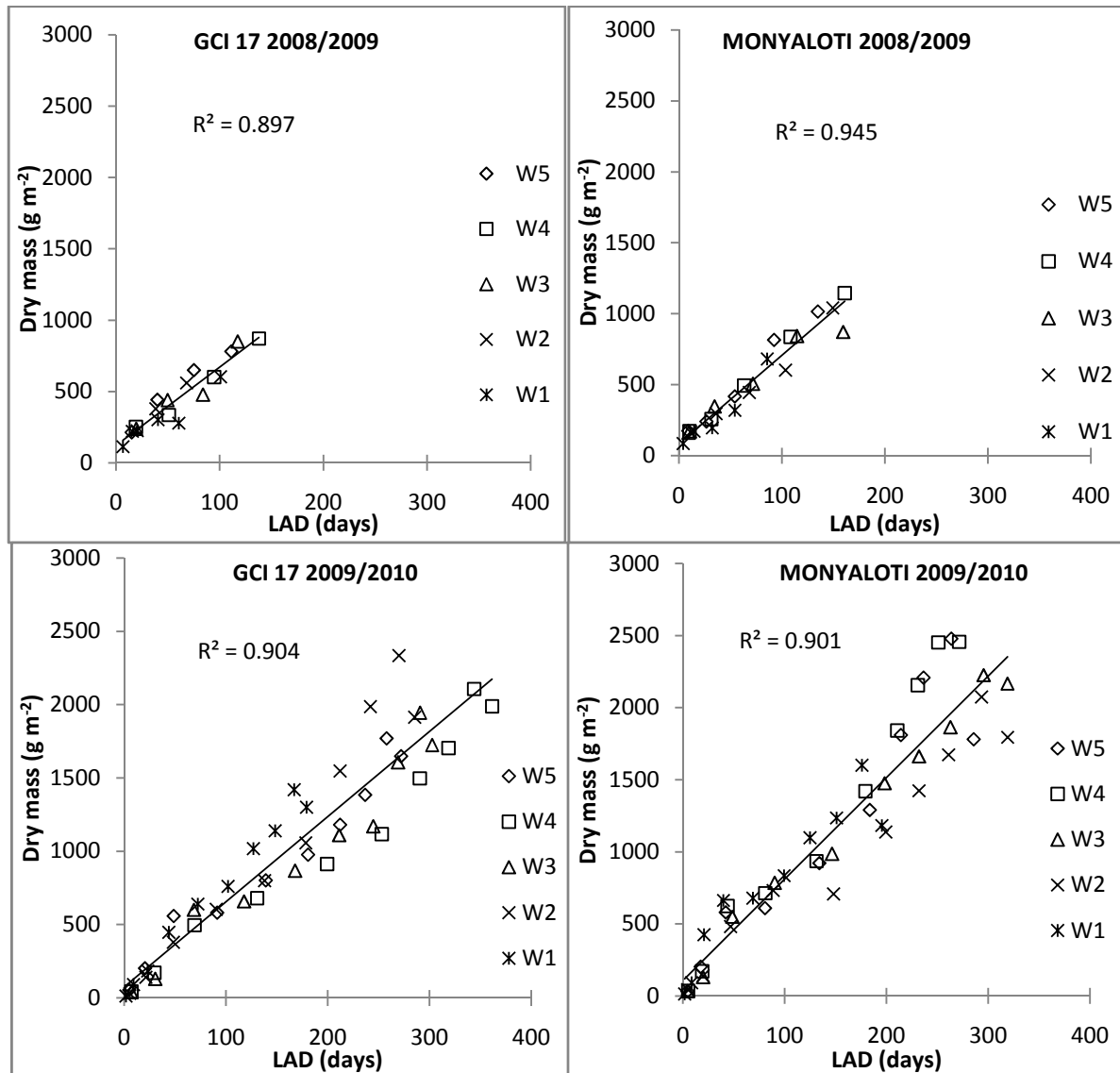
Plants can be evaluated for growth and development both individually and within their community through the help of complete growth analysis (Gardner *et al.*, 1985). The LAI of the two lines of pearl millet as affected by water treatments verifies the expectation that irrigation improves plant growth and development of this C4 cereal. Singh and Singh (1995) reported LAI of 11.4, 9.3, 8.4 and 6.5 for pearl millet under wet condition, mild-stressed, moderately stressed and severely stressed respectively. van Oosterom *et al.* (2001) observed LAI between 4 and 6 for pearl millet grown under

rainfed, different plant population and extended daylength. These values are in accordance with the observation from this study. Maximum LAI were reached between 50 and 60 days for both lines of pearl millet (Figure 3.13) as was observed in experiments carried out by Chanda *et al.* (1987) and Singh *et al.* (2001). The LAI might be different for different treatments but they have reached their peak during this period. During the two seasons of the experiment, biomass increases with water supply for the two lines of pearl millet. The final biomass observed by van Oosterom *et al.* (2002) under well-watered condition was in accordance with the findings of this study. The relationship established between the biomass and the LAD in this study reflects the photosynthetic efficiency of leaf exposure to photosynthetically active radiation in terms of time and biomass production. Singh *et al.* (2001) also found a positive correlation between LAD and total dry matter at pre-harvest growth stage. This relation was found to be a positive correlation for open pollinated pearl millet compared to hybrid.

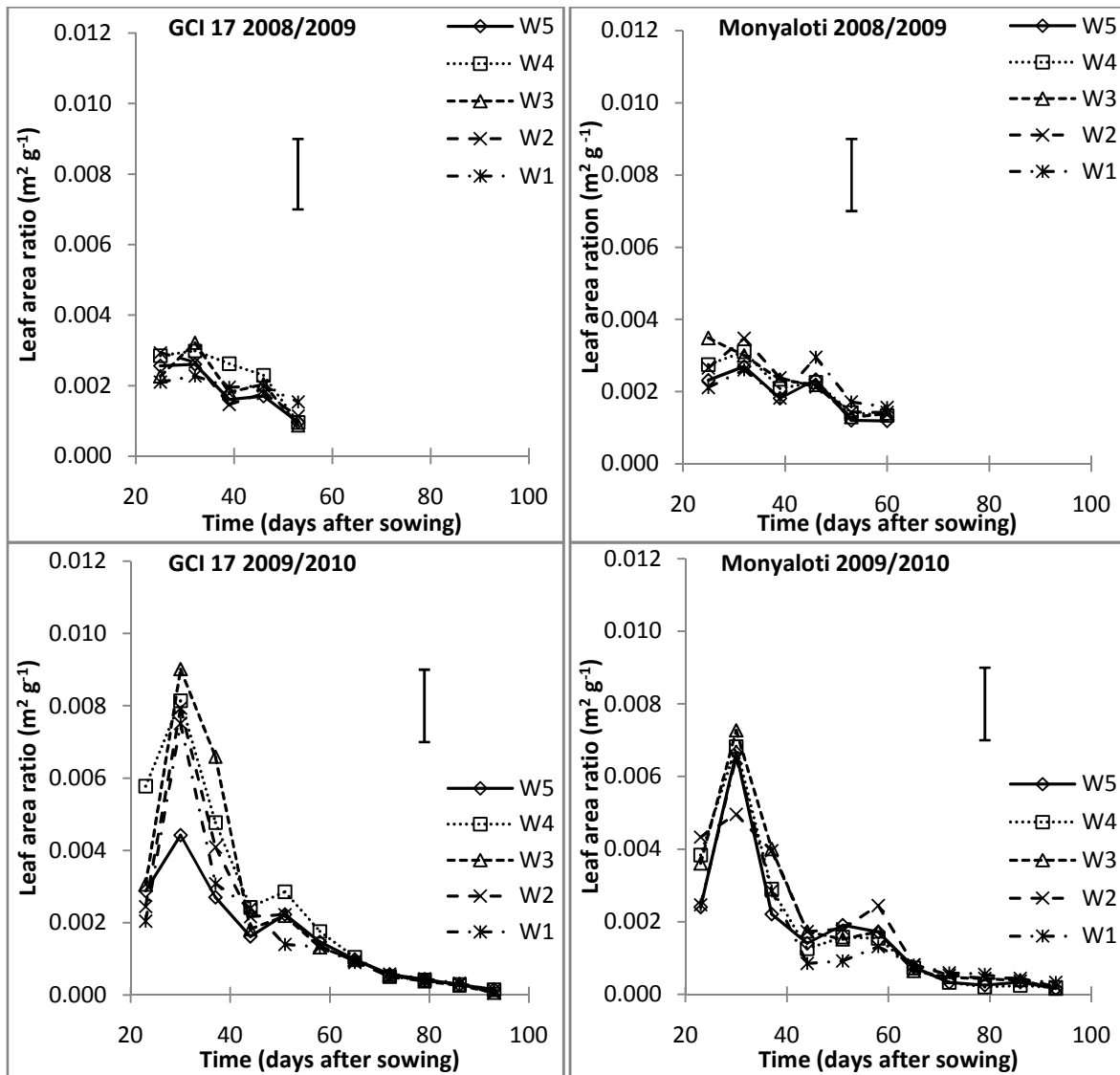


**Figure 3.14** Biomass production as affected by water treatment in pearl millet plots (2008/2009 & 2009/2010).

Leaf area ratio (LAR) can also be described as an index of plant leafiness and a morphological index of plant form (Radosevich *et al.*, 1997). Considering this present study, there was significant influence of water supply on LAR between the two seasons and the two lines of pearl millet. Higher LAR may be due to the availability of more precipitation in the second season than the first season. Ashraf *et al.* (2001) also reported significant effect of water deficit on leaf area, LAR, RGR for two lines of pearl millet.



**Figure 3.15** Relationship between leaf area duration (LAD) and biomass for the two lines of pearl millet as affected by water treatment (2008/2009 & 2009/2010).



**Figure 3.16** Leaf area ratio (LAR) of the two lines of pearl millet as affected by water treatment (2008/2009 & 2009/2010).

The decline in RGR is attributed to a decreasing portion of the plant biomass that actively participates in photosynthesis as non-photosynthetic organs develop and increase in size, and the efficiency of the lower leaves decreases (Hunt, 1990). The RGR declined from 30 days after sowing throughout the period of study which is a result supported by the literature. Payne *et al.* (1991) also observed decline in RGR with time in non-water stressed and water stressed pearl millet. There was a sharp decline in NAR of the two lines of pearl millet before ascending after 60 days after sowing. The decline in NAR may be explained by the fact that mutual shading of leaves increases with new leaves emerging which reduce the dry matter gain per unit leaf area (Gardner *et al.*, 1985; Payne *et al.*, 1991).

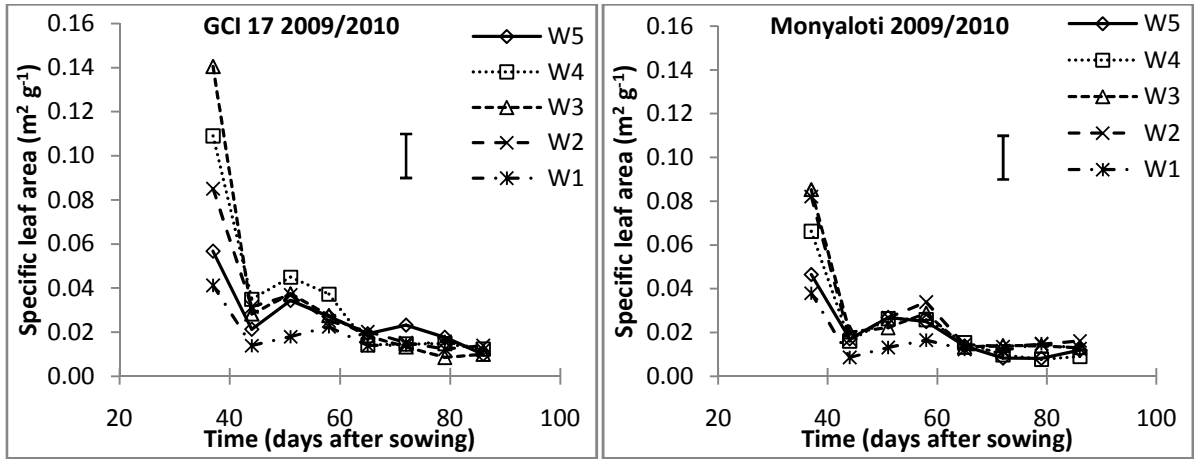


Figure 3.17 Specific leaf area (SLA) of the two lines of pearl millet as affected by water treatment (2009/2010).

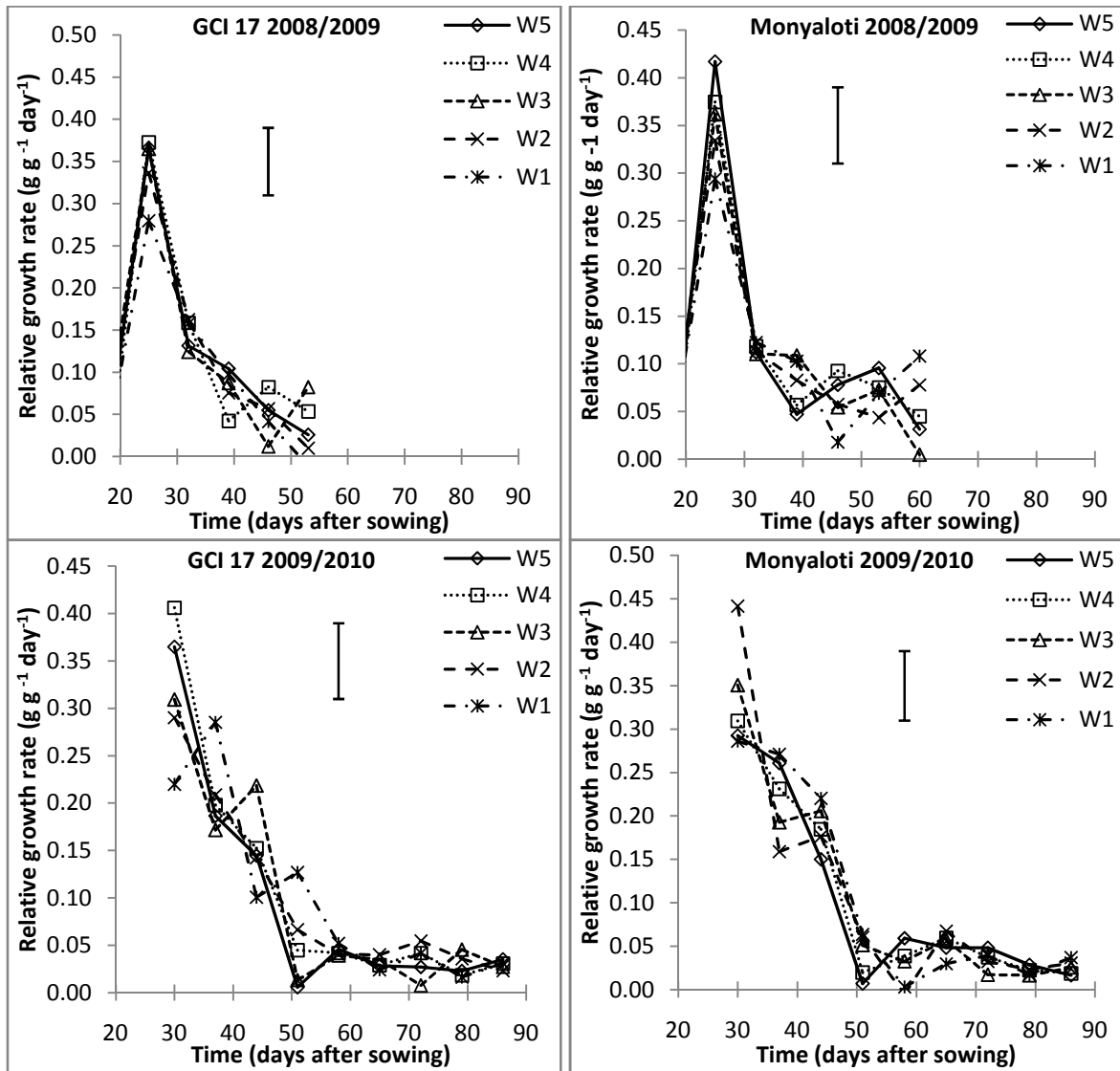
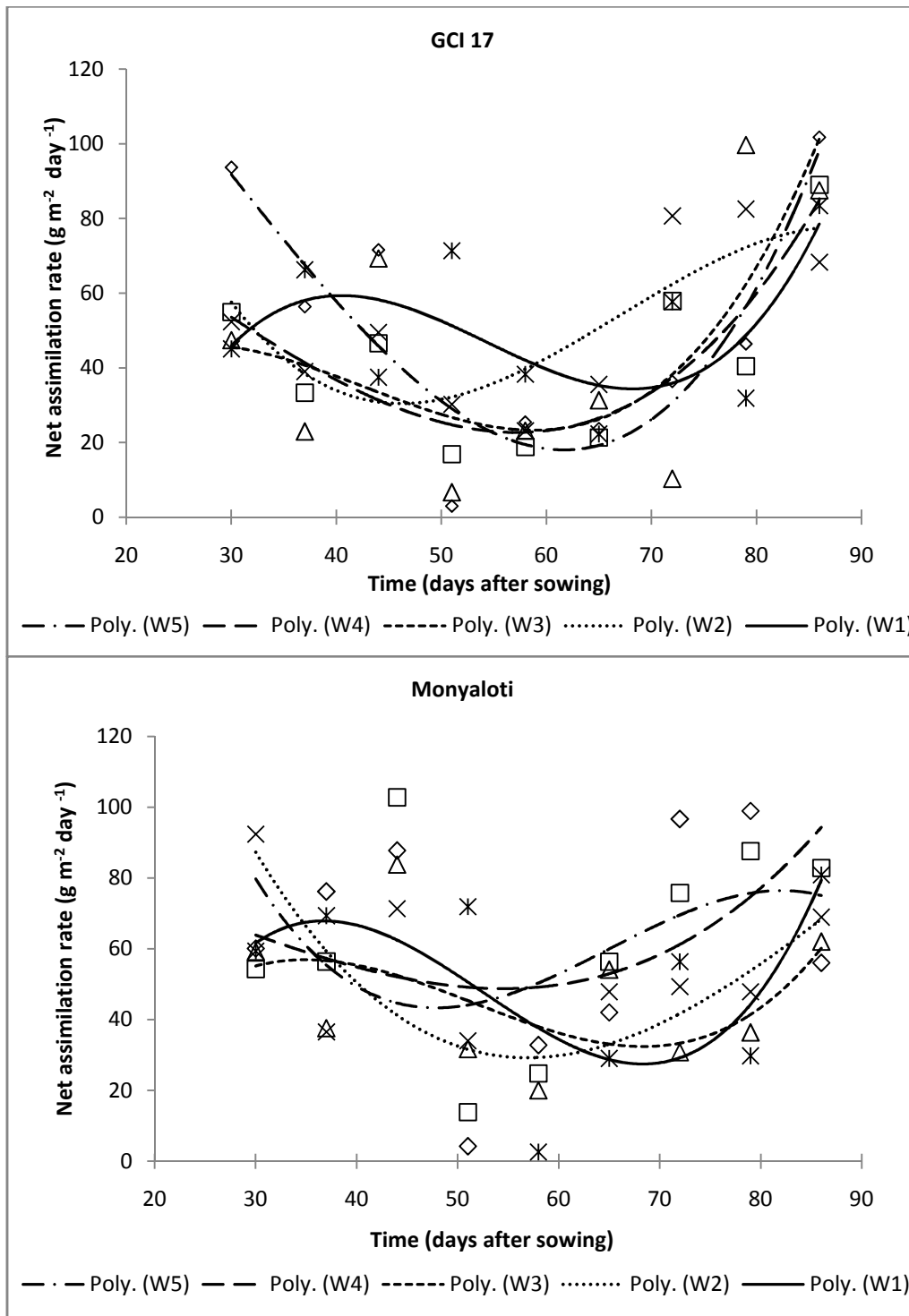
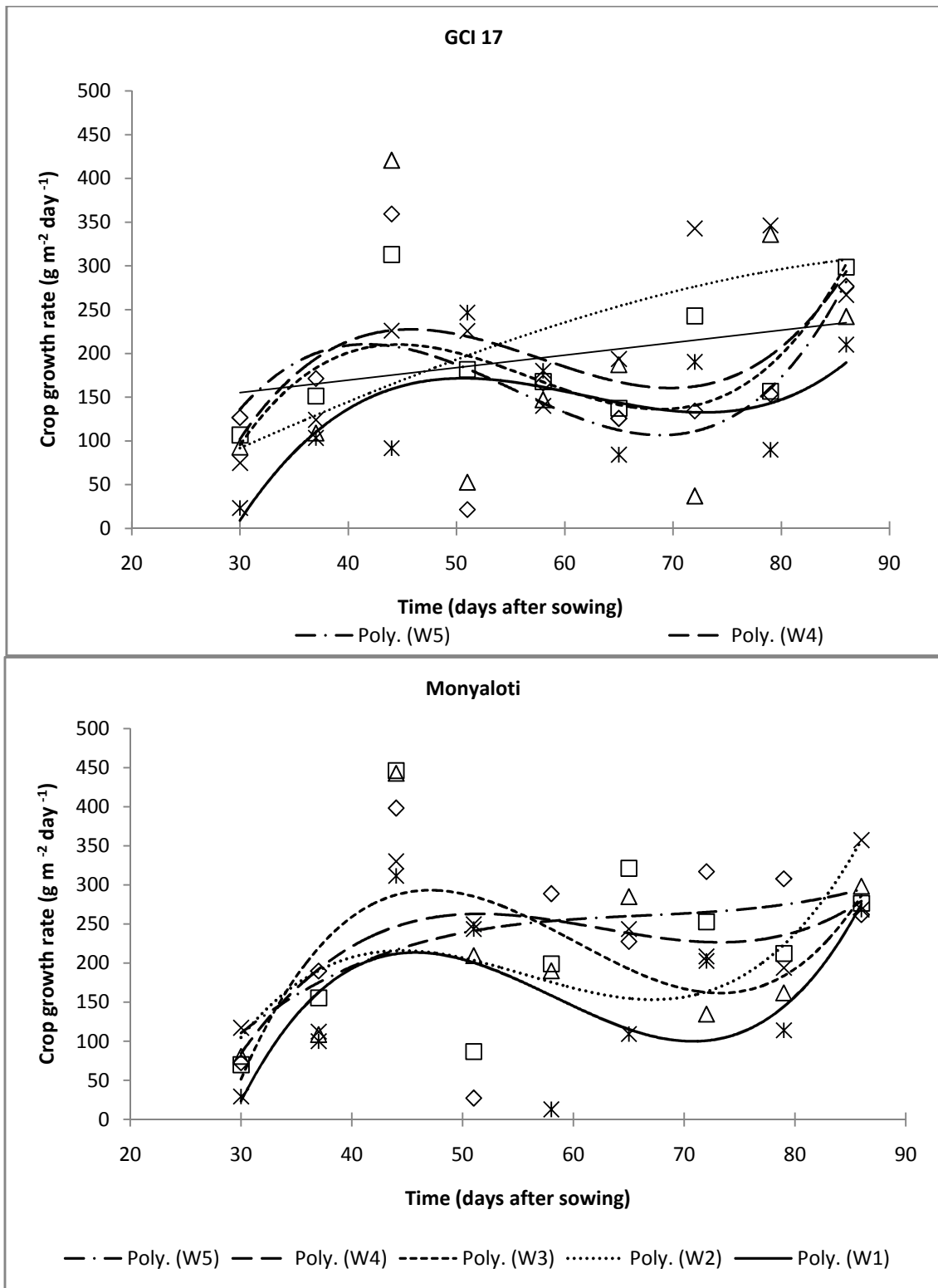


Figure 3.18 Relative growth rate (RGR) of the two lines of pearl millet as affected by water treatment (2008/2009 & 2009/2010).





**Figure 3.19** Net assimilation rate (NAR) of the two lines of pearl millet as affected by water treatment (2009/2010).



**Figure 3.20** Crop growth rate (CGR) of the two lines of pearl millet as affected by water treatment (2009/2010).

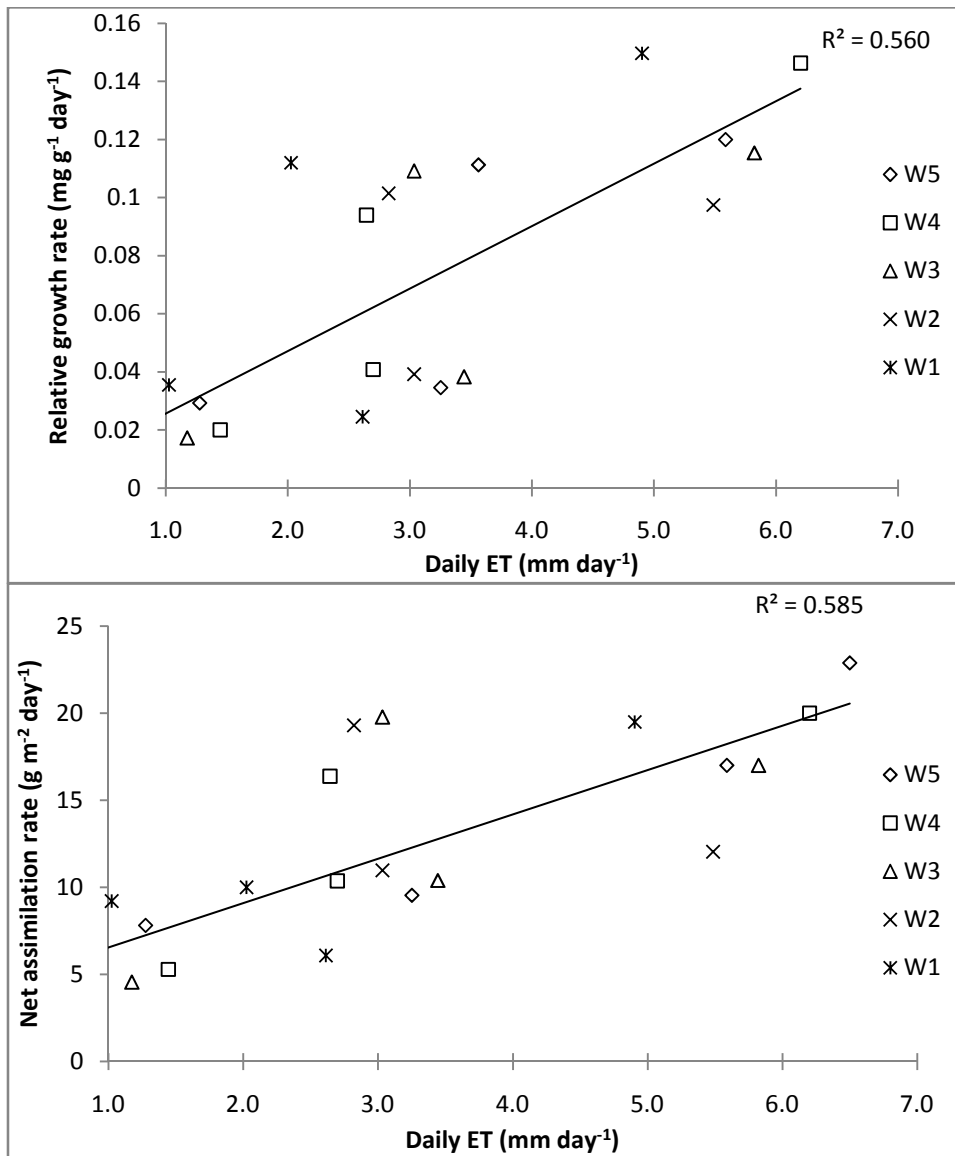
### **3.3.4 Relationship between growth rate and water use of vegetable and grain crops**

#### **3.3.4.1 Amaranthus**

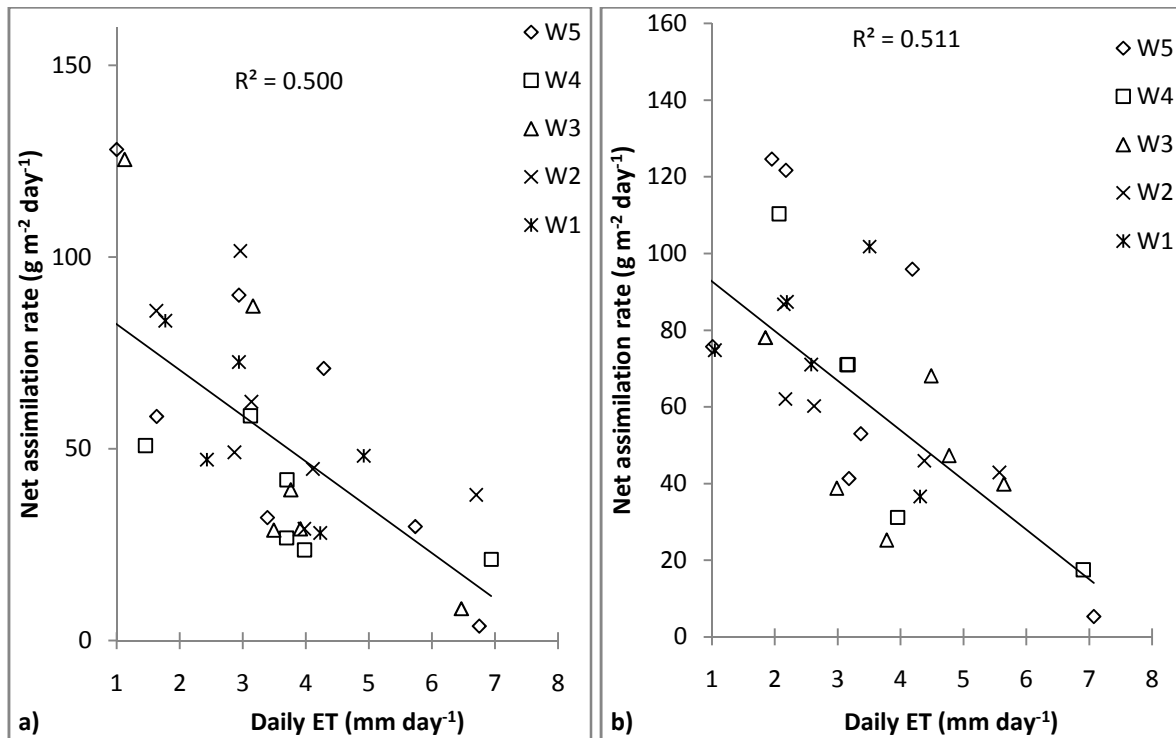
In order to establish a relationship between the growth rate efficiency indices and the water use both growth parameters (RGR and NAR) were applied during the growing period. For crop water use the evapotranspiration (ET) which can be daily, water use per day, or seasonal, cumulative water use was used. For these parameters, daily ET is relevant as the growth rates parameters were expressed in daily unit. Measurement and calculation of ET from soil water balance will be explained in detail in Chapter 4. However, this daily unit was calculated as average of the period of the measurements. Figure 3.21 shows that there is a positive linear relationship ( $R^2$  of 0.56) between RGR and daily ET for amaranthus. Increase in daily ET signifies increase in biomass produced per unit of plant material. Therefore, ET of 6 mm d<sup>-1</sup> can produce 0.12 mg of biomass from 1 g of above ground standing biomass plant material. This can be expected because daily water use of a crop usually increases with time and size of the crop. Water use of a crop close to the end of the cropping season will be low (as leaves senesce) while the water use efficiency depends on amount of biomass produced by the crop during this period. A similar relationship found between RGR and daily ET was also observed between NAR and daily ET (Figure 3.21). The correlation coefficient of 0.585 shows the positive linear effect of water use on photosynthetic activity of the crop. From Figure 3.21, it appears that if 3 mm of ET is used daily by the crop, 10 g of biomass will be able to be synthesised from 1 m<sup>2</sup> of leaf area. This shows that in the presence of water deficit, when the leaf stops expanding, the available water will be conserved as the water use is determined by the size of the leaf area for transpiration of the crop.

#### **3.3.4.2 Pearl millet**

Relationships between RGR, NAR and water use (daily ET) is also reported for the two lines of pearl millet. Contrary to the observation in amaranthus, there was no good relationship between RGR and daily water use in both lines of pearl millet. However, a negative relationship between NAR and daily ET was observed for the two lines of pearl millet with  $R^2$  of 0.500 and 0.511 for GCI 17 and Monyaloti respectively (Figure 3.22). The higher the water use, the less biomass produced by the leaf. This could be a coping mechanism for the crop under excess water conditions. The crop might not be able to photosynthesize efficiently with high daily ET. Due to the fact that daily ET increases with the age of the crop then, and the leaf growth will be low after completion of the vegetative stage.



**Figure 3.21** The relationship between relative growth rate (RGR) (a), and net assimilation rate (NAR) (b) versus water use (daily ET) of amaranthus (2009/2010).



**Figure 3.22** The relationship between net assimilation rate (NAR) versus water use (daily ET) of two lines of pearl millet for the 2009/2010 season ((a) GCI 17 and (b) Monyaloti).

### 3.4 CONCLUSIONS

Results obtained in this study demonstrate the amaranthus and pearl millet response to water application. In amaranthus, growth parameters increased with irrigation but not necessarily linear with the level of irrigation. Since the differences between the leaf area indices were not significantly different, leaf growth was not distinctive for the treatments. However, the assimilate production efficiency of the crop was not compromised. Pearl millet exhibited a more direct response to water treatments. All the irrigated plots performed well compared to the rainfed plants. Rainfed plots also produced efficiently as shown by the growth analysis. A relationship between growth rate parameters and water use was determined. It was also observed that both amaranthus and pearl millet use water more effectively in accordance to each crop coping mechanism against water stress either limited or excessive condition. Investigation on effect of type of nutrients, either macro or micro nutrients, on amaranthus production, and a study on interaction effect of nutrient and irrigation on amaranthus production might be able to reveal reasons for the observed response of amaranthus to water.

## CHAPTER 4

### WATER USE AND PRODUCTIVITY OF AMARANTHUS AND PEARL MILLET UNDER IRRIGATED AND RAINFED CONDITIONS

#### 4.1 INTRODUCTION

In semi-arid regions, water is the most limiting factor affecting crop production. The climatic conditions of the semi-arid regions are characterized by periodic drought coupled with high temperature and erratic low rainfall which are lower than potential evaporation (Zhai & Zhang, 2004). The central part of South Africa is a semi-arid region where the annual precipitation is between 400 and 550 mm with an annual ETo of 2198 mm (Hensley *et al.*, 2000). Some crops such as sorghum, wheat, millet and sunflower are adapted to the environmental conditions of semi-arid areas as they have an ability to adapt by using water efficiently for biomass and yield production. Blum's (2005) review found that efficient water use is based on reduced water consumed to produce a high yield under water limited conditions. The efficient use of water is measured as crop water productivity with various parameters including water use efficiency (WUE), water productivity (WP) and how the water use affects the harvest index (HI). Water use efficiency is the measure of the conversion ability of water to biomass or grain yield by a crop during the cropping season (Tanner & Sinclair, 1983). Zwart and Bastiaanssen (2004) refer to WUE as the marketable crop yield produced per unit actual crop evapotranspiration (ET). The marketable crop yield could be biomass, grain or any form of economic yield of a specific crop and ET is the sum of soil surface evaporation (E) and crop transpiration (T). The concept of WUE in relation to underutilized crops, *viz.*, amaranthus and pear millet production in semi-arid areas is important and may have implications in dry land farming.

Many studies reported a linear relationship between the water use and yield of a crop as the WUE. Maman *et al.* (2003) and Hatfield *et al.* (2001) reported linear relationship between water use and yield of pearl millet and sorghum for two seasons but with different WUE for each year and crop. However, there have been lots of criticisms of the term water use efficiency as it is better to use the term water productivity (WP). One of the reasons is the lack of clarity and large number of different parameters that have been used in the calculation of WUE. The separation of ET into evaporation (E) and transpiration (T) shows that T is the only productive amount of water used by the crop. Water productivity is defined as the biomass produced per unit land area per unit of water transpired (Steduto *et al.*, 2007). In some literature, WP is called transpiration efficiency or transpiration use efficiency (Bierhuizen, & Slatyer, 1965; Zhang *et al.*, 1998). Water productivity is preferred to WUE due to the fact that it has been found relatively stable for a particular crop and environment (Tanner & Sinclair, 1983). Different types of crops possess different levels of WP. The value of WP is higher for C4 crops such as maize and sorghum than for C3 crops like sunflower, wheat and legumes (Tanner &

Sinclair, 1983; Ogindo & Walker, 2004). This is due to the fact that C4 crops exhibit higher photosynthetic and lower transpiration rates (Hamerlynck *et al.*, 2000). In agreement with the performance of crops based on their carbon pathways, high WUE was associated with reduced transpiration in rice by Kobata *et al.* (1996) and with reduced evapotranspiration in sorghum by Tolk and Howell (2003). Thus, in the case of amaranthus and pearl millet, as C4 crops, their water use can be used to address the effect of environmental conditions and their genetic traits. Therefore, the purpose of this study was to assess and compare both the water use efficiency and productivity of vegetable amaranthus and pearl millet under irrigated and rainfed conditions in a semi-arid area.

## **4.2 MATERIAL AND METHODS**

### **4.2.1 Site description, facilities and treatments**

With the aim to investigate the water use efficiency and productivity of underutilized crops, a pot experiment for amaranthus in a greenhouse and a lysimeter trial for pearl millet at the lysimeter facility were carried out during the 2010/2011 cropping season. With the field data, evapotranspiration (ET), yield and water relation of the crop were able to be estimated at weekly intervals for the two cropping seasons (2008/2009 and 2009/2010). The description of the pot experiment, lysimeter trials and field experiment, treatments and plot layouts, experimental design and agronomic practices employed in these experiments are detailed in Chapter 2, Section 2.4.1-2.4.3. Accordingly, the treatments for this set of experiments, pot, lysimeter and field trials are represented as below:

Pot experiment:

- Well-watered
- Water stressed

Lysimeter trial

- WW - well-watered treatment
- VS - vegetative stage stress
- RS - reproductive stage stress
- GS - grain-filling stage stress
- RGS - reproductive and grain-filling stress

Field experiment

- W5 - Fully irrigation
- W4 - Adequate irrigation
- W3 - Moderate irrigation
- W2 - Least irrigation
- W1 - Rainfed

#### 4.2.2 Weather variables

Weather variables monitored at the experimental site by the automatic weather station (AWS) include maximum and minimum air temperature ( $^{\circ}\text{C}$ ), solar radiation ( $\text{MJ m}^{-2}$ ), wind speed ( $\text{m s}^{-1}$ ), rainfall (mm) and relative humidity (%) and were used to calculate the reference evapotranspiration,  $ETo$  using FAO-56 Penman Monteith equation (Allen *et al.*, 1998).

#### 4.2.3 Experimental approach

##### 4.2.3.1 Field trial

The soil water was measured at weekly intervals, for each plot, and for each crop during each season. The soil water balance calculation was to estimate evapotranspiration (ET) which represents the crop water use during each season (see section 2.3.2, Chapter 2, Equation 2.3). Change in soil water content ( $\Delta\text{SW}$ ), which is one of the soil water balance components, was monitored with the Waterman Neutron moisture meter, Campbell Pacific Neutron Water Meter, Model 503DR. Access tubes, 2 m deep were installed at the centre of each treatment plot that enable measurements to be made at six levels down to 1.8 m depth at 30 cm interval. Other soil water balance components are precipitation (P), irrigation (I), deep percolation (D) and runoff (R). The D and R are assumed to be negligible.

##### 4.2.3.2 Amaranthus pot experiment

Pots with the volume of 28.5 L were filled with top soil from the experimental site, soil was oven dried and then filled with water till saturation. The pots were weighed daily until constant mass was observed in each pot. This was to determine the full water holding capacity in the pots and calculated as the difference between the dried and drained soil mass. Any difference in the mass of the pots over a 2 day interval is taken as water uptake of the plants which represents the water transpired (Equation 4.1). This is because the pots were covered with quartz to prevent or minimize soil surface evaporation. The water uptake was converted from mass to volume in reference to the surface area of the pot (see section 2.4.1, Chapter 2 for more details). Then transpiration is calculated:

$$\text{Transpired water, } T \text{ (mm)} = \text{PW}_n - \text{PW}_f \dots\dots\dots\text{Equation 4.1}$$

where  $\text{PW}_n$  is the initial mass of the pot on a given date and  $\text{PW}_f$  is the mass of the pot at the end of the interval.

##### 4.2.3.3 Pearl millet lysimeter experiment

Water use of each of the lines of pearl millet grown on each lysimeter was considered to be the amount of transpired water. Evapotranspiration (ET) is widely considered to be water use by field crops. However, partitioning of the ET into E and T provides the opportunity to quantify the actual amount of water uptake and lost by the crop as transpiration (T) through the leaves, which is the only productive water within the soil-plant-atmosphere-continuum (SPAC). Therefore, for the lysimeter



study, transpiration was observed as water use by the crop because soil evaporation (E) was negligible due to the quartz gravel covering the surface soil of the lysimeter. Transpiration was calculated using equation 2.6 (see section 2.4.2, Chapter 2). The rainfall value (P) was zero as rainfall was excluded with the aid of the rain shelter which was closed during each rainstorm throughout the study period while drainage (D) and runoff (R) were also negligible.

#### **4.2.4 Water parameters and physiology**

##### **4.2.4.1 Stomatal conductance**

The instrumentation and procedure for leaf water potential measurement and stomatal conductance was again detailed in section 2.3.4. Moreover, the procedure for relative water content (RWC) measurement is found in section 2.4.1 of Chapter 2. Leaf water potential measurements were only carried out on pearl millet and RWC was only measured for amaranthus in the pot trial.

#### **4.2.5 Crop parameters**

##### **4.2.5.1 Yield**

The economic yield of amaranthus is fresh mass because it is a leafy vegetable crop. Therefore, each weekly total aboveground fresh mass was regarded as yield for that specific period of time. Amaranthus yield was also reported as dry mass for the purpose of agronomic and productivity quantification. In order to represent marketable yield in the field experiment, amaranthus was harvested regularly at 30 cm above ground at 14 day intervals. This yield was regarded as the edible portion of the plant. The edible portion was reported in fresh and dry mass for both seasons. Pearl millet grain yield for the field experiment was from harvest from 1 m<sup>2</sup> of each treatment plots while that of lysimeter was from each tank of the lysimeter. Yield was reported in tons per hectare. (See section 2.3.5 of Chapter 2 for details).

##### **4.2.5.2 Dry matter production**

In amaranthus pot trials, four plants per treatment were harvested for biomass at every sampling time. Biomass of the lysimeter trial was only measured at the end of maturity when all the plants in each lysimeter tank for each treatment were harvested as the total aboveground biomass produced. However, for field trials, during each season, one plant per replicate of each treatment was sampled from amaranthus plots while for pearl millet plots, one plant per stand per replicate of each treatment for each pearl millet line were sampled every week. The plant material collected were oven dried at 65°C for 36-48 hours to determine aboveground dry mass.

#### **4.2.6 Water use and productivity**

The following parameters were used to evaluate the productivity of the two crops in terms of yield produced by a unit amount of water and on a unit of land area.

#### 4.2.6.1 Water use efficiency (WUE)

Water use efficiency (WUE) is a measure of how efficient a crop uses water to produce a certain amount of yield (Tanner and Sinclair, 1983) and calculated as follows:

$$WUE_{gy} = \frac{GY}{ET} \dots \dots \dots \text{Equation 4.2}$$

$$WUE_{bm} = \frac{BM}{ET} \dots \dots \dots \text{Equation 4.3}$$

where  $WUE_{bm}$  = water use efficiency for biomass;  $WUE_{gy}$  = water use efficiency for grain yield, and ET = seasonal evapotranspiration. All WUE are in  $kg\ ha^{-1}\ mm^{-1}$  or  $t\ ha^{-1}\ mm^{-1}$  while ET is in mm.

#### 4.2.6.2 Water productivity (WP)

Since transpiration is the only productive loss of water by ET, WP is the measure of the efficient use of transpired water for conversion into biomass or economic yield. It is said to be constant for a given crop and climatic condition (de Wit, 1958; Hanks, 1983; Tanner & Sinclair, 1983).

$$WP = \frac{Y}{\sum T} \dots \dots \dots \text{Equation 4.4}$$

where Y can be grain yield or total biomass at harvest and  $\sum T$  is cumulative transpiration.

### 4.2.7 Statistical analysis

Data collected from all the experiments were statistically analysed with the aid of Statistical Analysis System (SAS) program 9.2 package for Windows V8 (Statistical Analysis System Institute Inc, 1999-2010). Means were compared using the least significant difference (LSD) test at a probability level of 5% using the Duncan Multiple Range tests. Empirical relationships of the parameters were also derived using regression procedures.

## 4.3 RESULT AND DISCUSSION

### 4.3.1 Weather conditions

The rainy season is from November through April, although some rain also occurs during September, October and May. During the two growing seasons (Nov. – Apr.) precipitation was 229.2 mm and 248.7 mm, respectively (Table 4.1). Rainfall was erratic in nature and the major amount of precipitation concentrated in January and February for both cropping seasons. During January, the crop received 86 mm and 153 mm of rainfall in the first season and second season.

The average monthly maximum temperatures show similar values between the two growing seasons, except that during the first growing season the maximum temperature was higher (by about 2 °C) in November, compared to the second growing season (Table 4.1). December was the hottest month with a mean maximum temperature of 32.3°C in the 2008/2009 season and 32.8°C in the 2009/2010 season. April was the coolest month of the two growing seasons with a mean minimum temperature of

10.3°C during the first season and 10.9°C in the second season (Table 4.1). The monthly reference evaporation (ET<sub>o</sub>) for each growing season was at the maximum in December (Table 4.1). The occurrence of high temperature and evaporation rates, while only receiving low and unevenly distributed rainfall during the growing season, often expose the crops to water deficit causing stress.

**Table 4.1** Monthly means of climatic data at Kenilworth experimental site for the cropping season 2008/2009 and 2009/2010, from ARC-ISCW weather station

Weather parameters	2008/2009						2009/2010					
	Nov	Dec	Jan	Feb	Mar	Apr	Nov	Dec	Jan	Feb	Mar	Apr
P (mm)	69.0	40.5	86.8	77.7	35.5	18.0	81.0	59.0	153.2	151.0	103.0	44.0
T <sub>max</sub> (°C)	29.7	32.3	31.1	27.6	28.3	25.7	27.3	32.8	28.3	29.4	28.4	24.0
T <sub>min</sub> (°C)	13.9	16.5	16.4	16.2	13.3	10.3	11.6	15.1	16.7	16.7	14.7	10.9
U (ms <sup>-1</sup> )	0.5	1.7	2.5	1.9	1.4	1.7	2.4	3.5	2.5	2.0	1.7	2.0
RH (%)	81.2	59.7	88.1	86.4	80.3	77.6	76.1	77.5	86.9	83.1	82.5	82..1
ET <sub>o</sub> (mm)	197.3	218.6	182.6	134.8	126.8	109.9	172.6	240	152.3	155.5	134.3	93.7

P = monthly precipitation, T<sub>max</sub> & T<sub>min</sub> = average maximum and minimum air temperature, U = average wind speed, RH = average relative humidity, and ET<sub>o</sub> = monthly reference evaporation

#### 4.3.2 Irrigation application

For the amaranthus field trials, the total irrigation water supplied for the 2009/2010 season was higher than the previous season (Table 4.2). The highest full irrigation water applied (W5) was about 200 mm for the 2009/2010 cropping season, which was 68 mm higher than the first season. In the case of other treatments (W4, W3 and W2), the irrigation applied during the second season was nearly double compared to the first season. During the 2008/2009 season, irrigation was low, which may be due to transplanting done in the month of high rainfall incidence.

**Table 4.2** Amount of irrigation water (mm) supplied in both growing seasons (2008/2009 and 2009/2010) for Amaranthus and pear millet

Crop	Growing seasons	Treatments				
		W5	W4	W3	W2	W1
Amaranthus	2008/2009	122.0	89.1	69.5	47.6	0
	2009/2010	199.7	167.0	131.0	93.0	0
Pearl millet	2008/2009	134.2	97.8	76.4	52.2	0
	2009/2010	58.1	41.5	20.6	11.1	0

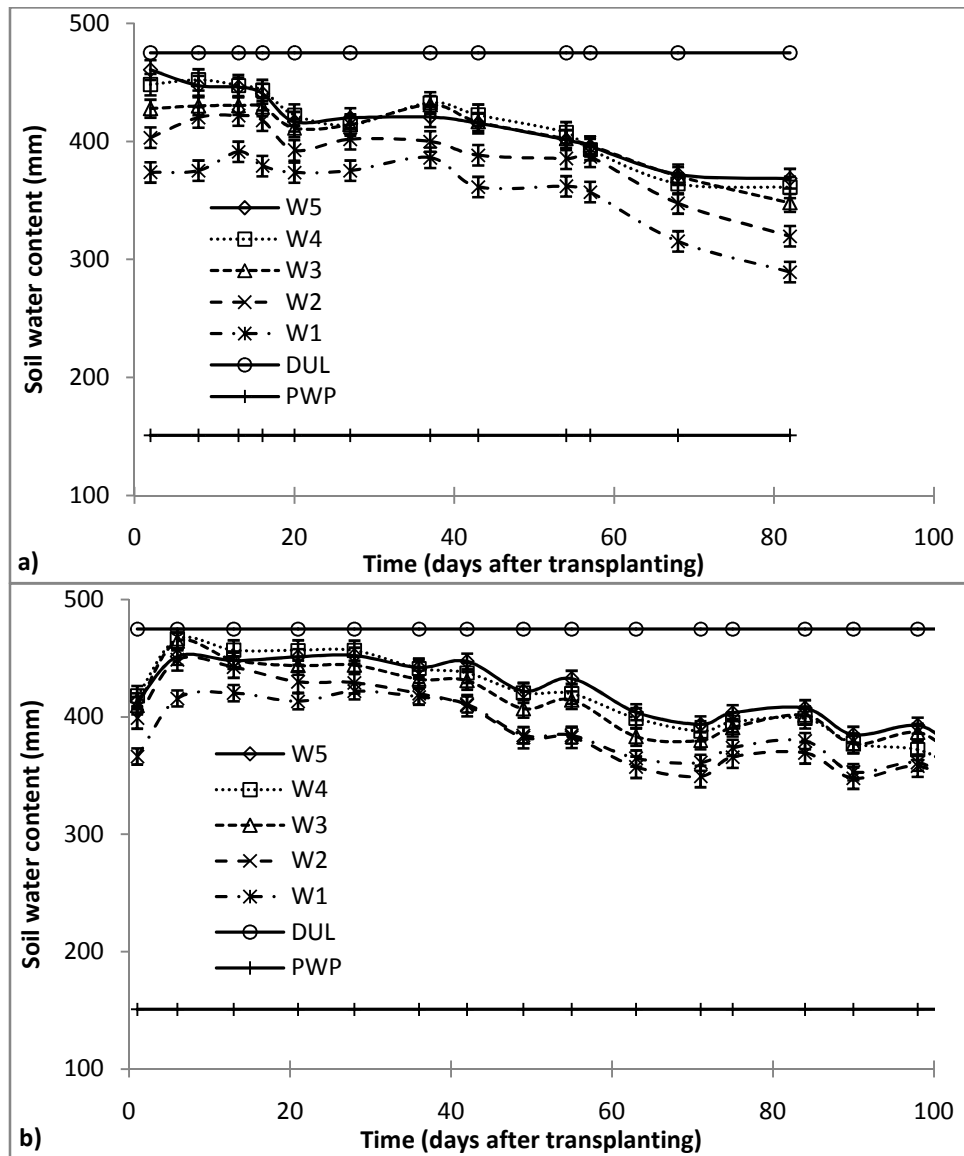
On the contrary, for pearl millet the 2008/2009 season received more irrigation water than the 2009/2010 season (Table 4.2). The difference in irrigation water supplied during the two seasons was

more than double for treatments W5 and W4 and nearly four-fold for lower irrigation water treatments, viz., W3 and W2 (Table 4.2). This may be due to the high rainfall recorded during the 2009/2010 growing season, which resulted in lower total water supplied for the season across all treatments. The only exception was found in the rainfed plots where the plots in 2009/2010 received more water than the previous season due to the higher rainfall. Furthermore, this variation in amounts of irrigation water applied was also caused by the late planting of amaranthus and early planting date of pearl millet in the first cropping season (30 Dec and 11 Nov, 2008) compared to the second cropping season (28 Nov and 16 Dec, 2009), respectively which resulted in the crop experiencing a higher evaporative demand. Thus, for both crops, the amount of rainfall received and variations of irrigation water applied during the growing seasons had influence on soil water content pattern.

### **4.3.3 Field trial for vegetable amaranthus**

#### **4.3.3.1 Soil water contents**

The soil water content for the two seasons shows that rainfed plots recorded the lowest soil water content for the two cropping seasons which was expected (Figure 4.1). In 2008/2009, W2 had lower soil water than the rest of the irrigated plots throughout the season. However, during the 2009/2010 season, at 28 days after transplanting, soil water in the W2 had declined to the same level as the rainfed (W1) plots. Extraction of water from the soil by the crop in these plots (W2) might be faster than that of the rest of the treatments. This could be due to high transpiration rate of the crops from these plots as larger plants were observed from this treatment plots. Crop water demand is dictated by rate of transpiration, atmospheric evaporative demand, size of the crop and crop type (Kramer & Boyer, 1995). The soil water content for the rest of the irrigated treatments was not different due to frequency of water application.

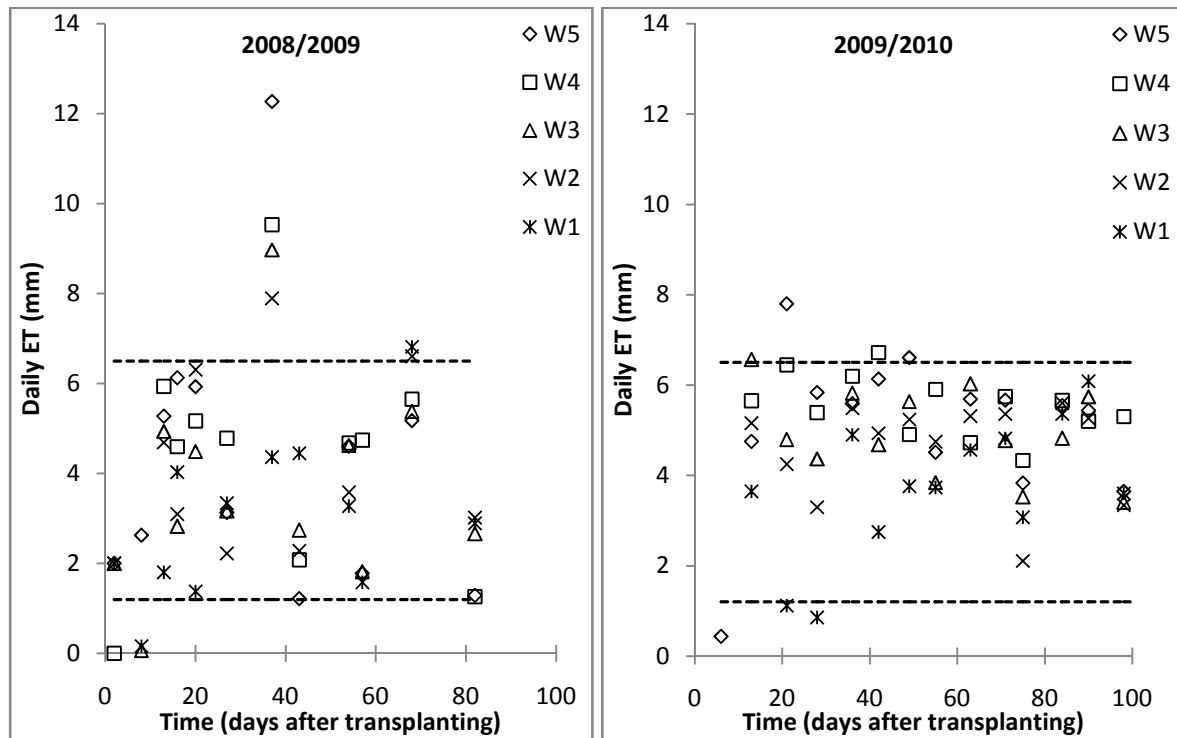


**Figure 4.1** Soil water content patterns of amaranthus plots as affected by water treatments under irrigation and rainfed condition over the two cropping seasons. (a) 2008/2009 and (b) 2009/2010.

#### 4.3.3.2 Water use

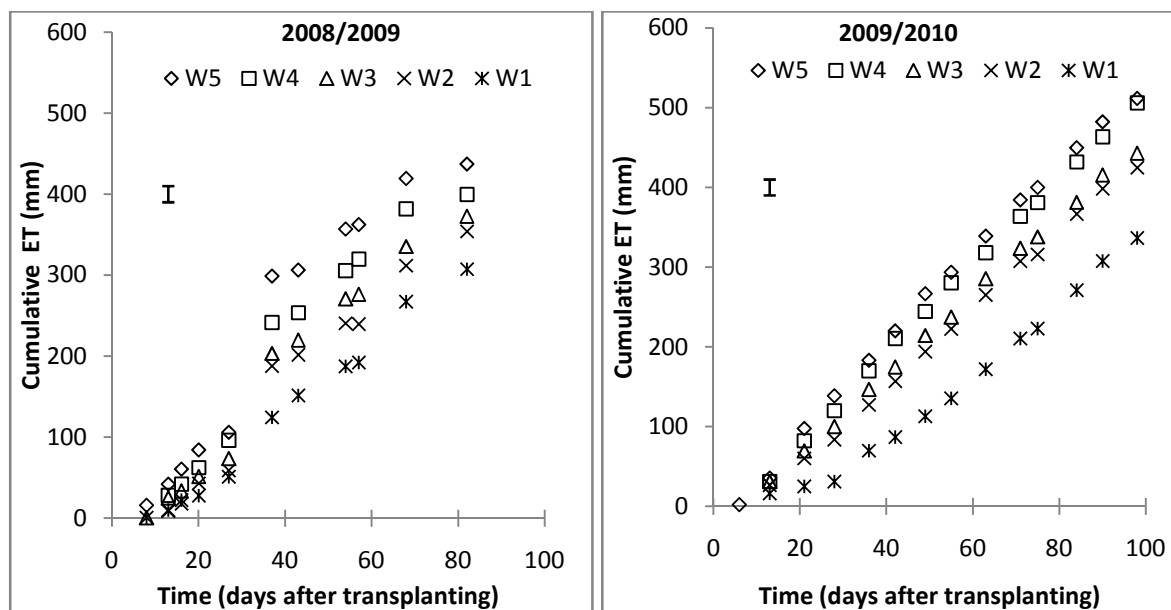
The water use of amaranthus for the field trials is reported as evapotranspiration (ET) which was calculated from the water balance using the change in soil water content measurements, irrigation, and rain (see Equation 2.3). The cumulative ET is taken as the total ET for the season while the daily ET was determined by the average of ET for a specific time interval of measurements. The evapotranspiration rate of all the treatments for the two seasons mostly fall in the ranged between 1.2 and 6.5 mm day<sup>-1</sup> (Figure 4.2). In the 2008/2009 season, an exception was observed at 37 days after transplanting with daily ET reaching up to 12 mm day<sup>-1</sup> in fully irrigated plots (W5). For this period, daily ET for all the irrigated plots was above the range specified. These high values of daily ET might have been observed during a very wet period (after irrigation or rain). The actual ET can be higher when the soil or crop surface is wet than when dry because the free surface evaporation portion of ET

increases significantly resulting in higher ET (Kramer & Boyer, 1995). During the 2009/2010 season, W5 recorded the highest daily ET of 7.8 mm day<sup>-1</sup> at 21 days after transplanting. Daily ET as high as 6 mm day<sup>-1</sup> was observed at the beginning of the season during both cropping seasons. High daily ET at the beginning of the season could be attributed mostly to evaporation from a wet bare exposed soil surface rather than transpiration.



**Figure 4.2** Daily evapotranspiration (ET) over different irrigation water treatments during both growing seasons a) 2008/2009 and b) 2009/2010, the dotted lines demarcate the most of the daily ET.

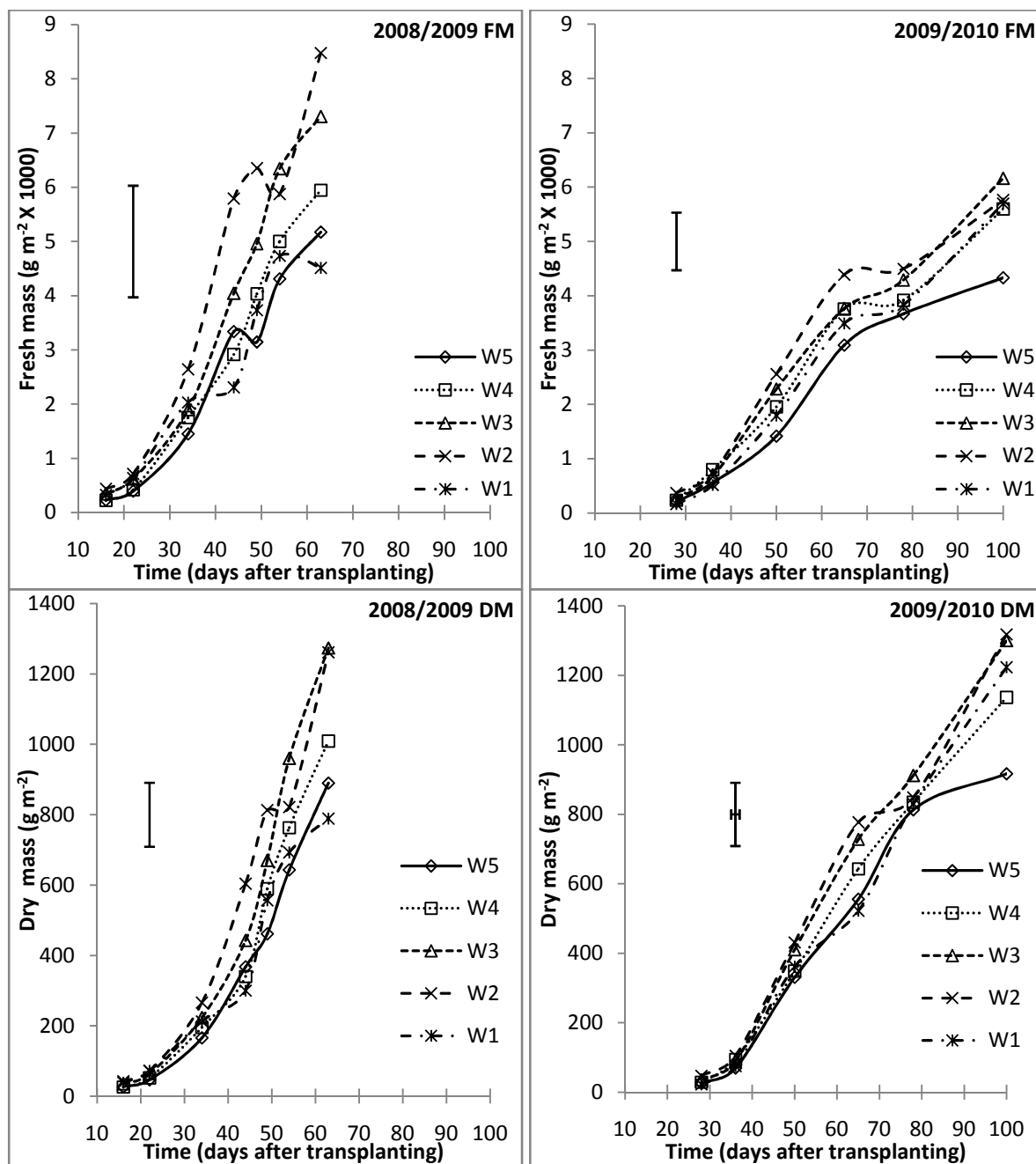
Canopy size can determine the amount of soil surface that is exposed to evaporation. As at this stage, the canopy size of the crop will still be small influencing high soil surface evaporation. In accordance with this study, Fasinmirin *et al.* (2008) reported high daily ET of 12.87 and 9.96 mm day<sup>-1</sup> in 2005 and 2006 cropping seasons respectively for amaranthus cultivated on the field under drip irrigation. However, the seasonal water use (ET) for the 2009/2010 season was higher than the 2008/2009 season irrespective of the treatment (Figure 4.3). The highest water use in the 2008/2009 was 437 mm and 2009/2010 534 mm both in W5 plots. During the two seasons, the plants from the W1 plots had the lowest water use and were also significantly different from the other treatments. In the 2009/2010 season, there was no significant difference between the ET of the plants from the W5 and W4 plots.



**Figure 4.3** Cumulative evapotranspiration ( $\Sigma ET$ ) over different irrigation water treatments during the growing period for (a) 2008/2009 and (b) 2009/2010.

#### 4.3.3.3 Fresh mass, dry mass and continuous harvesting

Water applied significantly affected biomass production during the two seasons (Figure 4.4). The fresh mass production was significantly different during the seasons. It can be observed that the 2008/2009 crop produced higher fresh mass than the 2009/2010 season. At 63 days after transplanting during the 2008/2009 season, W2 produced fresh mass of  $8.47 \text{ kg m}^{-2}$  while it was  $4.39 \text{ kg m}^{-2}$  at the same time in 2009/2010 season. During the 2008/2009 season, the W1 plots produced the least fresh mass ( $4.51 \text{ kg m}^{-2}$ ) while the W5 produced the least ( $4.33 \text{ kg m}^{-2}$ ) in the 2009/2010 season. At the end of the season, dry mass was significantly affected by water treatment during the 2008/2009 season (Figure 4.4). The same trend found in the fresh mass was followed by the dry mass. In the 2008/2009 season, the highest dry mass was produced in W2 while the least was in rainfed, W1. The dry mass was not significantly affected by water treatments in the second season, 2009/2010. These results contradict the expectation of this study. Though irrigation increased the yield but the optimum amount to apply for high efficiency is still not clear. The highest level of irrigation was expected to produce the highest biomass which was contrary to the observation from this study. One still needs to explain the reason why the fully irrigated plots produce plants with less biomass than the other water treatment plots. Palada and Chang (2003) advised that while insufficient water application might cause yield reduction in amaranthus, over irrigation should also be avoided to prevent nutrient leaching. In accordance with the results of this study, Neluheni *et al.* (2007) reported that full irrigation (maintaining 100% plant available water irrigation regime) did not increase the yield significantly in amaranthus cultivated under a rain shelter. They observed that as little as 102.4 mm water for the season produced a good yield of leafy amaranthus under rain shelter during the study.

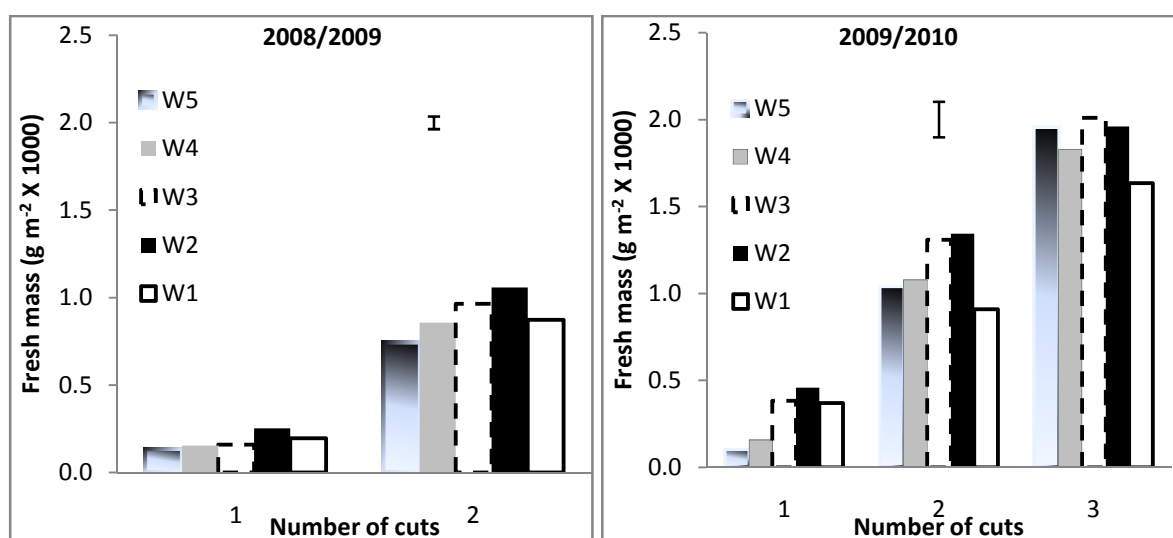


**Figure 4.4** Aboveground fresh and dry mass of amaranthus as affected by different water treatments during 2008/2009 and 2009/2010.

The importance of serial or continuous harvesting in leafy vegetable is to increase the average yield and quality of the crop. During the 2008/2009 season, W2 produced the highest biomass for the two cuttings, while W5 produced the least yield for this period (Figure 4.5). However, in the 2009/2010 season, W2 and W3 were not significantly different. The plants from the W1 plots produced the least fresh mass at the second cutting in 2009/2010. At the third cutting, the response of amaranthus to different amounts of water applied was less apparent between the treatments. The W2 treatment produced a larger edible portion at both the first and second harvests, showing that the crop can be



grown with a small amount of water. Regular or serial harvesting is advantageous as it produces small and succulent leaves that are more desirable and palatable as a leafy vegetable. Another importance of serial harvests is that more biomass is realised compare to the whole plant growing undisturbed. The final fresh mass harvest of the whole plants during the 2009/2010 season was used to justify the importance of continuous harvest method. Cumulatively, biomass produced from the cuttings was higher than the total above ground biomass of whole uncut plants at the end of 2009/10 season (Table 4.3). However, cumulative biomass of cuttings followed the same trend of biomass production. This illustrates the fact that this crop will be able to produce more leaves for food if it is harvested on a regular basis. However, this observation contradicts the findings of Mnzava and Ntimbwa (1985) and Allemann *et al.* (1996) who showed that yield decreased with subsequent harvest after the first cutting. The increase in biomass with serial cutting in this study might be due to the effect of water application.



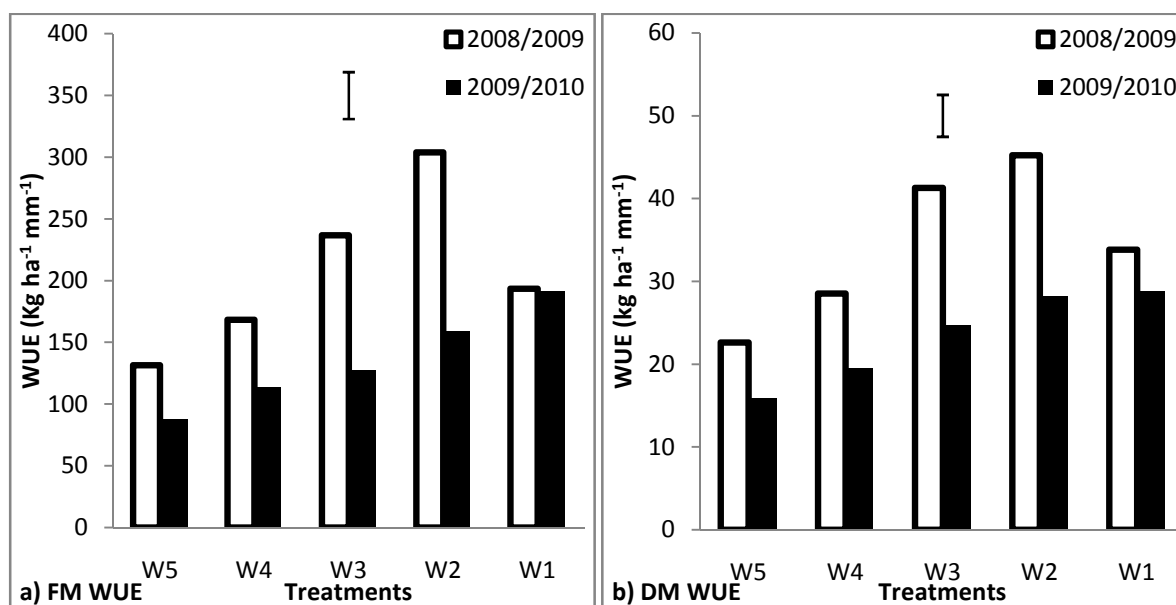
**Figure 4.5** Fresh mass of edible portion of amaranthus during the 2008/2009 and 2009/2010 seasons (30cm above ground harvest).

**Table 4.3** Total amaranthus leaf cuttings from serial harvesting versus final fresh mass of whole plants as affected by different water treatments during growing season 2009/2010

Treatments	Total cuttings (g m <sup>-2</sup> X 1000)	Final biomass whole plant (g m <sup>-2</sup> X 1000)
W5 (Full irrigation)	2.855b	1.849c
W4	3.056b	1.953c
W3	3.698a	2.282b
W2	3.757a	2.555a
W1 (Rainfed)	2.911b	1.792c

#### 4.3.3.4 Water use efficiency

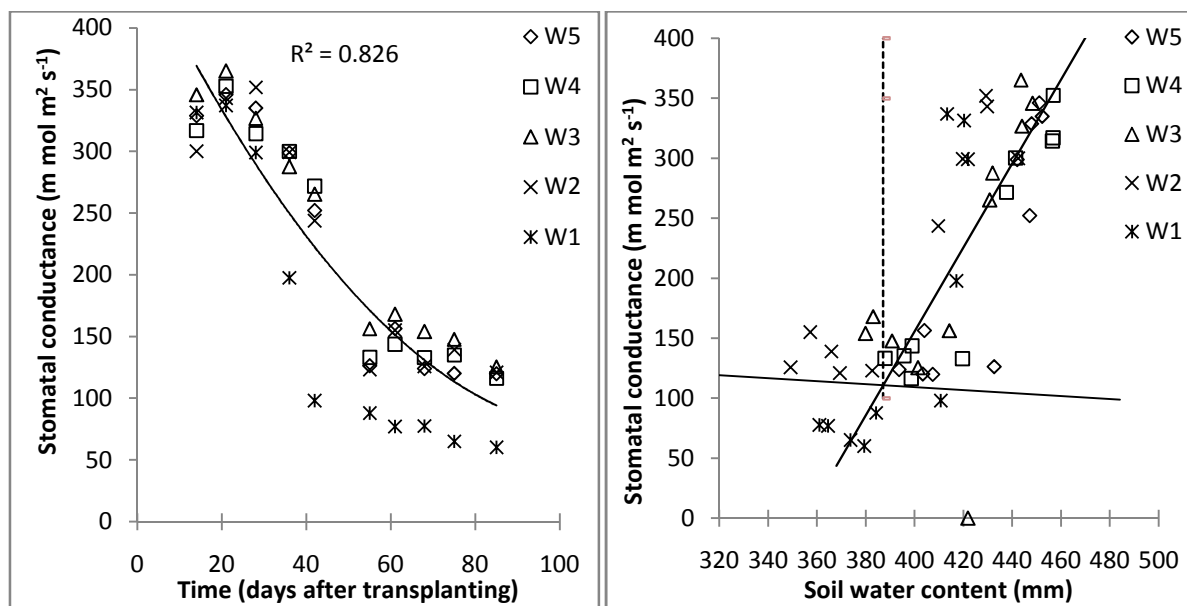
The water use efficiency (WUE) calculated during this study was as expected for both seasons. For both fresh and dry mass, WUE was higher in the first season than the second season (Figure 4.6). In 2008/2009 season, the WUE follows the same trend as the biomass production for all the treatments, The WUE increases with decreasing amount of water application. At the end of the 2009/2010 season, the treatment with the highest WUE was the rainfed plots. For 2008/2009 and 2009/2010 seasons, W5 had the lowest WUE of 131 and 88 kg ha<sup>-1</sup> mm<sup>-1</sup> for fresh mass; and 22 and 15 kg ha<sup>-1</sup> mm<sup>-1</sup> for dry mass respectively. However, the rainfed plots had the WUE of 192 kg ha<sup>-1</sup> mm<sup>-1</sup> for fresh mass and 28.7 kg ha<sup>-1</sup> mm<sup>-1</sup> for dry mass production in the 2009/2010 season. This proves that the rainfed crop used soil water more efficiently than the irrigated crops as it is the only source of water for this treatment. Higher WUE observed for fresh and dry mass in W2 and W3 plots than the rest of irrigated plots during the two seasons presents a means of improving WUE of a crop. Decreasing amount of irrigation seems to increase WUE in this study. Pandey *et al.* (2000) and Blum (2005) reported that a means of increasing yield under limited water availability or reducing water use of the crop will increase water use efficiency. It is also believed that closed canopy of a crop will increase the proportion of transpiration relative to evaporation which will leads to increase in biomass produced and consequently high water use efficiency (Turner *et al.*, 1986).



**Figure 4.6** Calculated water use efficiency (WUE) of amaranthus for a) fresh mass (FM WUE) and b) dry mass (DM WUE) production during the two cropping seasons (2008/2009 & 2009/2010).

#### 4.3.3.5 Stomatal conductance

Stomatal conductance was only reported for the 2009/2010 season because it was not measured during the first season. Figure 4.7(a) illustrates that stomatal conductance of amaranthus declined with time due to age of the crop. Vos and Oyarzun (1987) also reported declining stomatal conductance due to age for potato. The treatments were not significantly different in stomatal conductance except for the W1 treatment which was lower than the others. At 85 days after transplanting, stomatal conductance of W1 was  $60 \text{ mmol m}^{-2} \text{ s}^{-1}$  compared to the irrigated treatments plots that were around  $120 \text{ mmol m}^{-2} \text{ s}^{-1}$ . The difference could be attributed to the influence of irrigation on maintaining the higher stomatal conductance indicating that stomata are open. The signal from the root on the level of soil water as affected by irrigation or rain could have influenced stomatal closure. Plants under water stress condition usually exhibited low stomatal conductance (Hsiao, 1990). However, the plants from the W3 plots exhibited higher stomatal conductance than the rest of the treatments even during the later stage of growing period. This could be used to explain the highest biomass produced by the plants from this treatment plots during this season. High stomatal conductance is an indication of high transpiration rate which resulted in high biomass production. Liu and Stutzel (2002) found out that the genotype of amaranthus where the highest stomatal conductance was recorded had the highest transpiration rate allowing stomata to be wider open longer and consequently produced the highest biomass. Stomatal conductance can be used for monitoring water stress in plants. The relationship between the soil water content and stomatal conductance is shown in Figure 4.7(b). Data for all the treatments were pooled and two linear trend lines were constructed from this group. Regression equations from these two lines were used to form a system of simultaneous equations which was used to determine the optimum point for the two variables. It was observed that high stomatal conductance illustrates presence of sufficient soil water content for the plants to be out of water stress mode. At soil water content between 361 and 384 mm, the stomatal conductance of the plants of rainfed plots (W1) was below  $100 \text{ mmol m}^{-2} \text{ s}^{-1}$ , while at soil water below 360 mm stomatal conductance of the plants from the W2 plots were as high as  $155 \text{ mmol m}^{-2} \text{ s}^{-1}$ . Bates and Hall (1981) also reported that a decrease in soil water results in decrease in leaf conductance thereby confirming that stomata respond to change in soil water. The threshold of soil water for amaranthus to enter into water stress level was determined to be 387 mm. Points below 387 mm shows the point at which the stomatal conductance can indicate that soil water is limiting and cause water stress in the crop. Soil water content above 387 mm implies conditions are above the critical limit of soil water content concerning stomatal conductance. At this level, stomatal conductance could be as high as  $365 \text{ mmol m}^{-2} \text{ s}^{-1}$ .



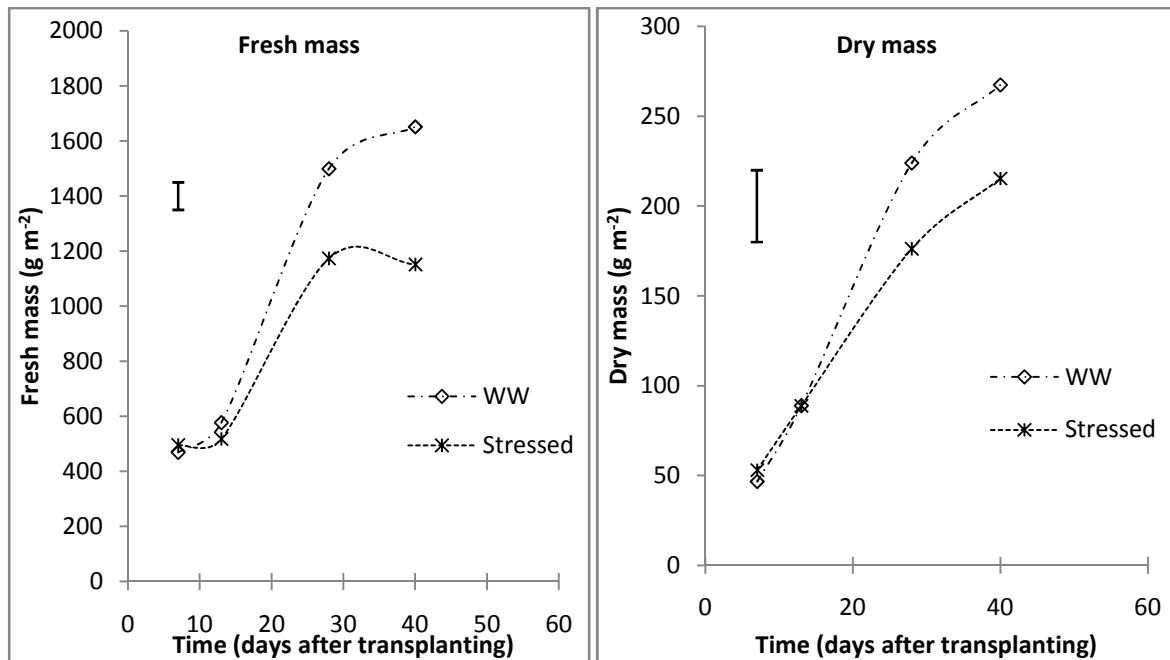
**Figure 4.7** (a) Stomatal conductance of amaranthus as affected by water treatments (polynomial curve representing overall trend of measured stomatal conductance) and (b) relationship between stomatal conductance and soil water content during the 2009/2010 cropping season with line showing the threshold point for stomatal conductance and water stress.

#### 4.3.4 Pot experiment for amaranthus

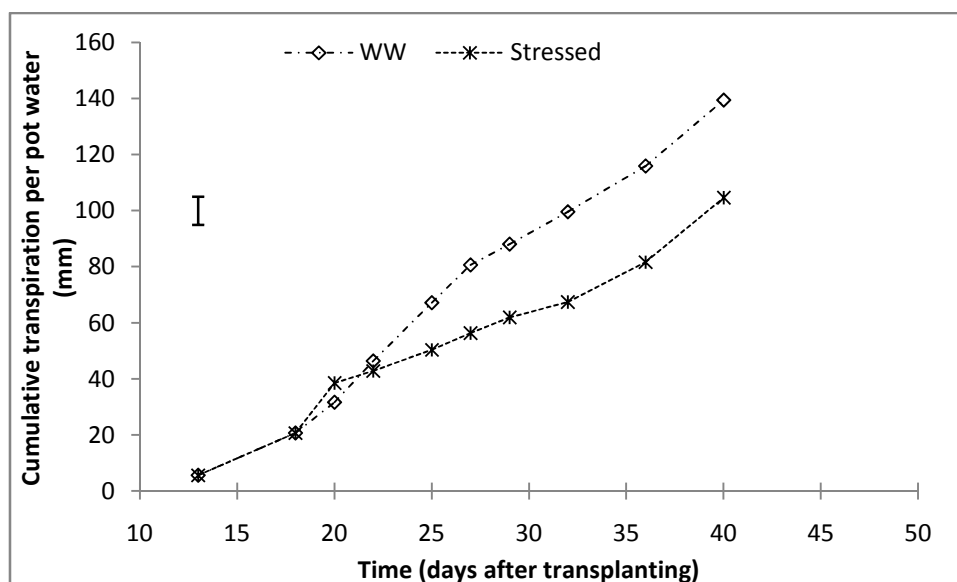
##### 4.3.4.1 Fresh mass and dry mass

At the end of the study, stressed plants had produced less biomass, both fresh and dry mass, than the well-watered plants (Figure 4.8). Well-watered plants continued to increase in biomass throughout the experiment. For the stressed plants, the highest fresh mass was produced around 30 days after transplanting and maintained the same mass at final harvest on 40 days after transplanting. Lower biomass production in water stressed pots than well-watered pots is one of the responses of the crop to water deficit. At harvest, the difference in fresh mass between the well-watered and stressed plants was  $501 \text{ g m}^{-2}$  which was almost half of the total fresh mass of the stressed plants while the difference in dry mass at harvest was  $52 \text{ g m}^{-2}$ . Water uptake by plants of the two treatments is represented by transpiration. Plants of the well watered treatments transpired more water than the stressed plants during the whole period of the study (Figure 4.9). The amounts of transpired water were not different for the two treatments until after 27 days after transplanting. The daily water uptake rate of stressed plants started to decline from then until the end of the study. This period coincides with the time that the fresh mass production became steady and at the peak. At the end of the study, well watered plants had used 139 mm of water compare to 104 mm used by stressed plants. Adequate water supply enhances crop growth and development of a large leaf area, which is the means of transpiration and a factor for photosynthesis and consequently leads to high biomass. Low transpiration is a signal of low soil water content. Studies have shown that transpiration is a function of soil water content. Soil drying does not affect transpiration until only one third of the available soil water is remained in the

soil and below this level, transpiration decreased until all the available soil water was exhausted (Sadras & Milroy, 1996). There is a direct relationship between biomass and transpiration. Due to decrease in transpiration rate as a result of low available soil water, the biomass will not attain a high value which will result in lower yields (Steduto *et al.*, 2012).



**Figure 4.8** Fresh and dry mass produced by amaranthus as affected by the two water treatments, well watered (WW) and stressed (SS).

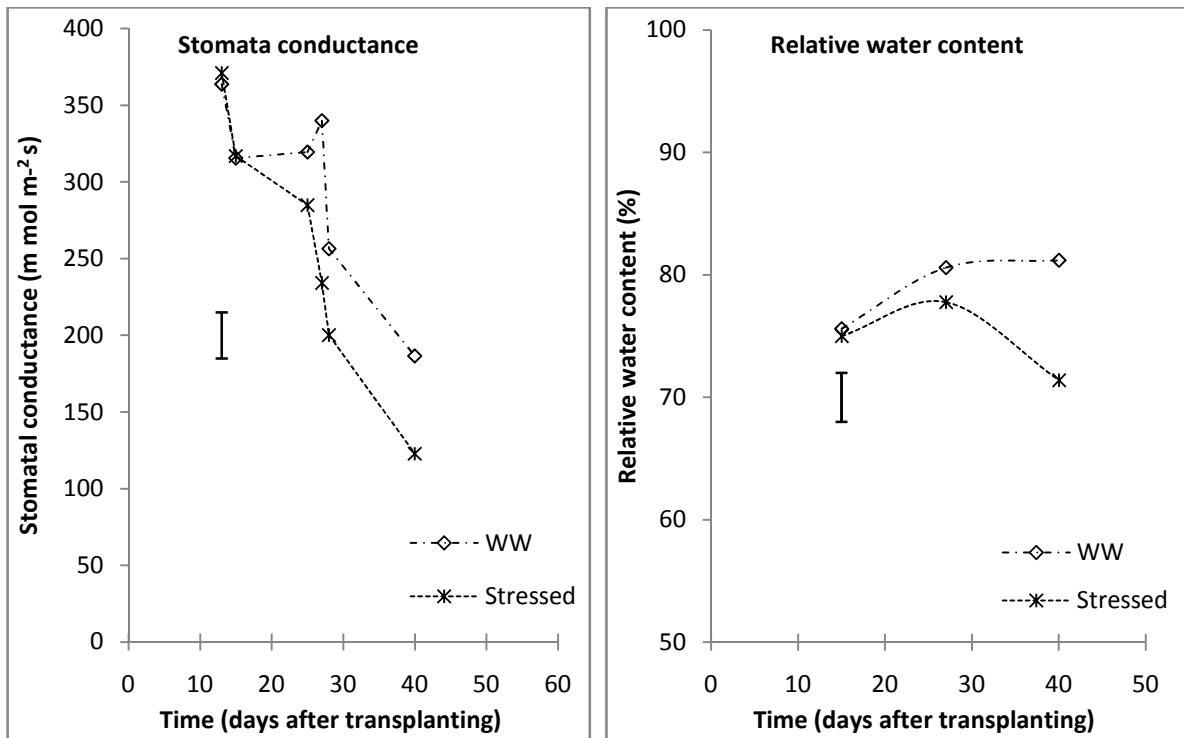


**Figure 4.9** Amount of water use (transpired water) by amaranthus for the two water treatment.

#### 4.3.4.2 Stomatal conductance and relative water content

Stomatal conductance declined steadily with time for the two water treatments (Figure 4.10) probably due to aging of the leaves. There was a decline in stomatal conductance of the leaves for both treatments between days 25 and 30 after transplant. However, stressed plants had lower stomatal conductance than the well-watered plants. Low stomatal conductance in stressed plants is a means of coping with the low water in the soil. The stomata closed to restrict and conserve the little available water in the soil. Cornic and Massacci (1996) reported that stomatal closure is a response of plants to water stress. The level of stomatal conductance also is directly proportional to available soil water and yield. Well-watered plants had higher relative water content than the stressed plants throughout the study period (Figure 4.10). Relative water content measures the water status of the plant and can be used as a selection criterion for drought tolerant crops (Matin *et al.*, 1989). Leaves of the two treatments were similar during the early stage of growth when there was adequate water available at 15 days after transplant as little, if any, stress had occurred by this stage. By day 40, the RWC of the well-watered was above 80% while the water stressed leaves were as low as 70%, giving an indication of the stress level (Figure 4.10). Hsiao (1990) reported that leaf that experiences RWC lower than 50% will suffer cell death and irreversible damage. RWC is also related to biomass production in the sense that it is a signal of water stress which affects biomass production (Umar, 2006).

Pot experiments provided a medium for closer observation of the crop even if it cannot totally represent the natural growing conditions in the field experiments (Townend & Dickinson, 1995). In pot experiments, a range of effects due to variation in plant growth condition were easily observed. Many studies have reported effects of water stress on crop water status in pot experiments. Crops subjected to soil drying will exhibit effects due to water stress. These effects may be observed in terms of biomass production, water uptake and physiological processes in crops. Liu and Stutzel (2002) observed differences in the rate of soil water extraction among four genotypes of amaranthus. They found a relationship between the rate of soil water extraction, the rate of leaf area expansion and stomatal conductance. In this present study, the well-watered plants transpired more water with a higher stomatal conductance than the stressed plants. This is in accordance with the results from the study carried out by Omami and Hammes (2006). They reported that low crop water use signifies low stomatal conductance of amaranthus. Liu and Stutzel (2002) found similar response of amaranthus to water stress in terms of relative water content (RWC) as in this study. The RWC of their well-watered plants was between 80-90% while that of stressed plants decreased to close to 70% at 25 days after imposition of stress.



**Figure 4.10** (a) Stomatal conductance and (b) relative water content of amaranthus subjected to two water treatments, well watered (WW) and stressed (SS).

The results of this trial show that performance of amaranthus can be improved with irrigation. Increase in biomass and edible portion of the crop confirm that low amounts of irrigation are needed to increase the production of amaranthus as was found by Neluheni *et al.* (2007). Serial harvesting at a specific height is more productive than allowing the plant to grow normally and then only harvest once at the end of the season. The serial harvesting produces smaller leaves that are succulent and preferable for human consumption as a fresh vegetable. There is a need to find the optimum threshold for water application amounts that will increase the yield of amaranthus leaves. The fully irrigated plots could be regarded as a waste of scarce water in semi-arid regions.

#### 4.3.4 Field trial for pearl millet

##### 4.3.4.1 Soil water content

Soil water contents of the plots of the two lines of pearl millet were different for the two seasons (Figure 4.11). During the 2008/2009 season, the soil water content of W5 in both lines of pearl millet reached field capacity at 42 days after sowing. As the same pattern was observed in rainfed plots (W1), this could be attributed to incidence of high rainfall during this period. The soil water content of the W5 treatment was consistently higher than the rest of the treatments in GCI 17 plots during the 2008/2009 season. However, the soil water of the W3 was higher than the rest of the treatments in Monyaloti plots during the 2008/2009 season from 71 days after sowing. Lateral movement of water is suspected to be the cause of this observation as there were no plastic dividing partitions between

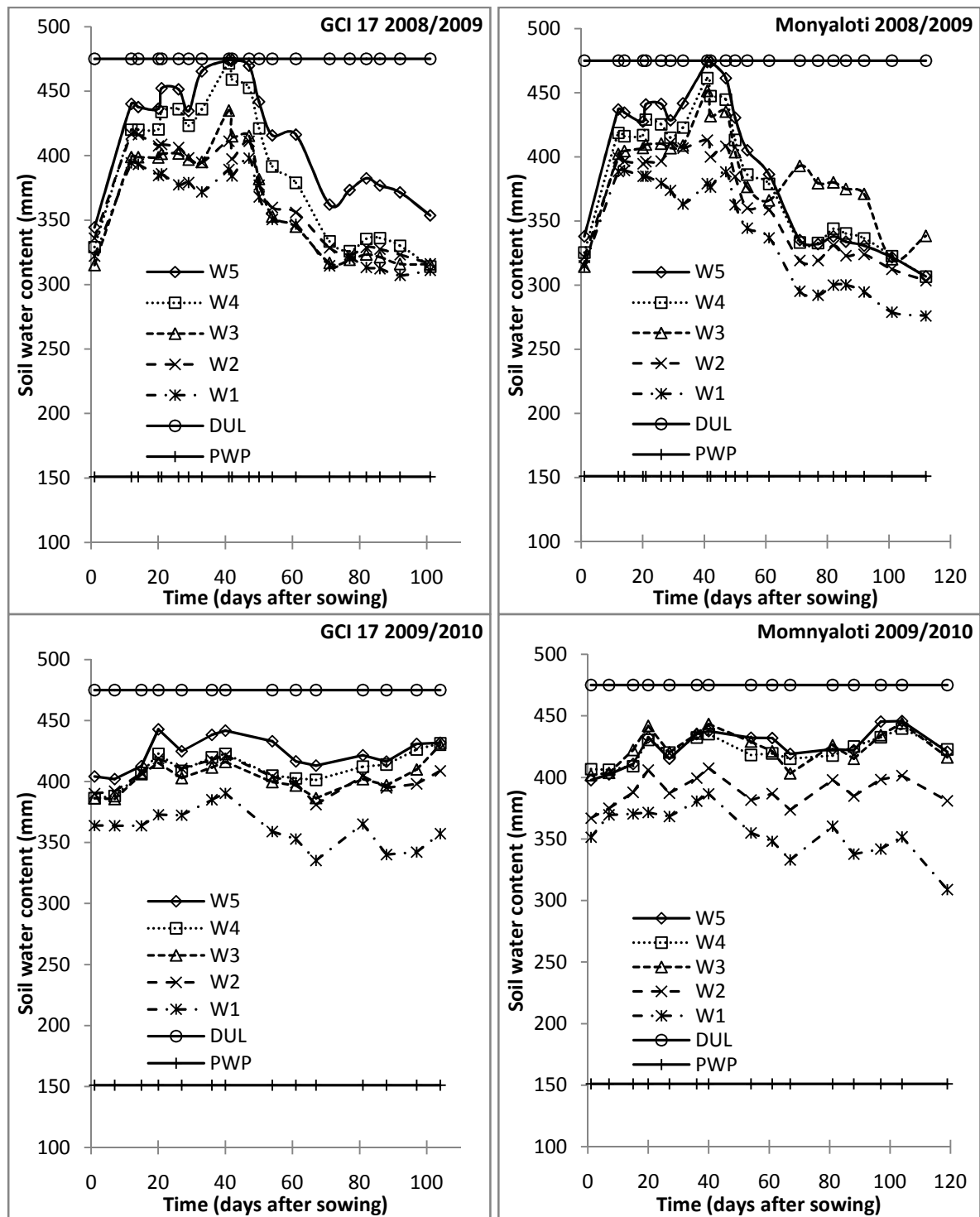
these field plots in the soil profile. In 2009/2010 season, the soil water contents of both lines of pearl millet were similar in pattern (Figure 4.11). The soil water of rainfed plots was lower than the irrigated plots throughout the season. In 2009/2010, rainfall is mostly responsible for the change in soil water of all the treatments considering the total amount of irrigation application, as this season was considered to be a wet year. Change in soil water content is an important component of water balance and normally has a great influence on daily and seasonal evapotranspiration. Pearl millet is a deep rooted crop and roots were reported to penetrate to 175 cm deep (Mangat *et al.*, 1999). This ability will help the crop to exploit soil water effectively and be able to manage water stress.

#### 4.3.4.2 Water use

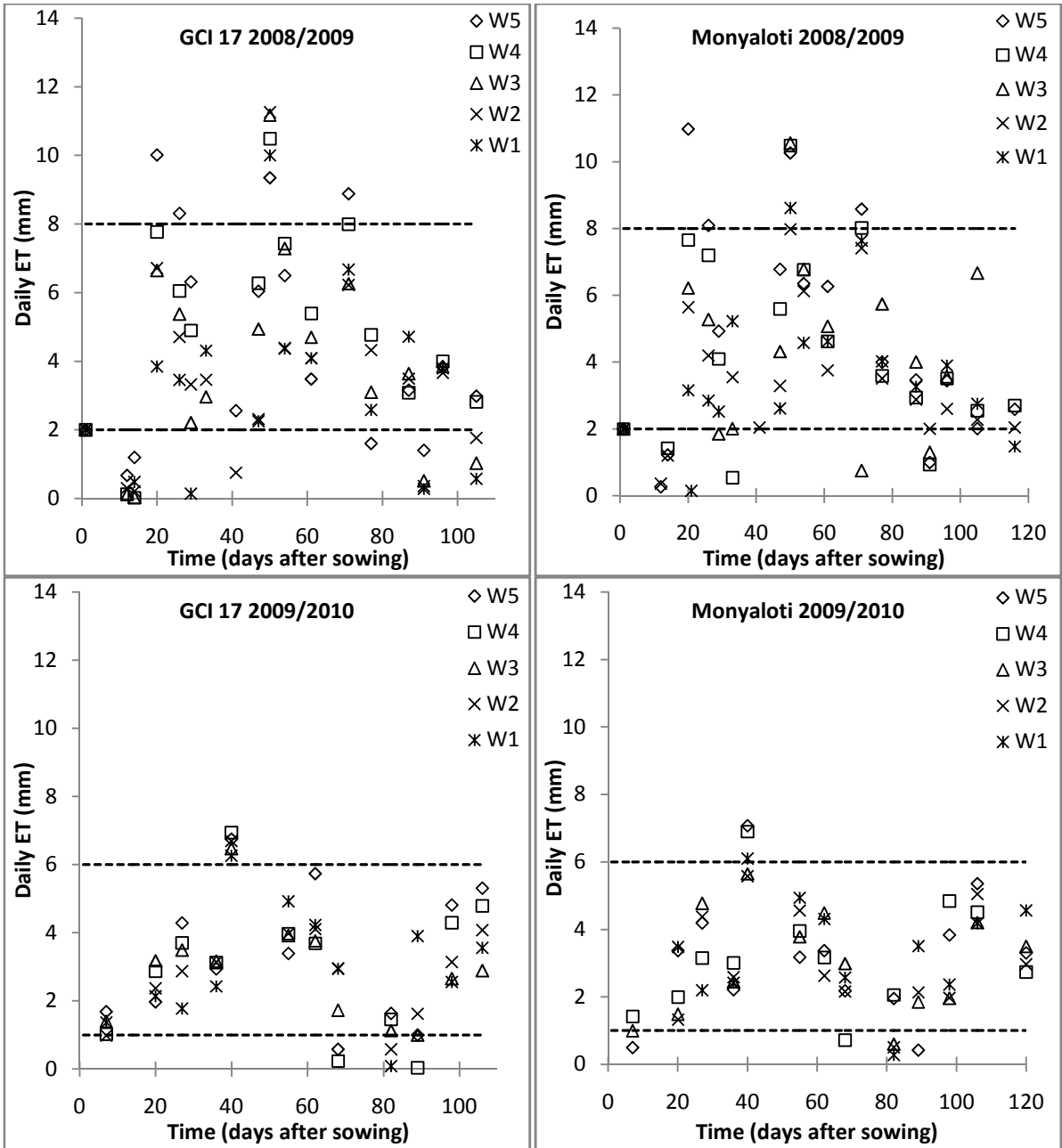
The daily ET for the two lines of pearl millet did not exhibit a uniform pattern during the two seasons (Figure 4.12). However, the daily ET observed during the first season (2008/2009) was higher than the second season. The highest daily ET in GCI 17 for the 2008/2009 season was 12 mm day<sup>-1</sup> found in rainfed (W1) plots while the highest in Monyaloti was 11 mm day<sup>-1</sup> found in W5 plots. It could be observed that during this season, optimum range of rate of daily ET was between 2 and 8 mm day<sup>-1</sup> for both lines. Daily ET observed during the 2009/2010 was generally lower when compared to the 2008/2009 season. The optimum range of daily ET during this season was between 1 and 6 mm day<sup>-1</sup> for both lines of pearl millet. The reason for higher rate of water use during 2008/2009 could be due to higher evaporative demand observed during this season (Table 4.1). Cumulative evapotranspiration was different for the two lines of pearl millet and seasons (Figure 4.13). The difference between the two lines of pearl millet within the season is mostly due to the different growing period of the lines, as the improved variety (GCI 17) takes 105 days to mature while the local variety (Monyaloti) takes 120 days. Cumulative ET for Monyaloti was higher than that of GCI 17 during both seasons and across treatments. During the 2008/009 season, W5 had the highest cumulative ET for both lines of pearl millet while the rainfed plots had the lowest cumulative ET. The case was different in the 2009/2010 season. The highest cumulative ET in the GCI 17 plots was not significantly different for all the treatments throughout the season. In the Monyaloti plots, the rainfed plots had the highest cumulative ET of 482 mm and the W3 treatments had the lowest cumulative ET of 420 mm by the end of the 2009/2010 season. Little or no difference in the cumulative ET occurred within the treatments of GCI 17 during the 2009/2010 season which could be due to the fact that the trend of change in soil water was consistent considering that the soil water content in all the irrigated treatments was relatively constant throughout the season. Crop water demand depends on climate and weather conditions, planting date and density, size of the crop and crop type, irrigation, and crop management (Allen *et al.*, 1998; Kramer & Boyer, 1995). Some of the factors that influence water use of the two lines of pearl millet in this study which support the information from the literature are weather conditions and the crop type. According to the weather demand of the two seasons, pearl millet as a drought tolerant crop used a low amount of water. This was also reported by Wahaj *et al.* (2006) that drought tolerant



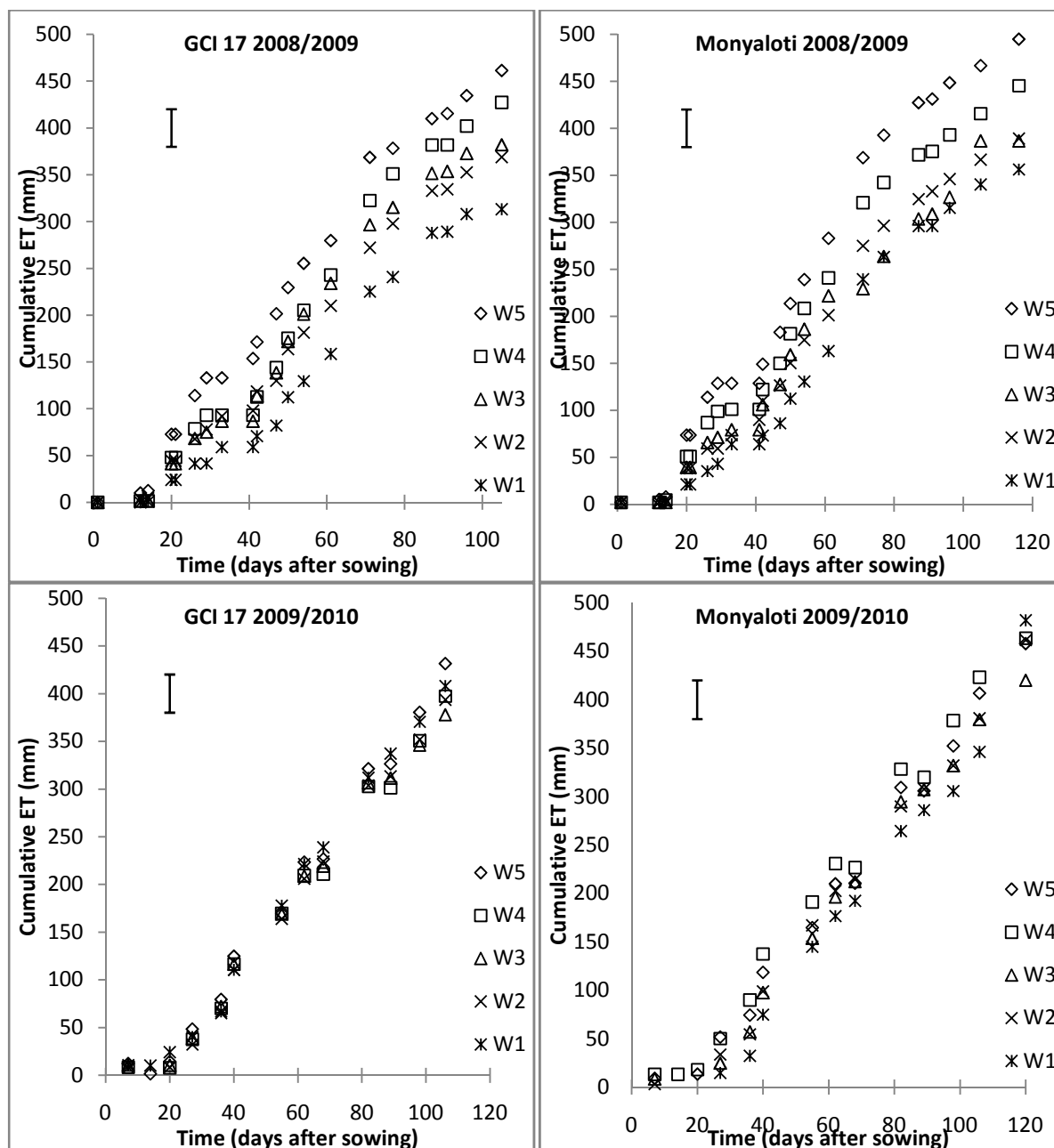
crops such as pearl millet and sorghum recorded lower amount of water use compare to maize in five countries.



**Figure 4.11** Change in soil water content of the plots of the two lines of pearl millet as affected by water treatments over the two cropping seasons (2008/2009 & 2009/2010).



**Figure 4.12** Daily evapotranspiration (ET) during the 2008/2009 and 2009/2010 seasons for the two lines of pearl millet. (Dotted lines illustrates range of daily ET).



**Figure 4.13** Cumulative evapotranspiration (ET) during the 2008/2009 and 2009/2010 seasons for the two lines of pearl millet.

#### 4.3.4.3 Biomass, grain yield and water use efficiency

The grain yield was reported only for the 2009/2010 season due to bird damage that occurred and could not be controlled in the 2008/2009 season. Therefore, final aboveground was the only yield parameter reported for 2008/2009 season. The water treatments significantly affected the biomass production between the lines and seasons (Table 4.4). The mean final above ground biomass for each of the two lines of pearl millet was higher during the 2009/2010 season than the 2008/2009 season due to more favourable conditions. During the two seasons, rainfed consistently produced the least total aboveground biomass in both lines of pearl millet. This proves that irrigation improves biomass

production of pearl millet as was also observed by Maman *et al.* (2003). In their study to investigate pearl millet response to water supply, they observed lower biomass in plots with no irrigation compared to irrigated plots for two seasons and two locations. In the 2009/2010 season, there was a significant effect of irrigation on grain yield (Table 4.4). The rainfed plots produced the lowest grain yield of GCI 17. Borrell *et al.* (2000) found result similar to this study, in that grain yield was low in water deficit plots for four varieties of sorghum. In the GCI 17 plots, the W4 plots produced the highest grain yield of 9.05 t ha<sup>-1</sup> compare with the lowest, 4.67 t ha<sup>-1</sup>, from the rainfed (W1) plots. The grain yield of Monyaloti did not follow the trend in GCI 17. It is difficult to explain the performance of Monyaloti with grain yield for the 2009/2010 season (Table 4.4). The variation in grain yield cannot be explained only by water treatments but probably due to the effect of soil variation as a result of previous tillage or cropping practices. The highest grain yield for Monyaloti was found in the fully irrigated, least irrigated as well as the rainfed plots. It was also observed that on average, Monyaloti produced higher grain yield than GCI 17. The difference in biomass production and grain yield between the two lines of pearl millet can be attributed to the effect of the genetic traits of the local crop variety. Therefore, local variety performed better in biomass and grain yield production than the improved line. Though, there was a significant effect of water treatment on HI for each line of the pearl millet but the two lines are not significantly different (Table 4.4) as the similar range of ratios of grain yield to total biomass was found. There was effect of irrigation on HI in the plots of GCI 17 with the plants from the W4 plots having the highest HI of 0.38 while the plants from the rainfed plots had the lowest HI of 0.28. During the 2009/2010 season, the plants from the rainfed plots of Monyaloti had the highest HI of 0.42 while the plants from the W4 plots had the least of HI with 0.22. Irrigation must have prevented water stress during flowering and increased partitioning and translocation into the grains in GCI 17 plots, resulting on a higher yield. Pearl millet harvest index has been observed to be increased if the water stress during flowering is avoided which will result in greater partitioning of biomass to the panicle and grain yield (Edmeades *et al.*, 1998). In Monyaloti plots, rainfed plants partitioned more biomass into grain to increase harvest index. The reason for this observation might be due to high water use of the treatment (482 mm) which was higher than the rest of the treatments for that season. This might have helped the plants from these plots to experience less water stress at this stage in the season which then influenced the HI. It was reported by de Lucas *et al.* (2001) that water stress during flowering stage reduces HI.

Water use efficiency (WUE) can be defined as a given level of biomass or grain yield per unit of water used by the crop (Hatfield *et al.*, 2001). The water use efficiency for biomass production (WUE<sub>bm</sub>) is significantly different between the two lines of pearl millet (Table 4.4). However, there is no significant difference between the years. The difference might be due to genetic factors (Sedhom, 2001). In GCI 17, on an average, WUE<sub>bm</sub> was 0.047t ha<sup>-1</sup>mm<sup>-1</sup> during the 2008/2009 season and 0.051t ha<sup>-1</sup> mm<sup>-1</sup> for the 2009/2010 season. This pattern of WUE<sub>gy</sub> is expected considering the values of HI

for different treatments. W4 had the highest  $WUE_{gy}$  with  $0.023t\ ha^{-1}\ mm^{-1}$  while the rainfed had the lowest with  $0.011\ t\ ha^{-1}\ mm^{-1}$ . However, it was observed that the high water use of Monyaloti for the 2009/2010 season recorded by the rainfed plots was used more efficiently used in grain yield production. In 2009/2010, rainfed plots of Monyaloti had the lowest  $WUE_{bm}$  ( $0.048\ t\ ha^{-1}\ mm^{-1}$ ) but with high  $WUE_{gy}$  of  $0.02t\ ha^{-1}\ mm^{-1}$  recorded for the treatment in the same season. There has been lots of work done on water use efficiency of pearl millet and results of many are similar to the findings of this study. Ismail (2012) reported decreasing irrigation water use efficiency with increasing water stress. Gaber *et al.* (2006) observed that water use efficiency was different for two varieties of pearl millet which is in support of the finding of this study. Improved and local variety of pearl millet had different WUE irrespective of the treatments. Gaber *et al.* (2006) also observed that the highest depth of irrigation water applied during the study produced the highest grain yield with the highest water use efficiency. In this study, plots with the adequate amount of irrigation (W4) in GCI 17 had highest WUE for biomass and grain production while in the Monyaloti plots, treatments with the highest (W5) and the lowest amount of irrigation (W2) had the highest  $WUE_{gy}$ .

**Table 4.4** Total above ground biomass (BM), seasonal evapotranspiration (ET), water use efficiency (WUE), grain yield (GY), harvest index (HI) of the two lines of pearl millet over the two cropping seasons (2008/09 & 2009/10)

	2008/2009			2009/2010					
GCI 17	BM	ET	$WUE_{bm}$	BM	ET	GY	HI	$WUE_{bm}$	$WUE_{gy}$
W5	18.53b	461.67a	0.040d	23.39a	431.47a	7.07b	0.30c	0.054b	0.016b
W4	18.16b	427.29b	0.043d	23.65a	397.55bc	9.05a	0.38a	0.059a	0.023a
W3	21.54a	381.97c	0.056a	20.85b	377.87c	7.10b	0.34b	0.055b	0.019b
W2	17.10bc	368.71c	0.046c	18.57c	393.47c	6.46c	0.35b	0.047c	0.016b
W1	16.15c	313.06d	0.052b	16.63d	407.90ab	4.67d	0.28c	0.041d	0.011c
LSD	2.61	33.25	0.003	2.05	19.11	0.54	0.02	0.003	0.003
	2008/2009			2009/2010					
Monyaloti	BM	ET	$WUE_{bm}$	BM	ET	GY	HI	$WUE_{bm}$	$WUE_{gy}$
W5	24.34b	494.95a	0.050c	29.53a	458.13b	10.32a	0.35b	0.064a	0.023a
W4	29.94a	445.49b	0.070a	25.68b	463.52b	5.70b	0.22c	0.055b	0.012c
W3	23.78b	386.56c	0.060b	25.31b	420.16c	6.01b	0.24c	0.060a	0.014c
W2	21.64c	388.94c	0.060b	28.51a	461.94b	10.38a	0.36b	0.062a	0.022a
W1	21.12c	356.43d	0.060b	23.01c	482.17a	9.69a	0.42a	0.048c	0.020b
LSD	2.43	25.13	0.007	1.85	27.97	3.1	0.05	0.005	0.002

$WUE_{bm}$  Water use efficiency for biomass,  $WUE_{gy}$  Water use efficiency for grain yield \*Units: BM = ( $t\ ha^{-1}$ ), GY= ( $t\ ha^{-1}$ ), ET = (mm),  $WUE_{bm}$  = ( $t\ ha^{-1}\ mm^{-1}$ ),  $WUE_{gy}$  = ( $t\ ha^{-1}\ mm^{-1}$ ). Values in the same column not sharing the same letter differ significantly at LSD (P=0.05).

### 4.3.5 Pearl millet production under lysimeter trial

#### 4.3.5.1 Application of irrigation

The total irrigation amount supplied during the trial shows that the two lines of pearl millet cultivated on Bainsvlei soil require less water than when cultivated on Clovelly soil under the no stress condition (WW) (Table 4.5). This may be due to the higher clay content property of the Bainsvlei soil than that of the Clovelly soil which increased its water holding capacity (see Ehler *et al.*, 2003). The least amount of water supplied was required in the treatment that was stressed during the reproductive to grain filling growth stages stress (RGS) for both the forms of soils.

**Table 4.5** Average amount of irrigation water (mm) supplied to different treatments on both soils of lysimeters (Abbreviations are as explained in materials and methods)

Growth Stages	Bainsvlei					Clovelly				
	WW	VS	RS	GS	RGS	WW	VS	RS	GS	RGS
Vegetative	57	37	57	55	58	54	34	51	49	44
Reproductive	122	136	-	122	-	122	122	-	122	-
Grain filling	265	257	287	-	-	287	287	287	-	-
Total	444	430	344	177	58	463	443	338	171	44

#### 4.3.5.2 Productivity and transpired water use

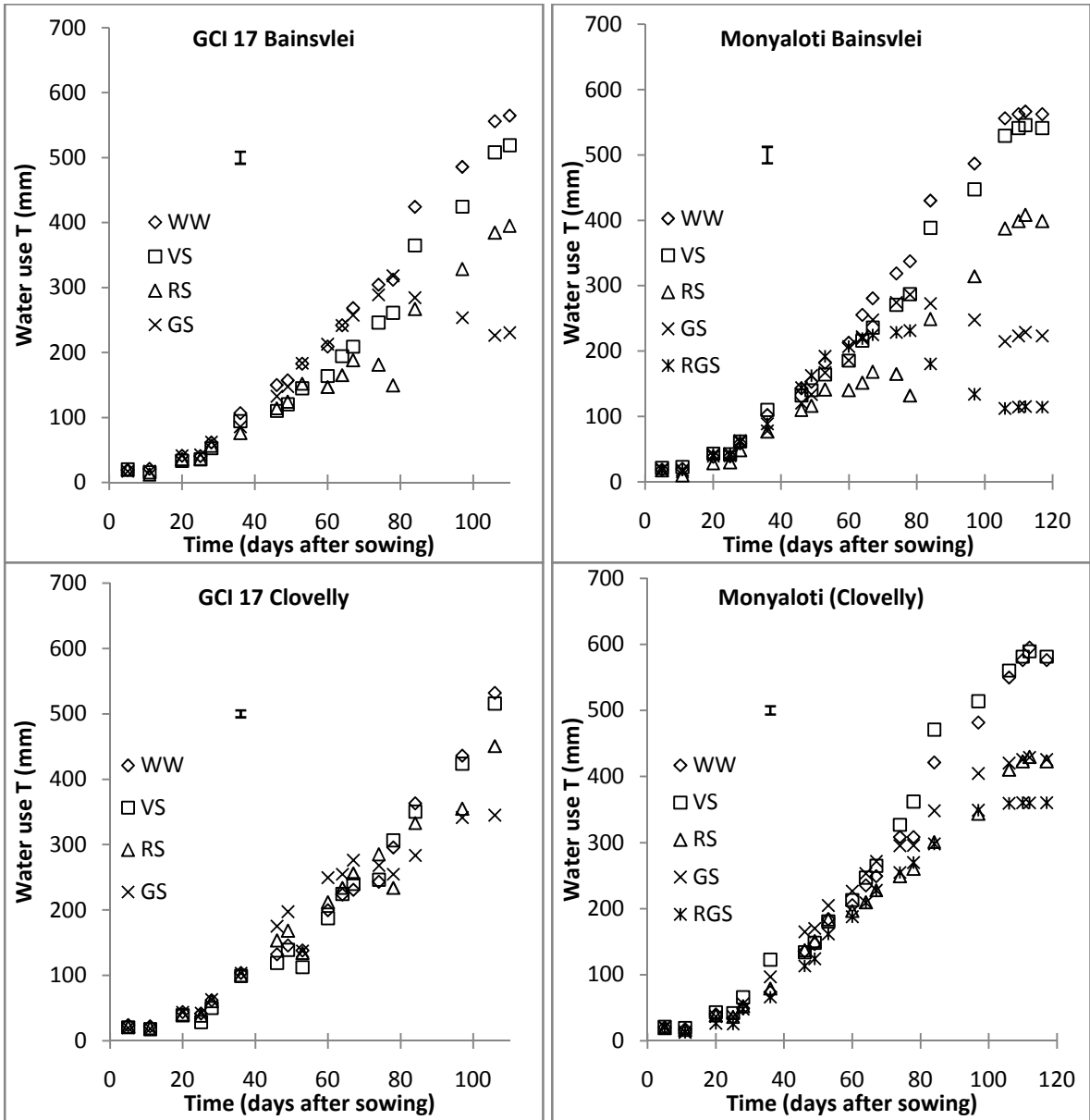
The transpiration (T) estimated for the two lines of pearl millet from the two soil forms shows that there were significant differences for all the treatments for water use on the two soil forms (Figure 4.14). Throughout all the treatments, low water use was found in GS and RGS treatments tanks irrespective of the two lines of pearl millet or soil forms. Since the amount of irrigation supplied is very low compared to the rest of the treatments this is in agreement with the low water use due to low soil water availability for these two treatments. The amount of water use (T) by the two lines of pearl millet ranges from 411 to 473 mm (Table 4.6). These are the maximum and minimum T for the two soils and were found on the Clovelly soil form.

Plants from the well watered treatment produced the highest total aboveground biomass and grain yield irrespective of lines of pearl millet and soil forms (Table 4.6). This was in accordance with the assumption of the study that the crop from this treatment are not expected to experience any stress during this study and should perform well under no stress condition. The number of heads per hectare is a yield component which may not be affected by imposition of stress at different growth stages (Table 4.6). This was due to the fact that there was no clear trend of the effect of stress on this yield component. It was reported that water stress during panicle development delayed flowering and increased the number of productive tillers (Mahalakshmi & Bidinger, 1985a) and consequently more panicles will be produced which will contribute towards increasing grain yield. However, this differs from the observation from this study. Final number of heads did not have any positive impact on grain yield as the yield does not follow the pattern of this yield component (Table 4.6). Grain yield of GCI 17 was almost equal on Bainsvlei and Clovelly soil form. The highest grain yields for GCI 17 and Moyaloti were found in the well watered treatment tanks while the lowest were found in the grain

filling stage stress tanks irrespective of the soil form. The mean grain yields for GCI 17 was 6.86 t ha<sup>-1</sup> on Bainsvlei and 6.49 t ha<sup>-1</sup> on Clovelly soils. In the Monyaloti tanks, the highest grain yield was 10.74 t ha<sup>-1</sup> from the WW found on Clovelly soil type while the lowest was 2.39 t ha<sup>-1</sup> from RGS found on Bainsvlei soil type. The huge difference in the grain yield observed in Monyaloti emphasise the impact of irrigation on pearl millet production. The grain yield reflects the trend of harvest index (HI) for each treatment. The average HI observed on Bainsvlei soil for Monyaloti was the smallest across the two lines of pearl millet. However, water stress did not affect the water productivity of GCI 17 on Bainsvlei soil form. The GCI 17 plants from the RS and GS treatments exhibited high water productivity (WP) for biomass and grain yield production with 0.036 t ha<sup>-1</sup> mm<sup>-1</sup> and 0.016 t ha<sup>-1</sup> mm<sup>-1</sup> for both treatments respectively on Bainsvlei soil. The mean WP<sub>bm</sub> of GCI 17 was 0.036 t ha<sup>-1</sup> mm<sup>-1</sup> for the both soil type while Monyaloti had WP<sub>bm</sub> of 0.037 and 0.035 t ha<sup>-1</sup> mm<sup>-1</sup> on Bainsvlei and Clovelly respectively. Reproductive stress (RS) resulted in high WP<sub>gy</sub> of 0.016 t ha<sup>-1</sup> mm<sup>-1</sup> in GCI 17 but very low WP<sub>gy</sub> of 0.006 t ha<sup>-1</sup> mm<sup>-1</sup> in Monyaloti on Bainsvlei soil. In this treatment for Monyaloti, it was suspected that flower pollination and development might have been affected by the water stress at this stage. This study is in accordance with the results from the Mahalakshmi and Bidinger (1985b) study. They reported that water stress caused delay in flowering and development of pearl millet and thereby reducing grain number and consequently reduced grain yield. It also supports the observation of Blum (2005) that water use efficiency of a crop increased as a means of water stress tolerance, but it is at the expense of its potential yield. Overall, the two lines of pearl millet recorded high WP for biomass production on both soils but with low grain yield.

#### 4.3.5.3 Leaf water potential

Leaf water potential of the two lines of pearl millet was affected by water stress at different growth stages (Figure 4.15). Leaf water potential declined throughout the study period for all the treatments and the two lines of pearl millet on the two soil forms. However, the lowest leaf water potential was measured during the RGS stress for Monyaloti plants but was not different from GS of the same line of pearl millet irrespective of the soil type. This could be a reflection of the soil water content of the lysimeters and the ability of the crop to adjust to water deficit condition. The rate of decline was occasionally disturbed by changes in soil water status due to application of irrigation water.



**Figure 4.14** Cumulative water use (transpiration) as affected by water stress at different growth stages of the two lines of pearl millet on two types of soil.

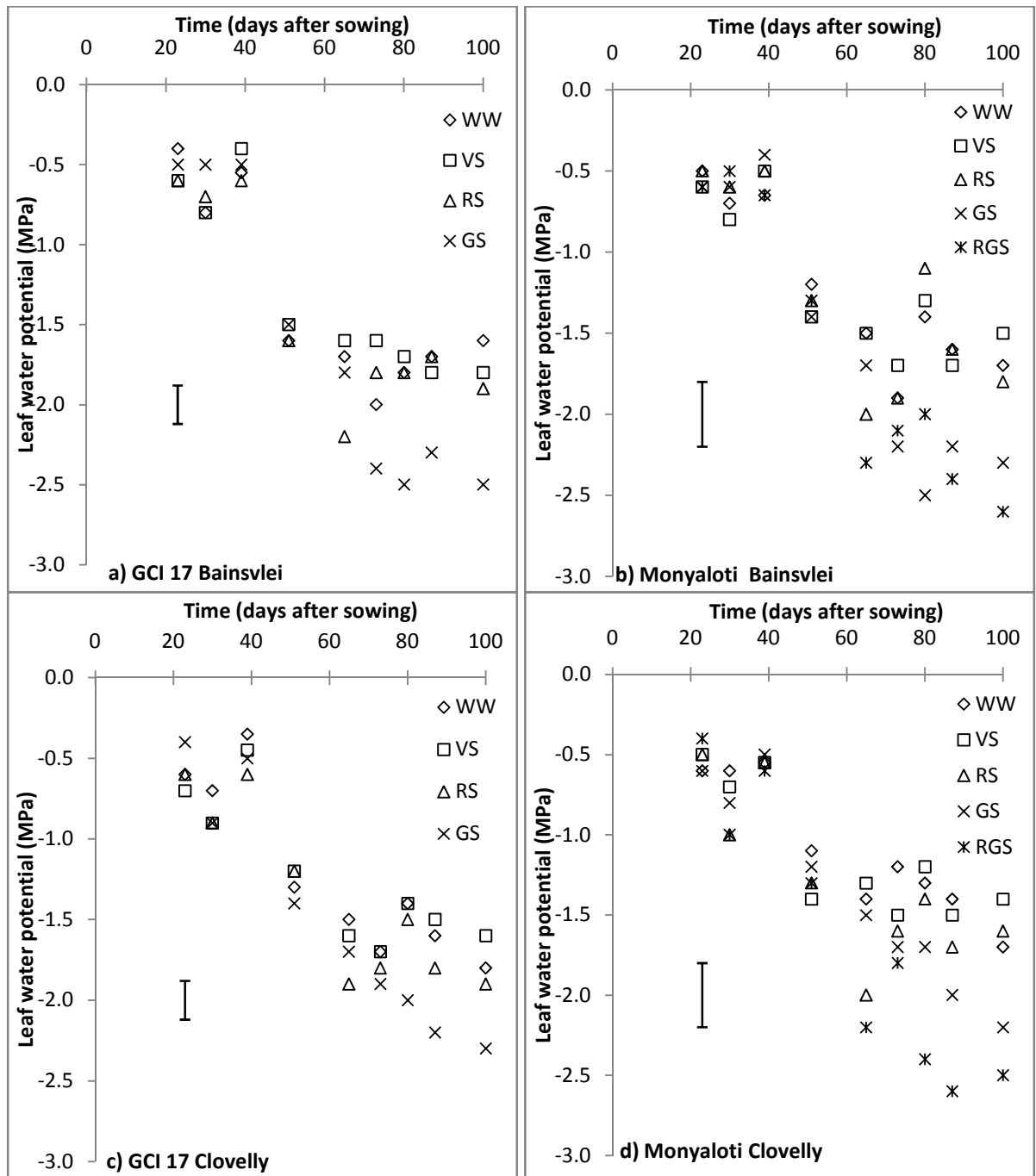


**Table 4.6** Seasonal transpiration, total above ground biomass (TBM), number of heads per plant stand, grain yield, harvest index (HI) and water productivity (WP) of the two lines of pearl millet subjected to water stress at different growth stages on two types of soil

GCI 17														
Treatments	Transpiration (mm)		TBM (t ha <sup>-1</sup> )		Number of heads ( X 1000 ha <sup>-1</sup> )		Grain yield (t ha <sup>-1</sup> )		Harvest index (HI)		WP <sub>bm</sub> (t ha <sup>-1</sup> mm <sup>-1</sup> )		WP <sub>gy</sub> (t ha <sup>-1</sup> mm <sup>-1</sup> )	
	<i>Bainsvlei</i>	<i>Clovelly</i>	<i>Bainsvlei</i>	<i>Clovelly</i>	<i>Bainsvlei</i>	<i>Clovelly</i>	<i>Bainsvlei</i>	<i>Clovelly</i>	<i>Bainsvlei</i>	<i>Clovelly</i>	<i>Bainsvlei</i>	<i>Clovelly</i>	<i>Bainsvlei</i>	<i>Clovelly</i>
<b>WW</b>	549.25a	531.94a	18.36a	16.75a	243.61a	172.89b	8.18a	8.31a	0.446a	0.496a	0.033c	0.031c	0.015b	0.016a
<b>VS</b>	482.26b	515.64b	17.77a	16.00b	220.04b	172.89b	6.79b	7.88ab	0.382a	0.493a	0.037a	0.031c	0.014c	0.015a
<b>RS</b>	410.29c	450.79c	14.82b	16.33ab	204.32c	172.89b	6.76b	5.22bc	0.456a	0.320b	0.036b	0.036b	0.016a	0.012b
<b>GS</b>	363.53d	345.10d	13.16c	15.32c	204.32c	192.53a	5.70c	4.54c	0.433a	0.296b	0.036b	0.044a	0.016a	0.013b
LSD	1.98	1.98	1.58	0.50	5.22	7.34	1.01	1.73	0.122	0.087	0.0005	0.004	0.001	0.001
Monyaloti														
Treatments	Transpiration (mm)		TBM (t ha <sup>-1</sup> )		Number of heads ( X 1000 ha <sup>-1</sup> )		Grain yield (t ha <sup>-1</sup> )		Harvest index (HI)		WP <sub>bm</sub> (t ha <sup>-1</sup> mm <sup>-1</sup> )		WP <sub>gy</sub> (t ha <sup>-1</sup> mm <sup>-1</sup> )	
	<i>Bainsvlei</i>	<i>Clovelly</i>	<i>Bainsvlei</i>	<i>Clovelly</i>	<i>Bainsvlei</i>	<i>Clovelly</i>	<i>Bainsvlei</i>	<i>Clovelly</i>	<i>Bainsvlei</i>	<i>Clovelly</i>	<i>Bainsvlei</i>	<i>Clovelly</i>	<i>Bainsvlei</i>	<i>Clovelly</i>
<b>WW</b>	562.31a	576.01a	22.71a	26.34a	180.75b	286.83a	6.60a	10.74a	0.290a	0.408a	0.040a	0.046a	0.012a	0.019a
<b>VS</b>	500.89b	581.71a	21.37a	19.29b	208.25a	220.04b	6.20a	6.93b	0.290a	0.359b	0.043a	0.033b	0.012a	0.012cd
<b>RS</b>	401.77c	422.91b	10.84c	13.96c	86.44d	168.96e	2.57c	5.97bc	0.237 b	0.428a	0.027c	0.033b	0.006c	0.014bc
<b>GS</b>	365.26d	425.45b	12.46b	14.19c	137.52c	176.82d	3.93b	6.78b	0.315a	0.478a	0.034b	0.033b	0.011ab	0.016b
<b>RGS</b>	229.56e	360.19c	9.39c	10.85d	86.44d	208.25c	2.39c	4.61c	0.254ab	0.425a	0.041a	0.030b	0.010b	0.013c
LSD	11.61	26.22	1.49	3.01	21.67	5.24	1.03	1.58	0.041	0.085	0.006	0.006	0.001	0.02

WP<sub>bm</sub> Water productivity for biomass

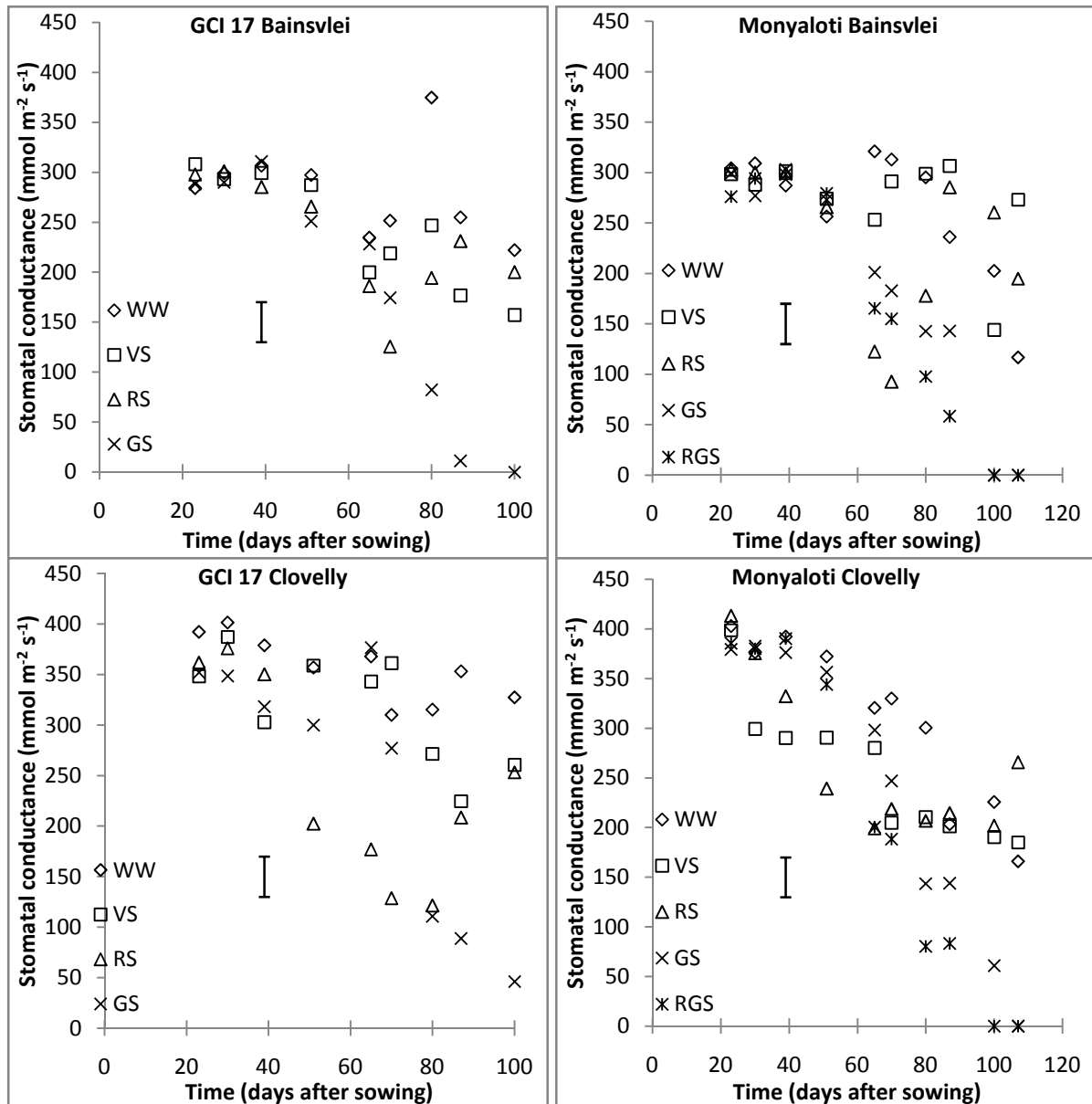
WP<sub>gy</sub> Water productivity for grain yield



**Figure 4.15** Change in leaf water potential with time of the two lines of pearl millet during stress at different growth stages on two types of soils.

#### 4.3.5.4 Stomatal conductance

Stomatal conductance of the two lines of pearl millet were different for all the treatments for the two types of soil (Figure 4.16). The stomatal conductance of the two lines of pearl millet from Clovelly were higher than Bainsvlei. The highest stomatal conductance observed on Clovelly soil was around 400  $\text{mmol m}^{-2} \text{s}^{-1}$  while it was around 300  $\text{mmol m}^{-2} \text{s}^{-1}$  on Bainsvlei soil for the two lines of pearl millet. At the end of the study, stomatal conductance of plants from RGS treatment lysimeter tanks was zero indicating that they were already into senescence at this particular time. The big difference between the well watered and RGS shows the severity of this water stress at the end of the study.

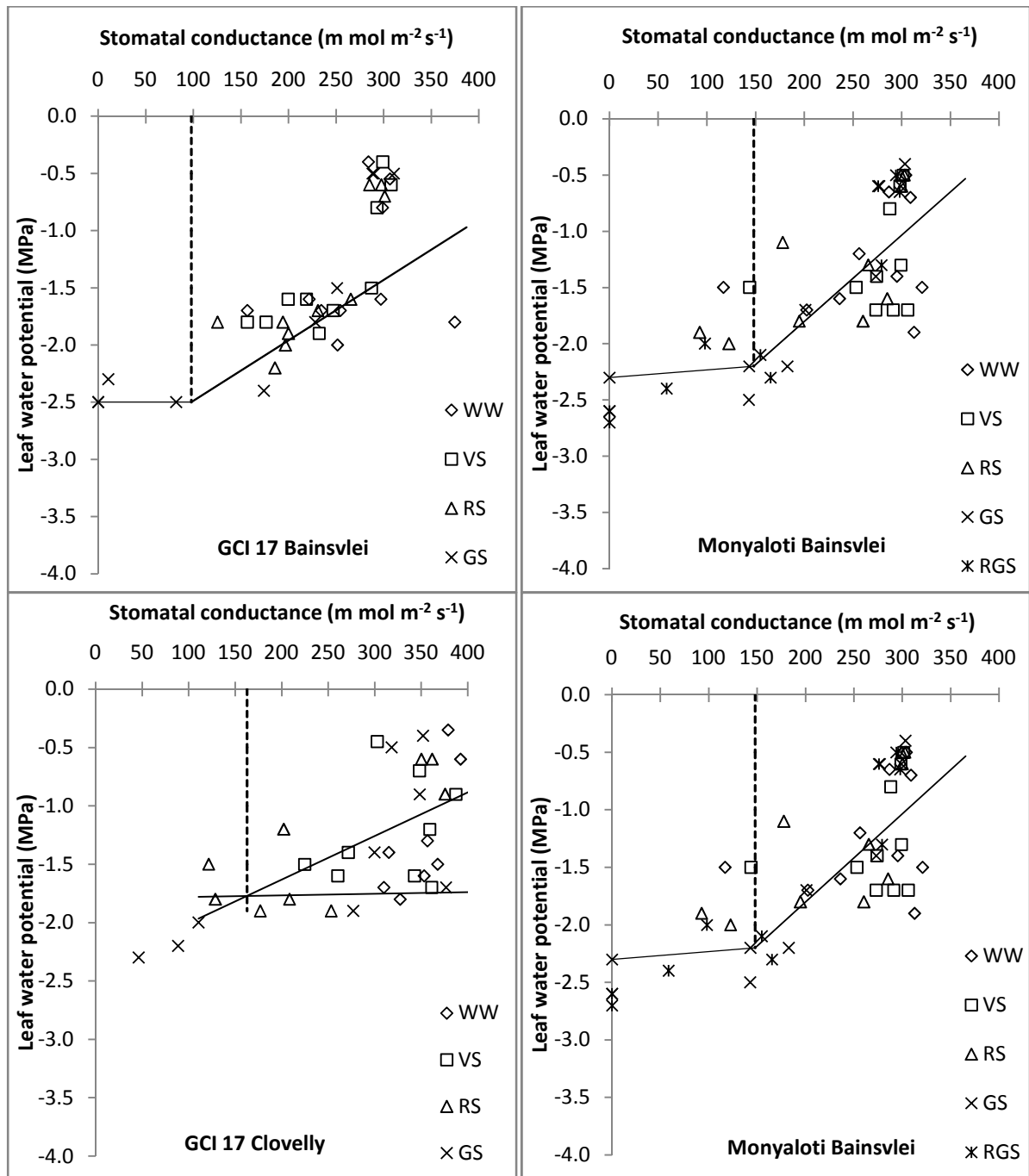


**Figure 4.16** Stomatal conductance of the two lines of pearl millet during stress at different growth stages on two types of soil.

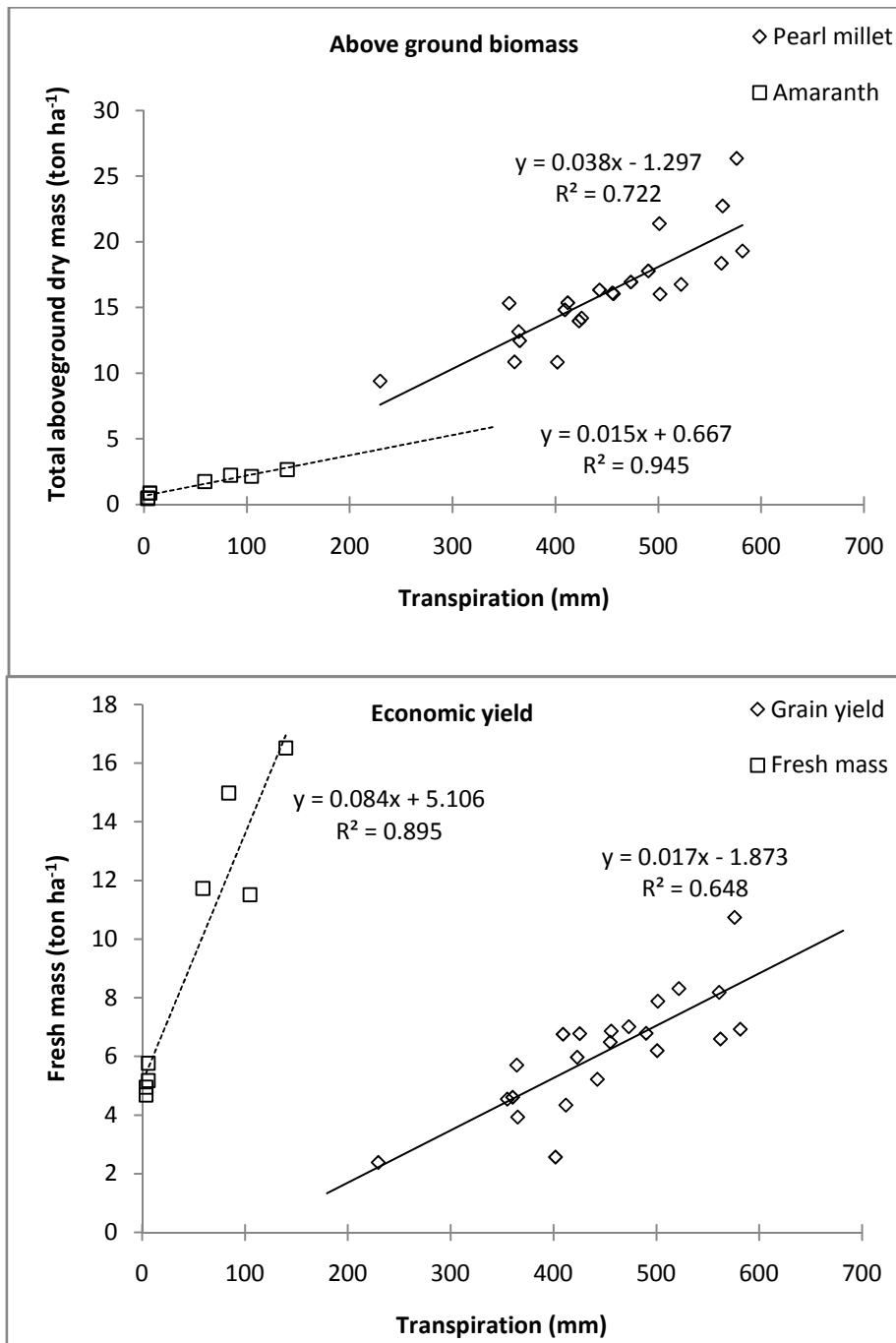
The relationship between the stomatal conductance and leaf water potential was determined to investigate the adjustment mechanism of the two lines of pearl millet on two soil types (Figure 4.17). The method used to determine the optimum point between stomatal conductance and soil water content for field amaranth as described in section 4.3.3.5 was also used for this purpose. The regression lines illustrated the relationship between the stomatal conductance and leaf water potential according to the levels of water stress sensitivity conditions. Figure 4.17 shows that stomatal conductance decreases with decrease in leaf water potential for the two lines of pearl millet on both soil types. Though, the relationship is linear but the stress sensitivity point for the leaf water potential and stomatal conductance determined for the two lines of pearl millet and soil types were different. However, the determined point is the point that could be identified as adjustment stage for the crop. On Bainsvlei soil, the sensitivity point for GCI 17 and Monyaloti are 98 and 148  $\text{m mol m}^{-2} \text{s}^{-1}$  at the leaf water potential of -2.44 and -2.21 MPa respectively. The sensitivity point on Clovelly soil is higher than that of Bainsvlei soil type. The stomatal conductance below 163 and 298  $\text{m mol m}^{-2} \text{s}^{-1}$  are the sensitivity points of the GCI 17 and Monyaloti on the Clovelly soil. Katerji *et al.* (1997) also observed that soil texture has an influence on stomatal conductance with soil of lower clay content performing better than the rest of the soil engaged in the study. The better adjustment was found in Clovelly in this study which probably due to its lower clay content than Bainsvlei soil type (see Chapter 2 section 2.4). Monyaloti has greater adjustment with higher stomatal conductance in reference to higher leaf water potential compare to those of GCI 17. The sensitive point as a sign of adjustment in the two lines of pearl millet could be explained as the point at which stomata closes to prevent excessive loss of water but maintaining constant leaf water potential to be able to keep the leaf turgid and prevent wilting (Gollan *et al.*, 1986).

#### **4.3.6 Comparison of water use for vegetable and grain crops**

In order to compare the water use and productivity of the two crops as C4 crops, economic yield and the total biomass of the two crops were used from the pot (amaranthus) and lysimeter trial (pearl millet). All the water use, biomass, grain yield, soil forms and lines of pearl millet data were pooled together. In amaranthus, fresh mass is the economic yield while it is grain yield for pearl millet. Figure 4.18 reveals a good linear relationship between transpiration and biomass production of amaranthus and pearl millet. Comparing the water use of the two crops, it was observed that pearl millet is more efficient (more than double) in converting a unit volume of water to biomass. However, in converting water use to economic yield, amaranthus is more efficient. Economic yield of amaranthus is fresh mass which is about 80% water content while the grain yield is only with 15% water content. Therefore, most of the water uptake by the amaranthus was still part of the yield.



**Figure 4.17** Relationship between leaf water potential and stomatal conductance of the two lines of pearl millet during stress at different growth stages on two types of soil.



**Figure 4.18** Relationship between water use (transpired water) and biomass production of amaranthus (pot experiment) and pearl millet (lysimeter trial).

#### **4.4 CONCLUSIONS**

In semi-arid regions, every drop of water counts and if yield can be improved with less water it will be better for the farmers. This study has provided lots of information on water influence on amaranthus and pearl millet production. Efficient production of amaranthus through irrigation requires a small amount of water but at a sufficient level. Irrigation can improve both biomass and grain yield of the crop of the two lines of pearl millet under investigation. Water stress does not limit the production of pearl millet as the rainfed yield was reasonably similar compared to the irrigated. However, information on factors affecting the water use of these crops will help in managing and improving their water use efficiency. Considering weather conditions, planting dates will determine evaporative demand which affects transpiration. Choice of crop variety is also important as available water needs to be well managed. In pearl millet, Monyaloti made use of large amount of water but with high water use efficiency. This line proves to be more tolerant to water stress. It was able to adjust to severe water stress by maintaining higher leaf water potential at higher stomatal conductance than the other line.

## CHAPTER 5

# CALIBRATION AND VALIDATION OF AQUACROP FOR AMARANTHUS AND PEARL MILLET

### 5.1 INTRODUCTION

#### 5.1.1 Motivation

Water, as an important crop production determining factor is becoming scarcer around the world. In agriculture, water is supplied by both rainfall and irrigation. Rainfall provides 65% of water needed for global food production, compared to only 35% from irrigation (Smith, 2000). However, in semi-arid areas, rainfall is erratic and not evenly distributed (Botha *et al.*, 2003). Water supply from rainfall in semi-arid areas is uncertain due to dry spells and droughts that severely impact water resources at catchment and field scales and threatens both rainfed and irrigated sustainable agriculture (Ferres & Connor, 2004). Low water availability in semi-arid areas calls for good alternative management practices which can be in the form of choice of crops, irrigation management and cropping systems. Due to erratic rainfall, crop production depends mostly on irrigation in semi-arid areas, as irrigation also helps to improve water use efficiency of the crop (Musick *et al.*, 1994). Irrigation and proper water management can play an important role in enhancing water productivity and reducing crop failure in semi-arid areas (Evetts *et al.*, 2003). Irrigation is also used in humid regions to avoid decline in crop yield and quality caused by short-term dry spell periods (Evetts *et al.*, 2003). However, irrigation consumes a large portion of the fresh water resources across the world as crop production depends highly on irrigation. In 2009, it was reported that irrigated agriculture consumed about 72% of available fresh water resources on a global scale (Geerts & Raes, 2009). In the future, irrigated agriculture is expected to reduce water usage and yet still produce sufficient food and fibre for the increasing world population (Garcia-Villa *et al.*, 2009). However, in South Africa, it has been observed that the water sources available for irrigation are all being utilized already (Backeberg *et al.*, 1996), thus there is a little scope for new irrigation expansion and development. This is forcing managers and irrigators to re-evaluate their strategies for growth in the agricultural sector (Haka, 2010). One of these strategies is to plant underutilized crops which is a niche market at present but could be expanded to provide food for the masses in the climates of the future.

Accurate quantification of water use of a crop is part of effective water management. Effective water use both in irrigated and rainfed crop production is a main requirement to design better strategies to manage available water resources (Smith, 2000). The importance of water for crop growth and development of major crops has been shown many times but little information on this has been documented for underutilized crops (Karunaratne *et al.*, 2011) such as amaranthus and pearl millet.



Available means of optimizing crop production per unit of water include identification of strategies to improve water use efficiency of rainfed and/or irrigated crop production. Computerized procedures, such as crop modelling, can help to form alternative strategies for crop production optimization. Crop models are an agricultural tools used to predicting water use and yield of many crops. However, few of the currently available crop models have been calibrated for minor or underutilized crops (Walker *et al.*, 2012).

There are many crop models that are either too general, or only for specific crops and/or agroecological zones. Crop models can be used as research tools. They help in research analysis, integration of knowledge across disciplines, experiment documentation, give assistance in genetic improvement and yield analysis of crops to mention a few (Boote *et al.*, 1996; Cheeroo-Nayamuth, 1999). Crop management including cultural practices and input management, site specific farming, planting dates, risk assessment and investment support are part of the decision support systems provided by crop growth models (Boote *et al.*, 1996; Cheeroo-Nayamuth, 1999; Jame & Cutforth, 1996). Crop models can be used as analysis tools for decisions such as selecting the best management practices; yield forecasting over a large area; introduction of new crops into a region and/or effect of global climate change on crop production (Cheeroo-Nayamuth, 1999; Murthy, 2003).

Some crop models perform better in achieving specific goals due to their designs and add on software. The CERES (Crop Environment Resource System) crop model, integrates the effects of temporal and multiple stress interactions on crop growth processes under different environmental conditions (Ritchie & Otter, 1985; Ritchie *et al.*, 1985). DSSAT (Decision Support Systems for Agrotechnology Transfer) is a framework that allows combinations of technical knowledge of crop growth models including CERES with economic considerations and environmental impact evaluations in order to facilitate economic analysis and risk assessment of farming enterprises (Jame & Cutforth, 1996). APSIM (Agricultural Production Systems Simulator) is one of the few crop models capable of dealing with water and nitrogen dynamics under different fertility management conditions for simulating crop growth and development at various scales from catchment to farm and field scale (Akponikpe *et al.*, 2010). The AquaCrop model requires a minimum number of crop parameters, while attempting to balance simplicity, accuracy and robustness with user friendliness (Steduto *et al.*, 2009). Spitters (1990) pointed out that a strategy to employ in developing a model is to develop a series of sub-models of varying complexity for different processes while emphases should be put on simple approaches. AquaCrop was developed, in the context of water scarcity, to help project managers, consultants, irrigation engineers, agronomists, and farm managers with the formulation of guidelines to increase the crop water productivity for both rainfed and irrigated production farming systems (Raes *et al.*, 2009). AquaCrop can simulate yield in response to water under various crop and field management conditions, including salinity and fertility conditions and also crop production under

climate change scenarios (global warming and elevated carbon dioxide concentration) (Steduto *et al.*, 2011).

The objectives of this chapter are to calibrate and validate AquaCrop model for two underutilized crops, namely amaranthus and pearl millet, under irrigation and rainfed conditions.

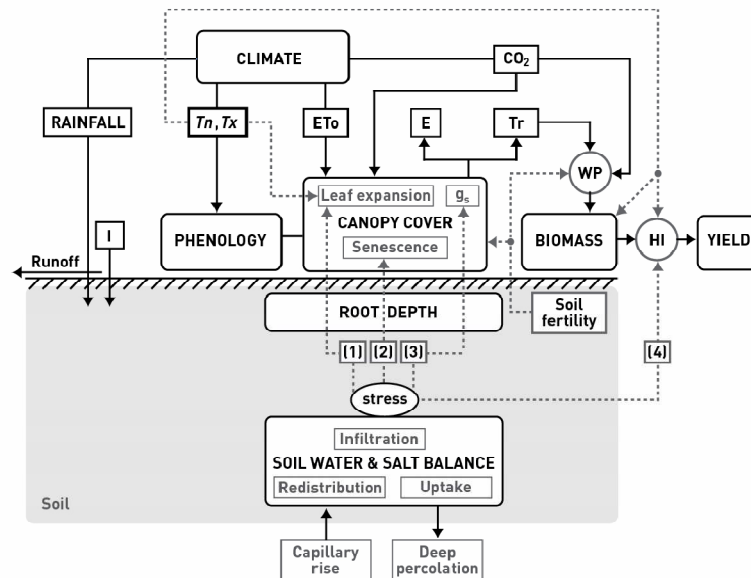
### 5.1.2 AquaCrop model descriptions

AquaCrop is a water-driven model which can be used for making management decision such as assessment of best management practices or irrigation requirements or for yield predictions. The Doorenbos and Kassam (1979) approach to determine the yield response to water of herbaceous and tree crops led to the evolution of AquaCrop model (Steduto *et al.*, 2008). In the Doorenbos and Kassam (1979) approach, relative evapotranspiration (ET) is used in calculating yield while AquaCrop took the approach further and separated ET into crop transpiration (T) and soil surface evaporation (E). In AquaCrop, a simple canopy growth and senescence model was developed as the basis for estimating T and its separation from E. The confounding effect of the non-productive consumptive use of water of E in the yield calculation was avoided by using the canopy ground cover instead of leaf area index (LAI) to calculate T (Steduto *et al.*, 2009). AquaCrop recognises final yield as a result of the part of the biomass partitioned to the yield component at a certain phenological stage of the crop as determined by the harvest index (HI). This allows the distinction of functional relationships between environment, biomass and HI (Raes *et al.*, 2009; Steduto *et al.*, 2009). Moreover, this relationship with biomass production led to the AquaCrop growth engine equation, (equation 5.1) as follows:

$$B = WP \times \sum T \dots \dots \dots \text{Equation 5.1}$$

where WP is the water productivity (biomass per unit of cumulative transpiration), which tends to be constant for a given climatic condition (de Wit, 1958; Hanks, 1983; Tanner & Sinclair, 1983) and WP becomes a conservative parameter once it is normalised appropriately for different climatic conditions (Steduto *et al.*, 2007). WP\* is water productivity normalized for the evaporative demand and CO<sub>2</sub> concentration of the atmosphere. This was done by dividing the biomass produced at a given time by the sum of the ratio of T to ETo for each day during the same period (Steduto *et al.*, 2009). The structure of AquaCrop model involves the entire soil-plant-atmosphere continuum as illustrated in Figure 5.1 which shows the functional relationship between the different components of the model. The atmosphere and soil environment are represented in a similar manner as in other models. The crop atmospheric environment is denoted by the climate component of the model (Figure 5.1). This climate component of the model requires input of daily maximum and minimum air temperatures, rainfall, reference evapotranspiration (ETo) and the mean annual carbon dioxide concentration (CO<sub>2</sub>) in the atmosphere (Steduto *et al.*, 2009). The soil environment in the model is made up of soil

horizons of variable depth (up to five layers) of different texture down the whole soil profile. Field capacity (FC) or drained upper limit of volumetric water holding capacity, permanent wilting point (PWP) or lower limit of the volumetric water holding capacity, drainage coefficient ( $\tau$ ) and hydraulic conductivity at saturation ( $K_{sat}$ ) are the soil water and hydraulic characteristics of the soil required for initialization of AquaCrop. The chart of AquaCrop (Figure 5.1) shows that the crop system has five major components: phenology, canopy cover, rooting depth, biomass and harvestable yield.



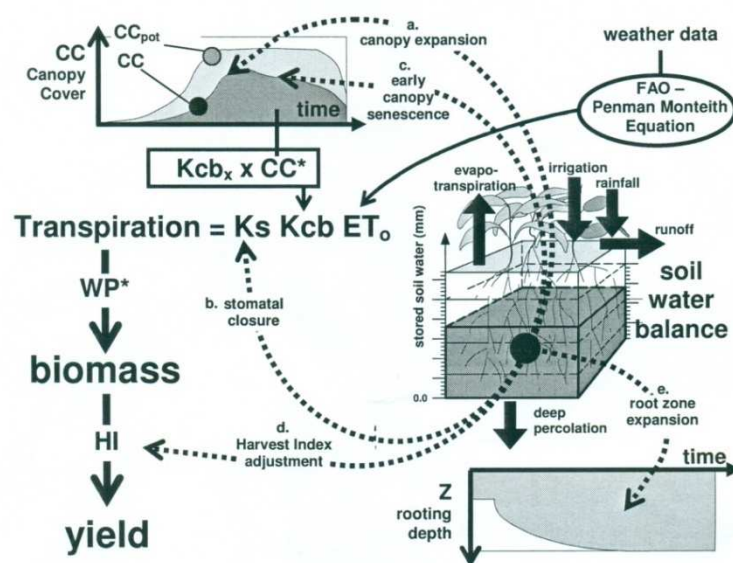
**Figure 5.1** The chart of AquaCrop (Steduto *et al.*, 2009).

(The chart of AquaCrop illustrating the main components of the soil-plant-atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production and final yield. (I, irrigation; Tn, minimum air temperature; Tx, max air temperature; ETo, reference evapotranspiration; E, soil evaporation; Tr, canopy transpiration; gs, stomatal conductance; WP, water productivity; HI, harvest index; CO<sub>2</sub>, atmospheric carbon dioxide; (1), (2), (3), (4), water stress response functions for leaf expansion, senescence, stomatal conductance and harvest index, respectively). Continuous lines indicate direct links between variables and processes. Dashed lines indicate feedbacks. Arrows show direction of flow information (Steduto *et al.*, 2009)).

Phenology in the AquaCrop uses thermal time (growing degree day, GDD) which is at default settings for the model. However, crop development can still be reported in calendar time if that option, calendar days is selected. Phenology of a crop depends mainly on interactions between cultivar characteristics and temperature regimes (Steduto *et al.*, 2009). However, the model provided calendar time as an option to select if the user does not want the output in thermal time. The major types of crops that the model can deal with are fruit or grain crops, root and tuber crops, leafy vegetable crops and forage crops. The canopy development component of AquaCrop is in terms of canopy cover (CC) and not leaf area index (LAI). The advantage of CC is that it can be obtained through remote sensing. The water productivity (WP) enables the model to calculate aboveground biomass (B) using transpiration (T) (Equation 5.1) while the yield of the crop is obtained by multiplying B by the harvest index (HI) of the crop. In the absence of water stress, the amount of water transpired is proportional to CC in AquaCrop model. AquaCrop uses an effective rooting depth and water extraction pattern of the roots to simulate the root system of a particular crop. Effective rooting depth is an important

component of AquaCrop model being defined as the soil depth where root proliferation is sufficient to enable crop water uptake (Steduto *et al.*, 2009). All of the above mentioned components are in the form of inputs stored in climate, crop, soil and management files for AquaCrop model. The model is user friendly due to the ability to observe the effects of input changes through the multiple graphs and schematic displays in the menu (Raes *et al.*, 2009).

The model follows the scheme illustrated in Figure 5.2 for its calculation. The total amount of water available in the root zone throughout the crop cycle is simulated by calculating a water budget of the rainfall and irrigation as the incoming water against runoff, evapotranspiration (ET) and deep percolation as outgoing water fluxes within the root zone boundaries (Raes *et al.*, 2009). Water depletion at the root zone determines the magnitude of the water stress coefficients (Ks) affecting the following plant processes: green canopy cover expansion, stomatal conductance which expresses transpiration per unit CC, canopy senescence and HI (Raes *et al.*, 2009). In the model, depth of the root system is a function of Ks for stomatal conductance. There are thresholds of depletion and also response curves for each of the above plant processes. Under a water stress condition, AquaCrop will simulate a lower CC than the potential canopy cover ( $CC_{pot}$ ) at no stress conditions. The coefficient for transpiration ( $K_{cb}$ ) is adjusted throughout the simulation according to the CC development. With the core equation (Equation 5.1), biomass (B) is derived from transpiration by means of the normalized water productivity ( $WP^*$ ) which is a conservative parameter. Conservative parameters do not change with time, management practices, and/or geographic locations (Raes *et al.*, 2009) once they are calibrated for a specific crop. Yield is calculated as the product of the simulated B and the adjusted HI (Raes *et al.*, 2009).



**Figure 5.2** The chart showing the calculation scheme of AquaCrop (Raes *et al.*, 2009).

## 5.2 MATERIALS AND METHODS

### 5.2.1 Field description and experimental procedures

The experiments were composed of three parts; greenhouse pots, lysimeter and field. Experiments were carried out in the greenhouse pot experiment on amaranthus and on the lysimeters with pearl millet during the 2010/2011 season, while field trials were during the 2008/2009 and 2009/2010 seasons for both amaranthus and pearl millet. These sets of experiments were used for calibration and validation of AquaCrop crop growth model. Details of the pot, lysimeter and field trials layouts, experimental design and agronomic practices employed in these studies are found in Chapters 2. The pot and lysimeter datasets were used for parameterization and calibration of the model while the 2008/2009 and 2009/2010 seasons field experiments were also for calibration and validation of the model (Table 5.1). The field data for the 2009/2010 season of amaranthus and that of the 2008/2009 season of pearl millet were used for calibration. Validation was done with the 2008/2009 season for amaranthus and the 2009/2010 for pearl millet.

**Table 5.1** Summary of source of datasets for calibration and validation of AquaCrop model

Experiment	Purpose for datasets	Crop	Season	Water regime			Sowing date
				Irrigation	Water stress	Rainfed	
Glasshouse	Calibration	Amaranthus	2010/2011	X	X		27/12/10
Lysimeter	Calibration	Pearl millet	2010/2011	X	X		16/12/10
Field trial	Validation	Amaranthus	2008/2009	X		X	30/12/08
Field trial	Calibration	Pearl millet	2008/2009	X		X	28/11/08
Field trial	Calibration	Amaranthus	2009/2010	X		X	11/11/09
Field trial	Validation	Pearl millet	2009/2010	X		X	16/12/09

### 5.2.2 Experimental data

The automatic weather station (AWS) at the experimental site was the source of the daily weather data, which included minimum and maximum air temperatures, rainfall, wind speed, relative humidity, and radiation. Data collected from the field studies for the two seasons and crops were leaf area, aboveground biomass and radiation interception at weekly intervals under the irrigated and rainfed treatments. Phenological development of the two crops was monitored on the field trials during the 2008/2009 and 2009/2010 seasons (Chapter 3). In the pot trial, transpiration rate was measured every other day. Soil water content was monitored twice a week in the lysimeter trial while it was done weekly in field trials during both seasons for both crops. Harvestable grain yield was measured at the end of second season for pearl millet (Chapter 2).

### 5.2.3 Model parameters and input data

#### 5.2.3.1 Climatic data

In order to create a climate file, daily weather data from the AWS at the study site, Kenilworth experimental station were used. The relevant daily weather data for AquaCrop climate file are minimum and maximum air temperatures, rainfall amount, wind speed, maximum and minimum relative humidity, and solar radiation. FAO ETo calculator (<http://www.fao.org/nr/water/eto.html>) was used to calculate ETo as recommended in AquaCrop model. The minimum and maximum air temperatures, and ETo then provided a measure of atmospheric evaporative demand. AquaCrop requires the temperatures in order to calculate growing degree days (GDD) which influence crop growth and phenology development (Raes *et al.*, 2009).

#### 5.2.3.2 Crop data

The observations from the field in terms of crop development and phenology were used to create a crop file. AquaCrop identifies crop canopy development as CC. Therefore, field measured LAI (see Chapter 2 section 2.3.3) was converted to CC using Equation 5.2 (Garcia-Vila *et al.*, 2009). In the absence of observation in terms of root development, information from literature was used for root deepening for the crop file (Mangat *et al.*, 1999).

$$CC = \left( \frac{(1 - e^{-LAI/1.3})}{(1 + e^{-LAI/1.3})} \right) X 100 \dots \dots \dots \text{Equation 5.2}$$

#### 5.2.3.3 Soil data

The information on soil characteristics from previous studies (Chimungu, 2009; Haka, 2010) were used for creating a soil profile characteristics file. The information include soil type for the whole profile and physical characteristics such as soil water content at saturation, field capacity (FC) and permanent wilting point (PWP), and saturated hydraulic conductivity ( $K_{sat}$ ) (Table 5.2). The model generated total available soil water (TAW) from the FC and PWP values and drainage coefficient (tau) was generated from the  $K_{sat}$  values.

**Table 5.2** Soil profile characteristics for the Bainsvlei soil as described by Chimungu (2009)

Soil layers	Description	Thickness	Soil water content at				$K_{sat}$	tau
			PWP	DUL	SAT	TAW		
		m	vol%			mm/m	mm/day	
1	loamy sand	0.25	8.3	22.8	38.0	145.0	800.0	0.90
2	sandy loam	0.45	8.3	24.3	41.0	160.0	500.0	0.76
3	sandy clay loam	0.50	8.3	26.8	47.0	185.0	125.0	0.47
4	sand	0.25	8.3	28.2	36.0	199.0	1500.0	1.00
5	sandy loam	0.40	8.3	28.2	41.0	199.0	500.0	0.76

#### 5.2.3.4 Field management

Data of the actual amount of irrigation water applied and dates of irrigations during the field trials were used in the irrigation file. The field management was set at the optimum field conditions of non-limiting soil fertility, without surface mulches and no temperature stress. Stepwise, datasets from the irrigated plots were used for calibrating the two crops for non-water stress condition while datasets from the pots and lysimeter trials under different water stress regime as well as the rainfed treatment for both the crops were used for calibrating the model for water stress conditions.

#### 5.2.4 Model calibration and validation

Calibration is adjusting certain model parameters to make the model match the measured values at the specific location (Farahani *et al.*, 2009). Simulation periods were linked to the growing cycle for each of the two crops starting with the initial soil water content measured in the field. The conservative parameters were selected as a default which should be generally applicable or for a given specie or specific cultivar. Default values were selected for some parameters that were not measured during the experimental studies. Examples of these parameters are CC cover per seedling, water extraction pattern and average root zone expansion. The observations such as phenological stages of the two crops from the pots, lysimeter and field trials were involved in parameterization of the model. Calibration was performed with the datasets of the field studies for amaranthus and pearl millet for both well-watered and rainfed conditions. Data from the 2009/2010 season were used for the calibration of the model for amaranthus because leaf area was not measured during the 2008/2009 season, then the 2008/2009 season datasets were used to validate the model for that crop. Therefore, for validation, only biomass, soil water content and cumulative ET parameters were used to evaluate the performance of the model.

The calibration process described by Steduto *et al.* (2009) and Raes *et al.* (2009) was followed for the calibration of AquaCrop for both crops. Inputs for the crop development parameters such as plant density, days to 90% emergence, time to recover, maximum canopy cover and time to harvest were from observations in the field studies while parameters such as canopy growth and canopy decline coefficients were generated by the model from the observed values. Calibration of the model for each of the two crops started with the green crop canopy (CC) development. During the calibration process, the importance of the coefficient of transpiration ( $K_{c_{tr}}$ ) was observed as it is proportional to CC (Karunaratne *et al.*, 2011). The canopy cover of the well-watered treatments was the first to be calibrated, before the rainfed, which was assumed to represent water stress conditions. Simulations were run and the  $K_{c_{tr}}$  was reduced until a good fit was achieved for the CC of each crop under the irrigated and rainfed treatments.

Biomass production was the next parameter for calibration. Values for the WP, which is a conservative parameter, were initially derived from the lysimeter and pot trials and adjusted with consecutive simulations to get a good fit for the biomass production. The reference harvest index (HIo) for a leafy vegetable was set at default for amaranthus (85%) while the HIo of pearl millet as a grain crop was set at 52%. This was to determine yield, product of HIo and B, for the two crops. Fine-tunings and adjustments of parameters were done until good matches between simulated and measured parameters were obtained. Responses due to salinity, fertility and temperature were not considered during the calibration and validation of the model for either of the two crops. Parameters evaluated for goodness of fit of the model were CC, Biomass, SWC and ET.

### 5.2.5 Statistics

Goodness of fit for the calibration and validation of the model was carried out with three statistical methods for each crop parameter stepwise. They are R<sup>2</sup>, which is coefficient of determination; root mean square error (RMSE) as described by Heng *et al.* (2009) calculated using Equation 5.3 and index of agreement (d) (Willmott, 1982) derived with Equation 5.4.

$$RMSE = [n^{-1} \sum_{i=1}^n (S_i - O_i)^2]^{0.5} \dots\dots\dots \text{Equation 5.3}$$

$$d = 1 - \frac{\sum_{i=1}^n (S_i - O_i)^2}{\sum_{i=1}^n (|S_i - \bar{O}| + |O_i - \bar{O}|)^2} \dots\dots\dots \text{Equation 5.4}$$

where n is the number of observations, S<sub>i</sub> and O<sub>i</sub> are the simulated and observed values for the corresponding parameter respectively and  $\bar{O}$  is the mean of the observed variable. The RMSE assume the same unit as the parameter under observation. The model goodness of fit increases as RMSE value approaches zero. The values of index of agreement (d) range from 0 to 1. The closer the d value to 1 the better the agreement between the simulated and measured values.

## 5.3 RESULTS AND DISCUSSION

### 5.3.1 Amaranthus

#### 5.3.1.1 Calibration for amaranthus

Table 5.3 presents the crop parameters and values resulting from the calibration of the model for amaranthus using the 2009/2010 season data. Crop parameters that depend on management include plant density (33,333 plants ha<sup>-1</sup>), time to recover after transplanting (4 days) and maximum CC (95%), while conservative parameters include water productivity normalized for ETo and CO<sub>2</sub>, WP\*, (28 tons ha<sup>-1</sup>) and crop transpiration coefficient, Kc<sub>tr</sub>, (0.8). The effect of soil water stress on canopy expansion, stomatal closure and early canopy senescence was set at moderately tolerant to stress for calibrating the model for this crop. The calibration shows a good match between the observed and the simulated for CC of well-watered treatment (W5) and the rest of irrigated treatments (Figure 5.3).



However, CC of plants from the rainfed plots (W1) was under estimated by the model throughout the growing season. Reasons for this may be due to the small value of the initial cover size of transplanted seedling ( $CC_0 = 0.67\%$ ) generated by the model which posed a major concern during the calibration process. The simulated CC was very low at 30 days after transplanting in all the treatments but was a good match by the end of the season in all the irrigated treatments. Overall, there was a moderately good agreement between the simulated and observed CC with  $R^2$  of 0.577 and  $d$  of 0.746 (Table 5.4).

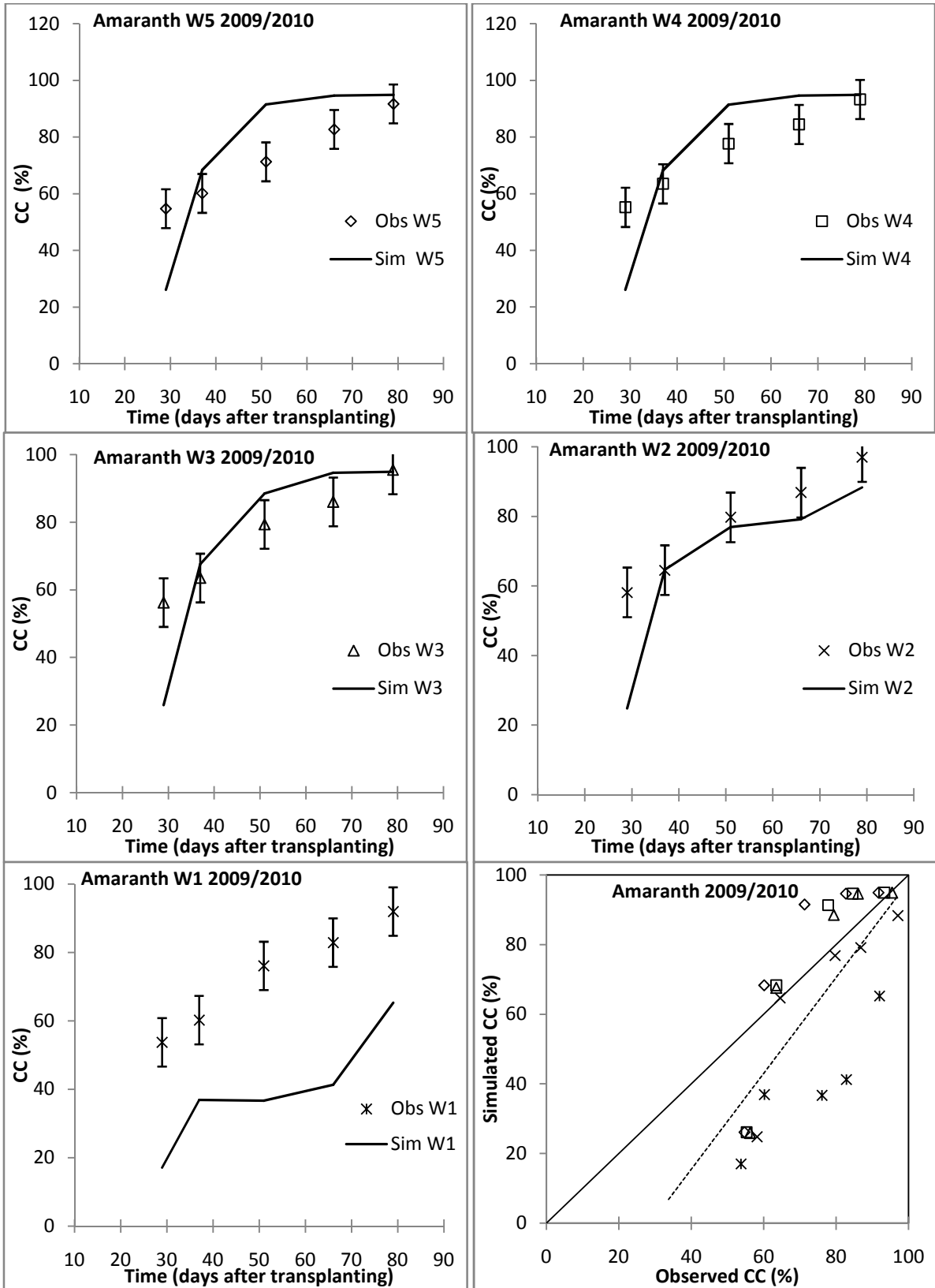
**Table 5.3** Selected crop parameters and values for calibration and validation of AquaCrop for amaranthus

Crop parameters	Descriptions	Input
Type of Crop		leafy vegetable
Carbon cycle		C4
T base	Base temperature ( $^{\circ}\text{C}$ )	7
Tupper	Upper temperature ( $^{\circ}\text{C}$ )	30
Method of planting	Sowing / Transplanting	Transplanting
Initial cover	Cover size transplanted seedling ( $\text{cm}^2\text{plant}^{-1}$ )	20
$CC_0$	Initial canopy cover (%)	67
Plant density	Plants $\text{ha}^{-1}$	33 333
Time to $CC_x$	planting to $CC_x$ (day)	55
$CC_x$	Maximum canopy cover (%)	95
CGC	Canopy growth coefficient ( $\%\text{day}^{-1}$ )	14.7
CDC	Canopy decline coefficient ( $\%\text{day}^{-1}$ )	8.0
Time for decline	Canopy decline (day)	37
Time to recover	transplants recovery (day)	4
Time to $Z_r(\text{max})$	from plant to max rooting depth (days)	60
Time to senescence	from plant to start senescence (days)	90
Time to harvest	from plant to maturity / harvest (days)	100
$Z_r(\text{max})$	Max effective rooting depth (m)	1.75
$Z_r(\text{min})$	Min. rooting depth (m)	0.3
Expansion	Avg. root zone expansion ( $\text{cm day}^{-1}$ )	2.7
$K_{c_{tr}}$	Coefficient for transpiration	0.8
Aging	Reduction with age ( $\%\text{day}^{-1}$ )	0.15
Green canopy cover	Effect of canopy in late season (%)	60
WP*	Water productivity ( $\text{ton ha}^{-1}$ )	28
Hlo	Reference harvest index (%)	85
Soil water stresses		
Canopy expansion		Moderately tolerant to water stress
	$K_s p(\text{upper})$	0.25
	$K_s p(\text{lower})$	0.6
	shape factor	6
Stomatal closure		Moderately tolerant to
	$K_s p(\text{upper})$	0.65
	shape factor	6
Early canopy Senescence		Moderately tolerant to water stress
	$K_s p(\text{upper})$	0.65
	shape factor	5
Aeration stress		Very sensitive to water

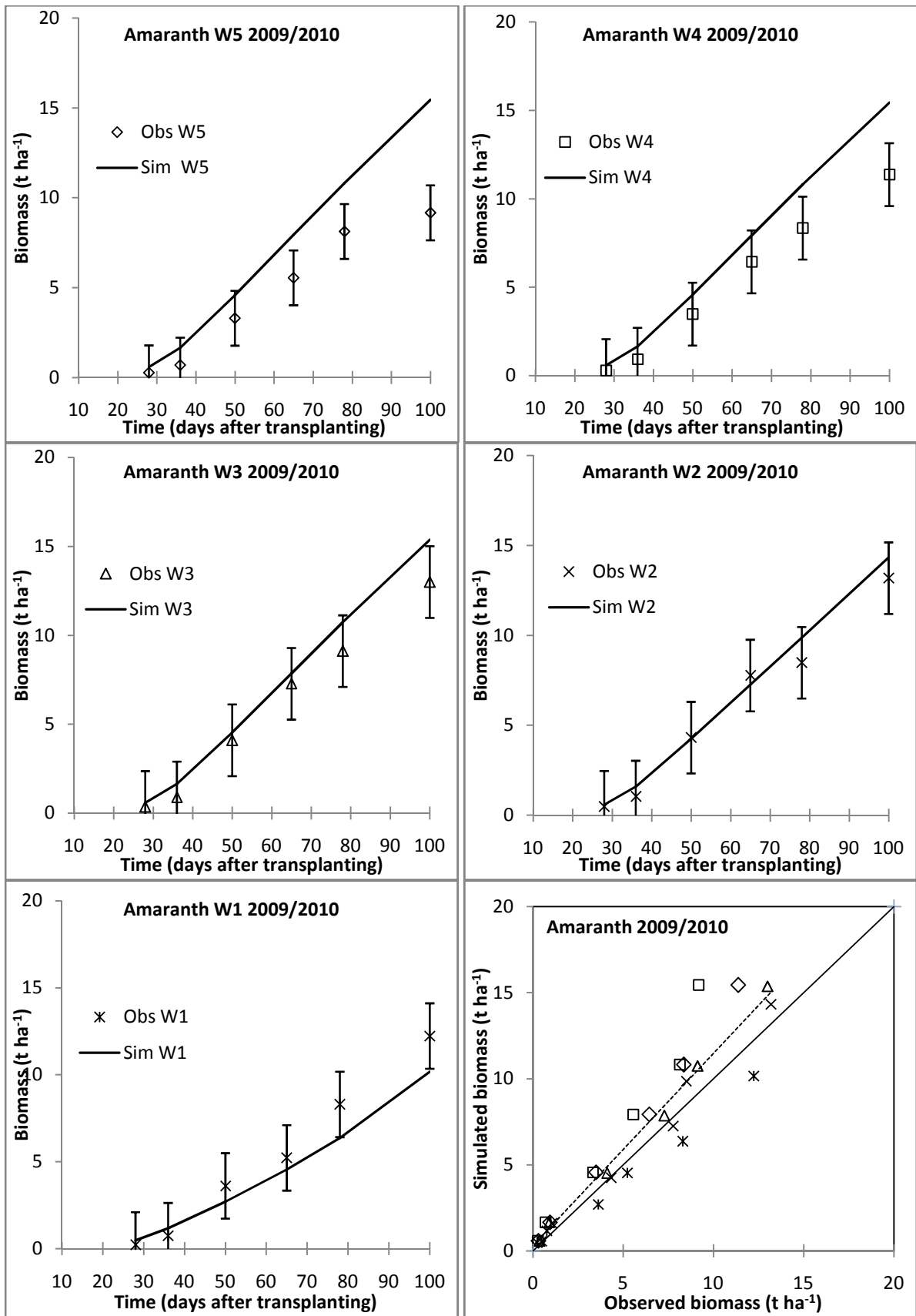
Biomass production of amaranthus was well simulated by AquaCrop for most of the treatments with the better fits found in the W2 and W1 treatments (Figure 5.4). There was overestimation of biomass production in the W5 treatment which it was suspected might be due to the effect of nutrient leaching in the field situation due to large amount of water applied as the nutrient stress was not considered during the calibration of the model. The RMSE ( $1.866 \text{ t ha}^{-1}$ ),  $R^2$  (0.900) and d (0.957) also support the good overall performance of the AquaCrop to simulate biomass production of amaranthus (Table 5.4). The simulated and observed soil water content had the best match in the W3 and W2 treatments (Figure 5.5). Although, the initial soil water content of the observed and simulated were the same but there was overestimation in well-watered treatment plots (W5) and underestimation in the rainfed (W1) plots from around 10 days after transplanting till the end of the season. The discrepancies between the simulated and observed maybe due to the fact that information from the literature was used to calibrate the model for effective root depth because no data was collected during the field studies for this parameter for amaranthus. The values of RMSE,  $R^2$  and d index of agreement for the performance of AquaCrop during the calibration of the model for soil water content were 50.466 mm, 0.454 and 0.802 respectively (Table 5.4). Good simulation of cumulative ET in all the treatments is illustrated in Figure 5.6. This was contrary to the model performance in simulating soil water content. There was  $R^2$  of 0.963 and d of 0.989 to prove the good performance of the model in simulating seasonal cumulative ET for amaranthus. In AquaCrop, cumulative ET is partitioned into evaporation and transpiration which are at their maximum rate when the soil is wet. Therefore, evapotranspiration is highly dependent on evaporative demand of the atmosphere, crop development and independent of the soil water content (Raes *et al.* 2009).

#### 5.3.1.2 Validation for amaranthus

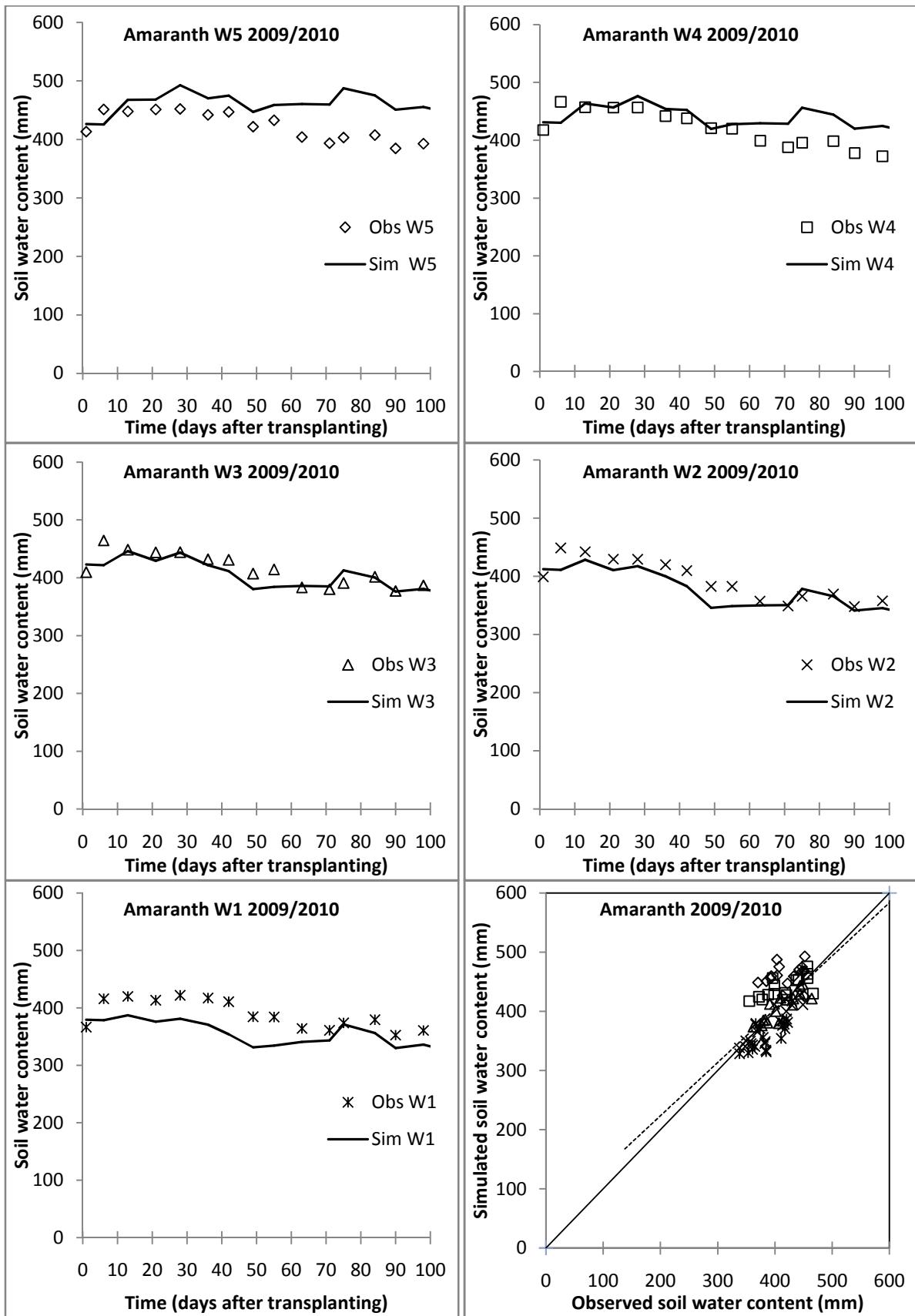
AquaCrop was able to accurately simulate biomass production for the well-watered (W5) and rainfed (W1) treatments (Figure 5.7). There was an underestimation of biomass produced at the end of the season for the W3 and W2 treatments. On average, the trend of biomass production with time was well predicted and this was supported statistically by RMSE of  $1.964 \text{ t ha}^{-1}$ ,  $R^2$  of 0.916 and d index of agreement of 0.905. Results of simulation of soil water content were not unexpected considering the performance of the model during the calibration process. AquaCrop overestimated soil water content around 40 days after transplanting until the end of the season in all the treatments but the trends of the observed and simulated were similar (Figure 5.8). However, the model performed fairly at simulating cumulative ET (Figure 5.9). The model over predicted at the earliest stage and under predicted cumulative ET at the later stage of crop growth. Out of all the treatments, the best agreement between the simulated and observed cumulative ET was found in the rainfed plots (W1). Consistently, AquaCrop performed well in simulating cumulative ET with RMSE of 75.635 mm,  $R^2$  of 0.912 and d index of agreement of 0.908.



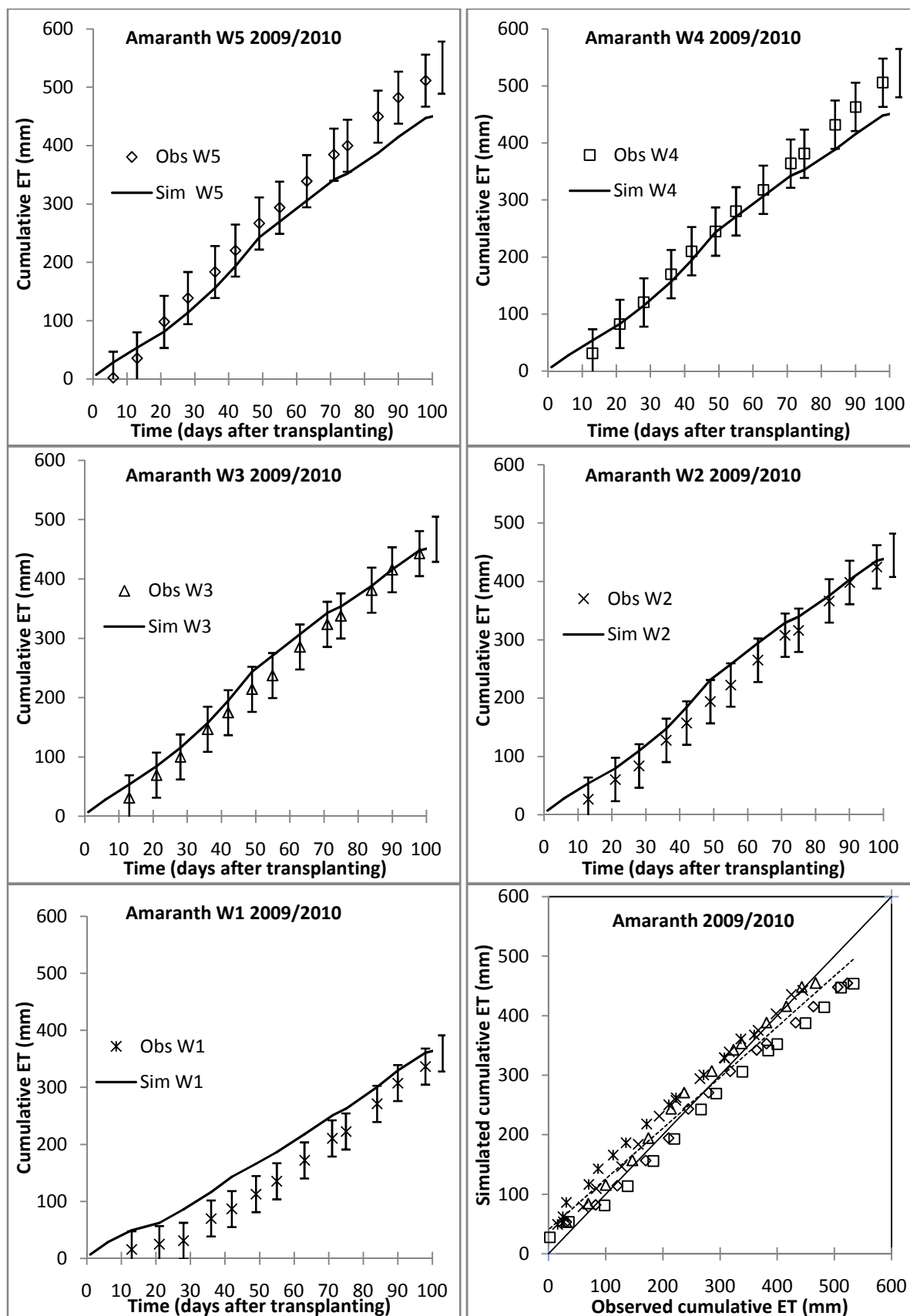
**Figure 5.3** Comparison of simulated and observed canopy cover (CC) under irrigation and rainfed treatments during the 2009/2010 season used for calibration of the AquaCrop model for amaranthus (Obs = observed, Sim = simulated).



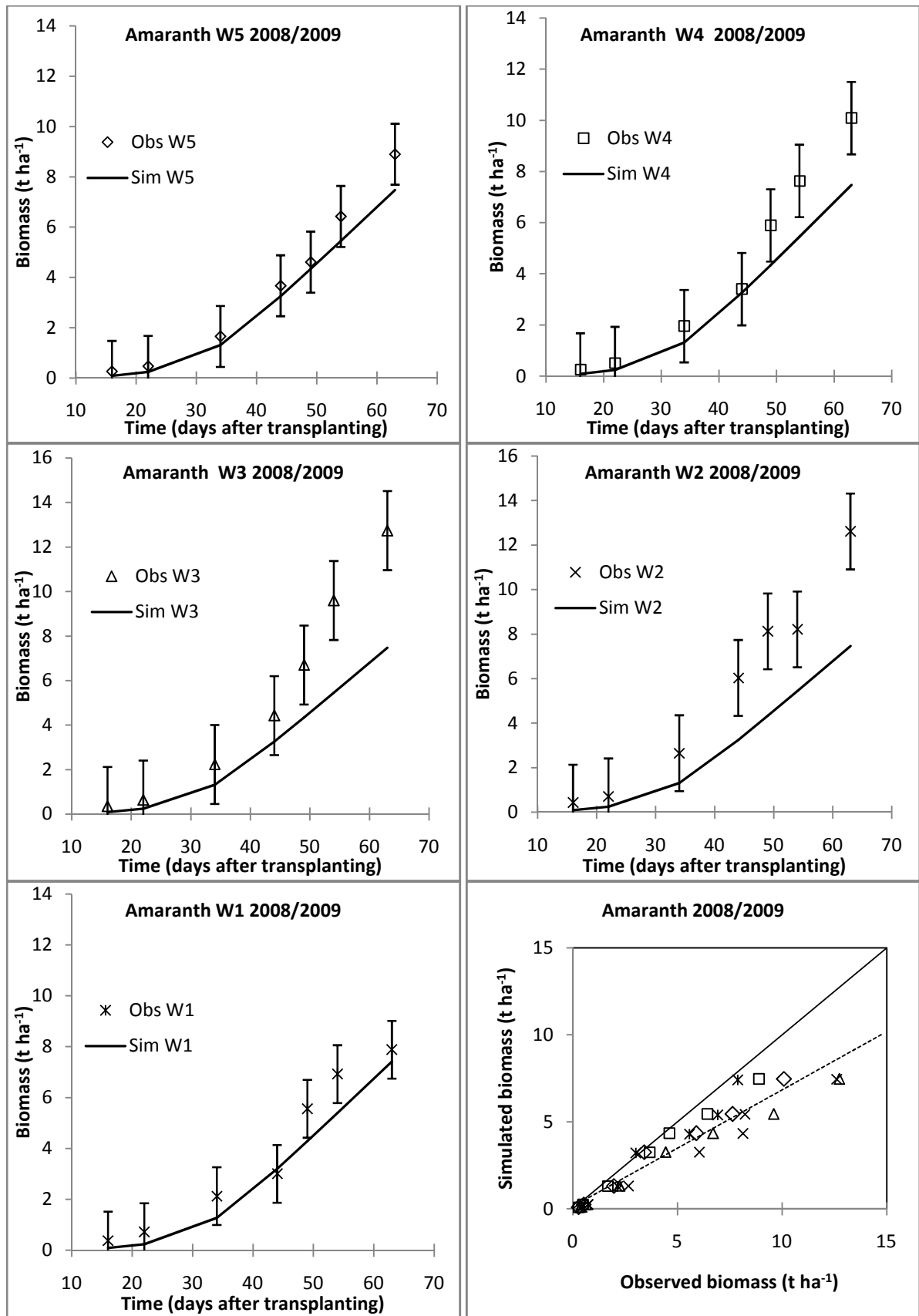
**Figure 5.4** Comparison of simulated and observed biomass under irrigation and rainfed treatments during the 2009/2010 season used for calibration of the AquaCrop model for amaranthus.



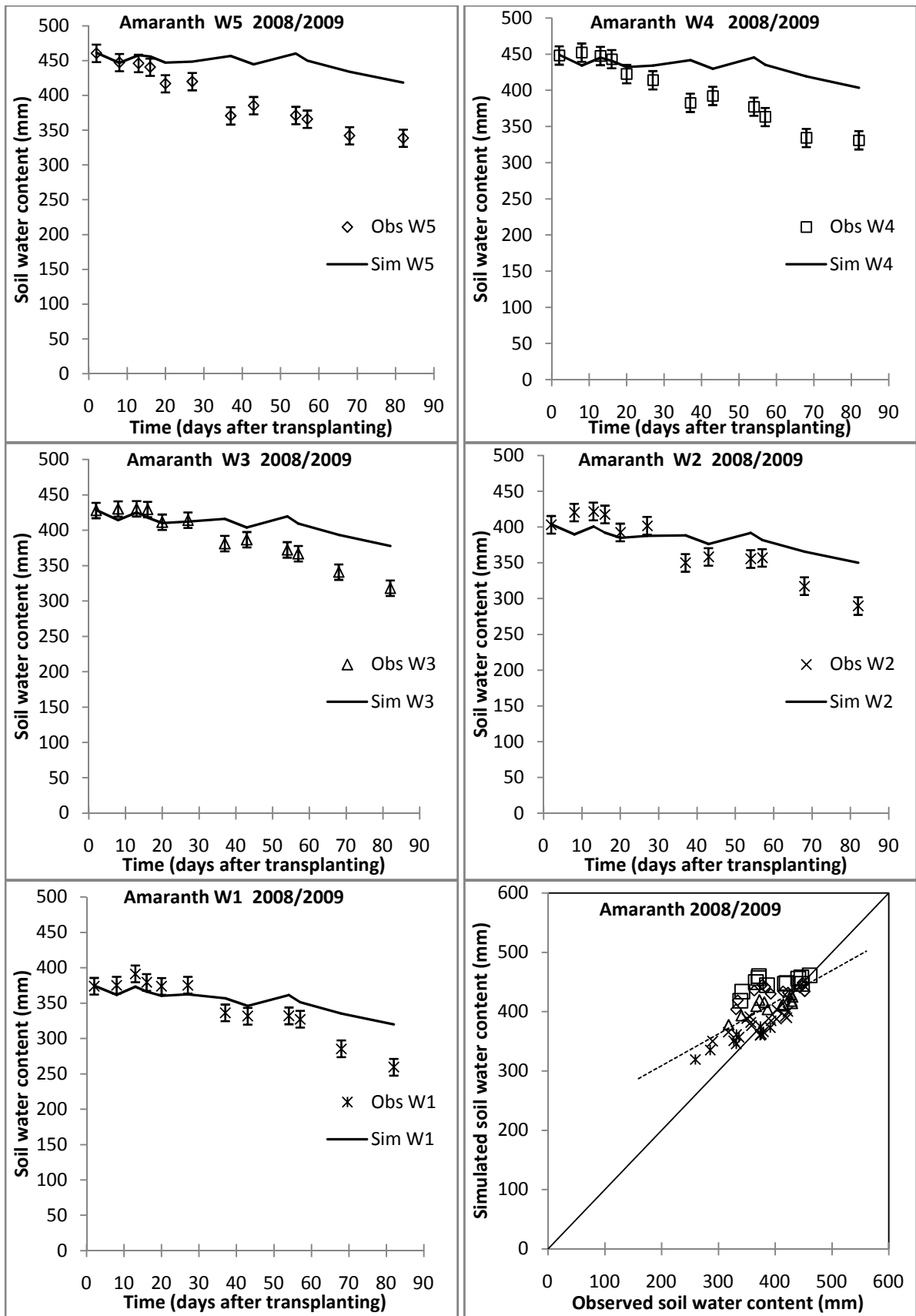
**Figure 5.5** Comparison of simulated and observed soil water content (SWC) under irrigation and rainfed treatments during the 2009/2010 season used for calibration of the AquaCrop model for amaranthus.



**Figure 5.6** Comparison of simulated and observed cumulative evapotranspiration (ET) under irrigation and rainfed treatments during the 2009/2010 season used for calibration of AquaCrop model for amaranthus.

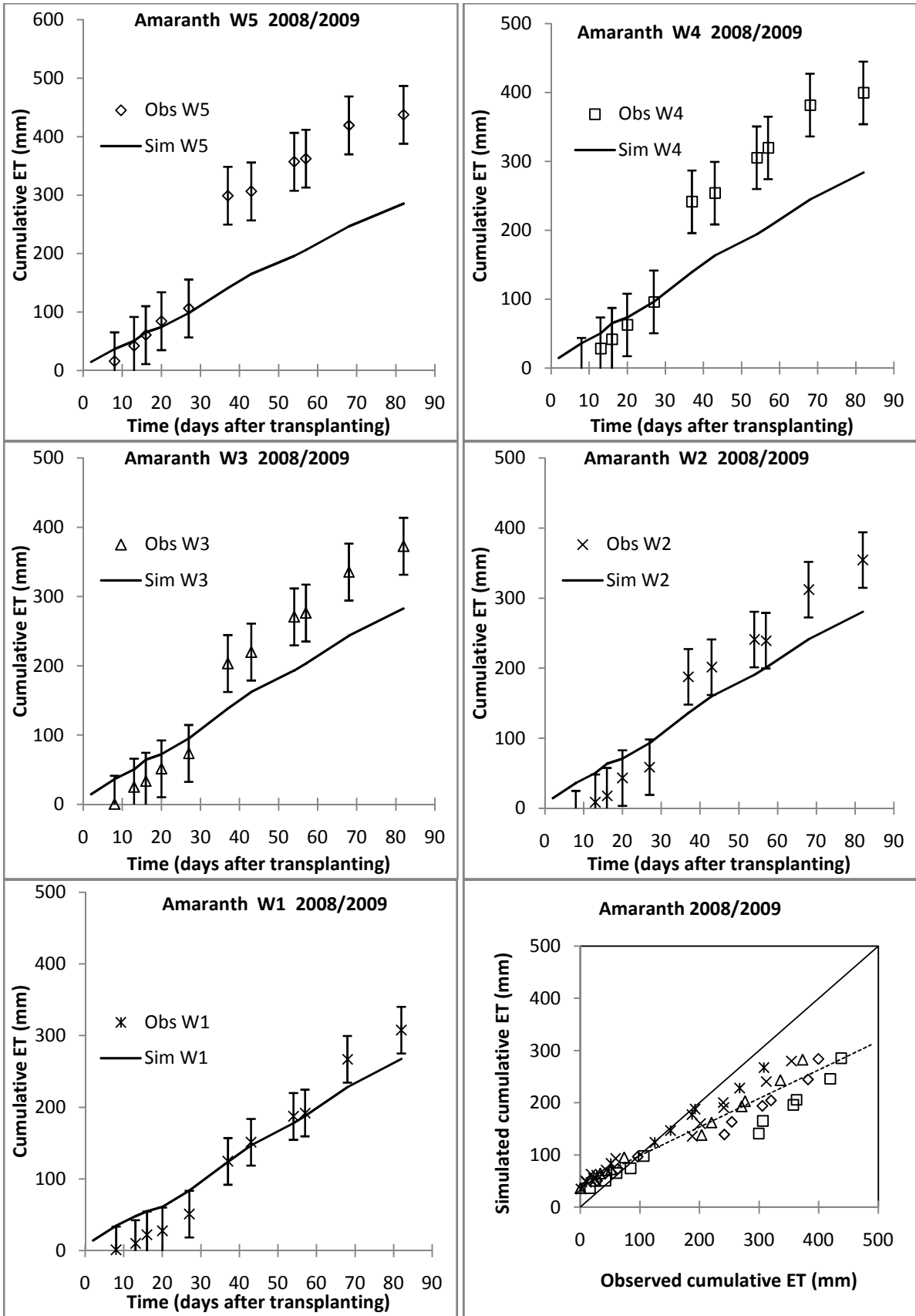


**Figure 5.7** Validation results and comparison of simulated versus observed amaranthus biomass under irrigation and rainfed treatments during the 2008/2009 season.



**Figure 5.8** Validation results and comparison of simulated and observed soil water content (SWC) in amaranthus plots under irrigation and rainfed treatments of the 2008/2009 season.





**Figure 5.9** Validation results and comparison of simulated and observed amaranthus cumulative evapotranspiration (ET) under irrigation and rainfed treatments of the 2008/2009 season.

**Table 5.4** The root mean square (RMSE), coefficient of determination ( $R^2$ ) and index of agreement (d) between simulated and observed values of canopy cover (CC), biomass production, soil water content (SWC) and cumulative evapotranspiration (ET) for the calibration and validation of the AquaCrop model for amaranthus

<b>Calibration 2009/2010</b>			
<b>Parameters</b>	RMSE	$R^2$	d
Canopy cover CC (%)	20.817	0.577	0.746
Biomass (ton ha <sup>-1</sup> )	1.866	0.900	0.957
SWC (mm)	50.466	0.454	0.802
Cumulative ET (mm)	34.113	0.963	0.989
<b>Validation 2008/2009</b>			
<b>Parameters</b>	RMSE	$R^2$	d
Biomass (ton ha <sup>-1</sup> )	1.964	0.916	0.905
SWC (mm)	50.616	0.302	0.666
Cumulative ET (mm)	75.635	0.912	0.908

Generally, calibration and validation of AquaCrop for amaranthus was satisfactory, although the  $R^2$  of simulated versus observed SWC for the calibration and validation were low with moderate d index of agreement. Tendency of the model to over predict SWC was similar to that found during the validation process for amaranthus was reported by Farahani *et al.* (2009) and Hussein *et al.* (2011). They reported that the model was able to give a good prediction of the trend of SWC with time due to irrigation events with absolute values deviating from measured values in cotton field experiments (Hussein *et al.*, 2011). Their reports also support the fact that results of AquaCrop simulation of cumulative ET were very good irrespective of the outcome of the simulation of SWC. Geerts *et al.* (2009) reported calibration and validation of grain quinoa, a crop similar to amaranthus, with good agreement between the simulated and observed values of CC and biomass in different agro-climatic regions under different management conditions. They reported that simulated versus observed biomass from eight quinoa fields used for calibration provided  $R^2$  of 0.91 while simulated versus observed values from 14 fields used for validation of the model for the crop provided  $R^2$  of 0.88. These are comparable to the values of  $R^2$  of 0.900 and 0.916 achieved during the calibration and validation of the model for amaranthus for this study near Bloemfontein.

### 5.3.2 Pearl Millet

#### 5.3.2.1 Calibration for pearl millet

The same process used for amaranthus was followed for the calibration of AquaCrop for pearl millet. The process is explained in section 5.2.4. Calibration was performed with the 2008/2009 season field observed data under the irrigation and the rainfed treatments. Some of the non-conservative parameters for the two lines of pearl millet are plant population (55556 plants ha<sup>-1</sup>), type of planting method (sowing), time to 90% emergence (4 days) and maximum canopy cover (95 & 98%) (Table

5.5). Differences between the two lines include days to maturity as GCI 17 and Monyaloti mature in 105 and 120 days respectively. Calibration was done at non-limiting fertility level while the effect of soil water stress on canopy expansion, stomatal closure and early senescence was set at extremely tolerant to water stress for both lines of pearl millet. The two lines of pearl millet exhibited differences in some parameters. It takes GCI 17 about 35 days to reach maximum canopy while it took 40 days for Monyaloti. GCI 17 has a higher crop growth coefficient (26.9%) than that of Monyaloti (23.3%) as calculated by AquaCrop model itself. The main difference between lines has to do with their water productivity (WP), as GCI 17 has WP of 35 g m<sup>-2</sup> and Monyaloti, 40 g m<sup>-2</sup>, both of which are within the range specified for C4 crops by the model.

Response of the two lines of pearl millet to the environment was well simulated for CC under irrigation (Figure 5.10). There was an underestimation of CC earlier in the season but the model was able to simulate CC accurately from 39 days after sowing in all the irrigation treatments and for both lines of pearl millet. Under the rainfed condition (W1), the simulation also underestimated the CC of both lines of pearl millet. However, there was a strong overall correlation with R<sup>2</sup> of 0.898 for the prediction of CC for the two pearl millet lines when comparing simulated and observed values. The model simulated CC accurately for GCI 17 and Monyaloti with R<sup>2</sup> of 0.906 and 0.914 and also d index of agreement of 0.837 and 0.783 respectively (Table 5.6). During the calibration of the model, biomass was accurately simulated for all the treatments (Figure 5.11), although it was slightly under predicted for GCI 17 and Monyaloti at the end of the season in all the treatments. The highest deviation between the simulated and observed biomass was found in the W5 and W4 treatments of Monyaloti. The deviation could be due to the rapid accumulation of biomass due to high canopy cover as influence by water applications. There were good agreement between the simulated and measured biomass of GCI 17 and Monyaloti indicated by R<sup>2</sup> of 0.963 and d index of agreement of 0.983 for GCI 17 and R<sup>2</sup> of 0.967 and d index of agreement of 0.968 for Monyaloti (Table 5.6). Consequently, overall, the simulation performed very well simulating biomass with R<sup>2</sup> of 0.961 and d index of agreement of 0.974.

There was again a mismatch of simulated and measured soil water content (SWC) of the two lines of pearl millet (Figure 5.12). Initial soil water content is an important parameter of the model in simulating measured values of different crop parameters as this is an important component of the water balance. Despite the fact that the actual field initial SWC was input before simulation, the SWC was under predicted for GCI 17 while it was over predicted for Monyaloti for the W5 and W4 treatments. AquaCrop simulated SWC accurately from 45 days after sowing for Monyaloti in the rest of the treatments (i.e. the drier range of the spectrum). Figure 5.12 also illustrated the mismatch of some of the treatments on the performance evaluation of the model for SWC (d = 0.556 and low R<sup>2</sup> of 0.127). The root mean square of error (RMSE), R<sup>2</sup> and d index of agreement of the simulated versus

observed SWC for each line of the pearl millet were also as low when all the results were combined for the two lines of pearl millet (Table 5.6). This indicates that the observation is not due to cultivar specific problem but could be due to soil characterization mismatch. It appears that some more work needs to be done on the simulation of the soil water balance under these semi-arid conditions.

Irrespective of the performance of the model simulating SWC, the cumulative ET was predicted accurately for both the lines of pearl millet with high values of  $R^2$  and d index of agreement (Figure 5.13). The observed cumulative ET was well simulated at the beginning of the season for the two lines of pearl millet, although as the crop approaches maturity the model underestimated cumulative ET for both lines of pearl millet for the well-watered treatment (W5). The cumulative ET was better calibrated for GCI 17 for the W3, W2 and W1 treatments, while there was underestimation of ET for Monyaloti from 80 days after sowing in all the treatments. This could be due to the fact that biomass for this variety was also underestimated for this period. Crop development is one of the factors determining evapotranspiration of crops (Raes *et al.* 2009). Table 5.6 present the statistical evaluation of simulation of cumulative ET with RMSE,  $R^2$  and d index of agreement for the two lines of pearl millet showing that there was a good agreement of simulated and observed cumulative ET. Overall, the agreement between the simulated and observed cumulative ET was very good with  $R^2$  of 0.876 and d index of agreement of 0.937.

Results of simulations of CC (Figure 5.10) for the two lines of pearl millet under rainfed conditions exhibited a similar trend to that reported by Heng *et al.* (2009) with good overall performance of the model. During the validation of AquaCrop for maize by Heng *et al.* (2009), the CC of a non-irrigated short season treatment was not well simulated with CC declining at 70 days after sowing. The underestimation of final biomass (Figure 5.11) of both the lines of pearl millet may be due to the fact that the dry matter accumulation increases after 60 days after sowing. Zeleke *et al.* (2011) reported that increase in dry matter accumulation in shoots of canola could be due to rapid growth that occurred once the canopy closure is reached, which is the maximum canopy cover it can achieve before slowing down as leaves senesce during pod filling. Rahman *et al.* (2010), Farahani *et al.* (2009) and Hussein *et al.* (2011) reported the tendency of AquaCrop to overestimate SWC when calibrating the model for potato and cotton. The SWC was over predicted (Figure 5.12) for these experiments but the patterns of the observed SWC were well reproduced. However, this does not influence the level of accuracy that the model simulates actual ET. Garcia-Vila *et al.* (2009) and Hussein *et al.* (2011) achieved goodness of fit of  $R^2$  of 0.908 and 0.998 and d index of agreement of 0.868 and 0.998 respectively when simulating cumulative ET of cotton using AquaCrop. These are not far from the values achieved when the simulated and observed cumulative ET were compared for each of the pearl millet lines (Figure 5.13).

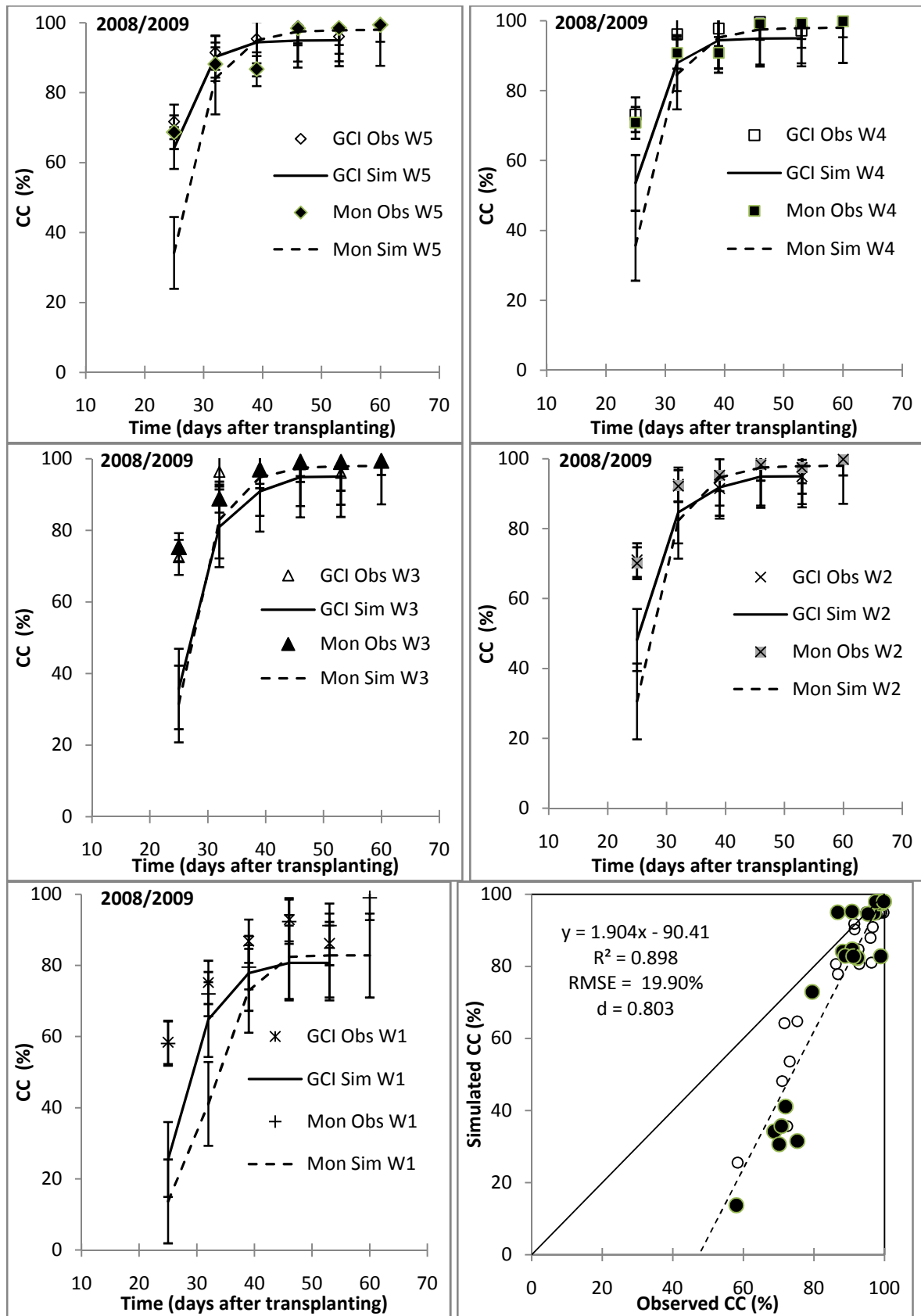
**Table 5.5** Selected crop parameters and values for calibration and validation of AquaCrop for pearl millet

Crop parameter	Description	GCI	Monyaloti
T base	Base temperature (°C)	8	8
Tupper	Upper temperature (°C)	32	32
	Type of planting method	sowing	sowing
Initial cover	Cover per seedling (cm <sup>2</sup> )	5	5
Plant density	Plants/ha	55 556	55 556
	Initial canopy cover (%)	Small	Small canopy cover
CC0	CCo	28	28
Emergence	Days to 90% emergence (calendar) (days)	4	4
CGC	Canopy growth coefficient CGC (%)	26.9	23.3
CDC	Canopy decline coefficient CDC (%)	9.6	9.6
Canopy decline	Canopy decline (%)	slow decline	slow decline
	Canopy decline (days)	30	31
Canopy expansion	Canopy expansion (%)	very fast	very fast
CCx	Maximum canopy cover (%)	95	98
CCx	Maximum canopy cover (description)	Almost	Almost entirely cover
Days to CCx	Time taken to achieve CCx (calendar)	35	40
Senescence	Days to senescence (calendar)	75	89
Flowering	Days to flowering	39	39
Duration of flowering	Length of flowering stage	20	20
Maturity	Days to maturity (calendar)	105	120
Yield formation	Days to yield formation (calendar)	66	81
Build-up in HI	Duration of HI build-up (calendar)	35	50
Zr (min)	Min effective rooting depth (m)	0.3	0.3
Shape factor	Shape factor	1.8	1.8
Zr (max)	Max effective rooting depth (m)	1.75	1.75
Zr (max)	Max effective rooting depth	medium-	medium-deep
Rooting depth	Time from sowing to maximum rooting depth (days)	45	45
Expansion	Average root zone expansion (cm day <sup>-1</sup> )	3.6	3.6
Kc <sub>tr</sub>	Coefficient for transpiration	0.7	0.6
	Green canopy cover (%)	60	60
	Reduction with age (% day <sup>-1</sup> )	0.15	0.15
Water extraction pattern	Maximum root water extraction (mm day <sup>-1</sup> )	56	56
S <sub>x, top</sub> top quarter of root zone	Maximum root water extraction ( m <sup>3</sup> m <sup>3</sup> day <sup>-1</sup> )	0.051	0.051
S <sub>x, bot</sub> botom quarter of root zone	Maximum root water extraction ( m <sup>3</sup> m <sup>3</sup> day <sup>-1</sup> )	0.013	0.013
WP	Water productivity (g m <sup>-2</sup> )	35	40
HI0	Reference harvest index	52	52
Water stress			
Canopy expansion		Extremely tolerant to water stress	
	Ks p(upper)	0.35	0.35
	Ks p(lower)	0.7	0.7
	shape factor	3.0	3.5
Stomatal closure		Extremely tolerant to water stress	
	Ks p(upper)	0.75	0.75
	shape factor	3.0	3.5
Early canopy Senescence		Extremely tolerant to water stress	
	Ks p(upper)	0.8	0.8
	shape factor	3.0	3.5
Aeration stress	Aeration stress	Sensitive to water logging	
	Ks <sub>aer</sub> (vol %)	15	15

### 5.3.2.2 Validation for pearl millet

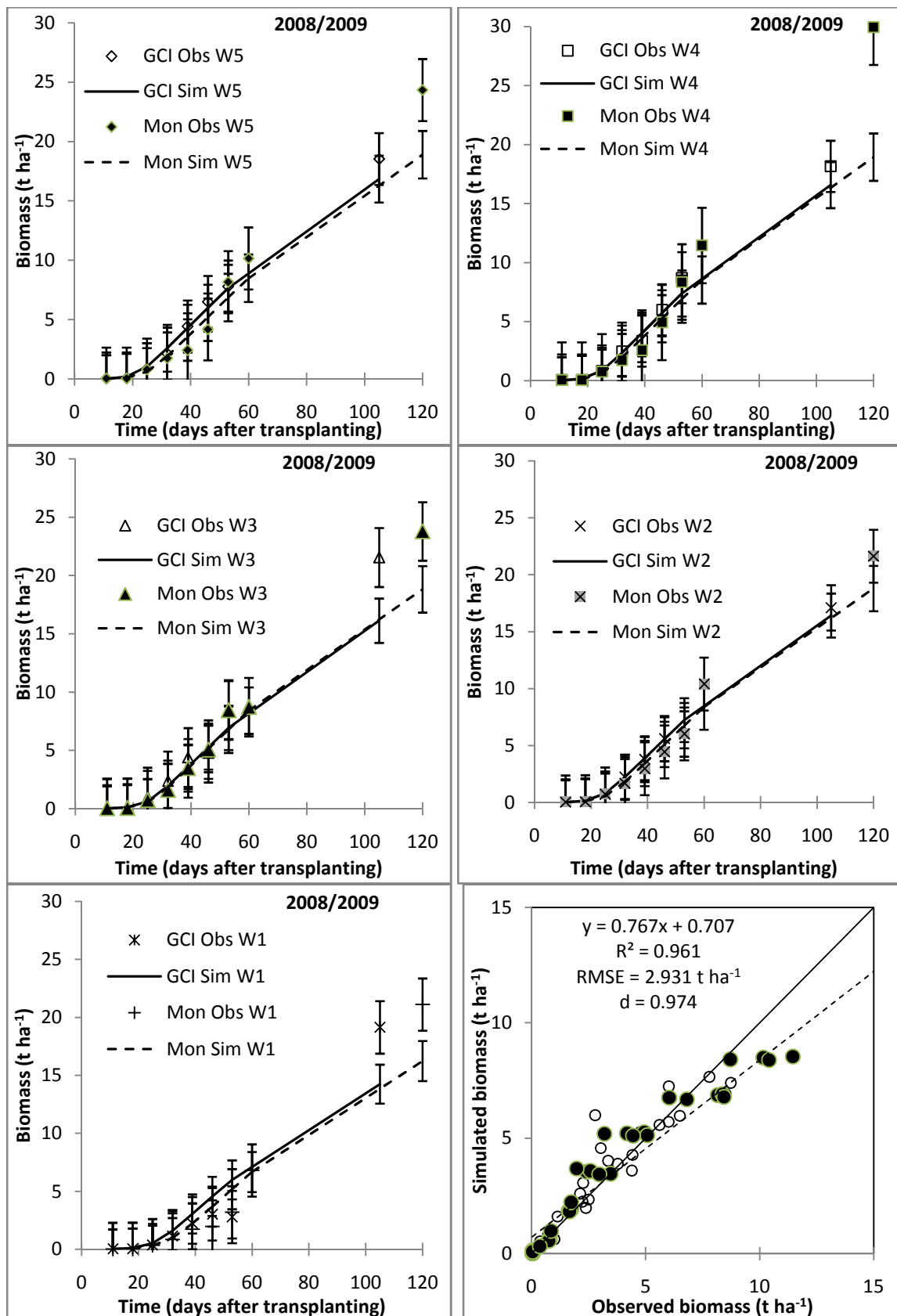
The crop parameters resulting from the model calibration were used for simulations runs of AquaCrop for pearl millet (Table 5.5). The 2009/2010 season observed datasets were compared with the simulations for the same season based on CC, biomass, SWC and cumulative ET of the two lines of pearl millet with the weather data measured at the field site. The simulations of CC for the two lines of pearl millet are illustrated in Figure 5.14. The predictions of CC for the two lines of pearl millet were accurate for all the treatments with strong agreement between the simulated and observed CC ( $R^2 = 0.782$ ; RMSE = 16.053%;  $d = 0.920$ ). However, for CC, it was observed that the start of senescence was delayed in the simulation for Monyaloti compared to the observed CC of Monyaloti that had started senescing about 80 days after sowing. Reasons for the delay in starting senescence during simulations could be due to the fact that the year was considered to be a good year (2009/2010) with high rainfall occurrence. Predictions of biomass for the two lines of pearl millet were in agreement with the observed during the first half of the 2009/2010 season in all the irrigated treatments (Figure 5.15). Biomass was underestimated for Monyaloti from 80 days after sowing in all the irrigated plots. However, throughout the season, simulation of biomass production under rainfed condition (W1) was accurate for the GCI 17 line. On average, the model simulated biomass accurately across the treatments and both lines of pearl millet with the  $R^2$  of 0.891 and  $d$  index of agreement of 0.924. Considering the calibration simulations, the model consistently reproduces moderately the trend of the SWC for the two lines of pearl millet (Figure 5.16). In all the treatments, there was over prediction of SWC after 100 days after sowing. The moderate fits of the simulations are demonstrated by  $d$  index of agreement of 0.659 combining results of all the treatments. The statistical proof of the goodness of fit for each line of pearl millet is illustrated in Table 5.6. It was shown that the performance of the model was consistent for the two lines of pearl millet. There were good simulations of cumulative ET for the two lines of pearl millet in all the treatments (Figure 5.17). However, the cumulative ET was slightly overestimated for GCI 17 in all the treatments. Generally, the simulated versus observed cumulative ET shows a good fit with  $R^2$  of 0.967 and  $d$  index of agreement of 0.981. The high RMSE recorded for the simulation of these parameters (CC, biomass, SWC and ET) could be as a result of sampling variations during the field experiment.

Validation of AquaCrop for pearl millet was satisfactory, considering all simulations and the statistical evaluation of the selected parameters under observation during the process. Canopy cover (CC), biomass and cumulative ET were well simulated by the model for these two lines of pearl millet. The soil water content was moderately simulated for the two lines of pearl millet but needs more improvement.



**Figure 5.10** Calibration results and the comparison of simulated and observed canopy cover (CC) of two lines of pearl millet under irrigation and rainfed treatments during the 2008/2009 season:

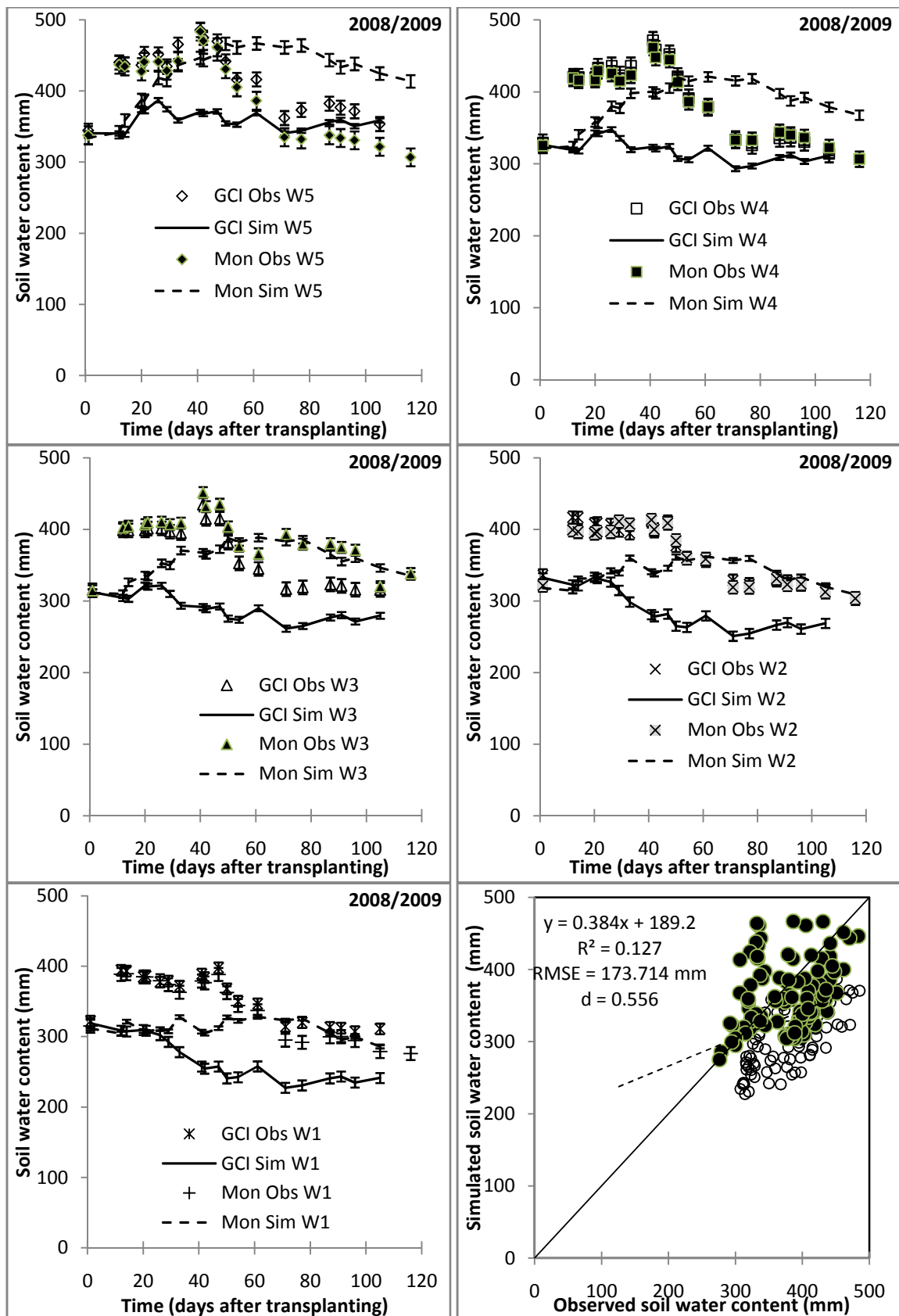
○ - GCI 17; ● - Monyaloti.



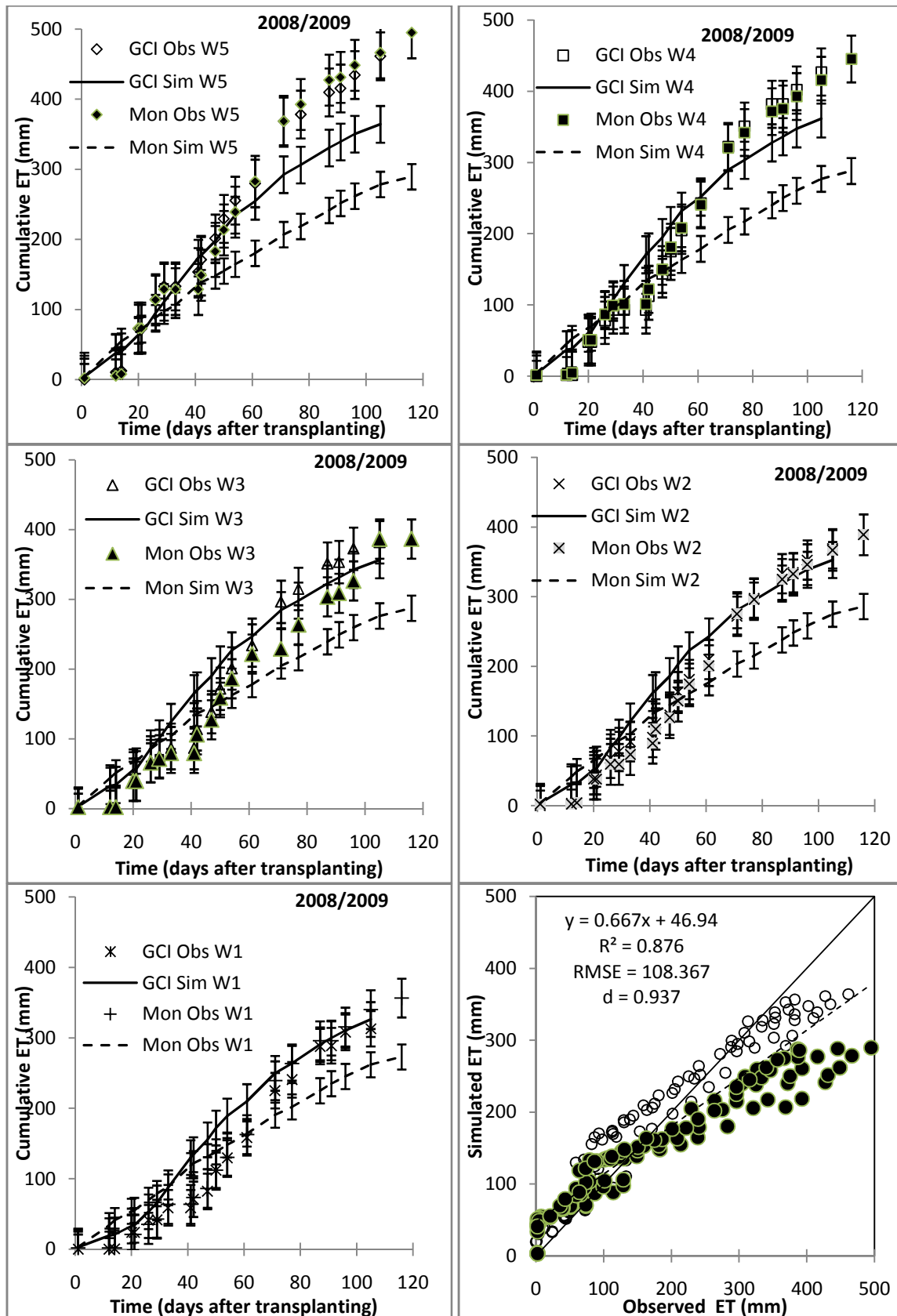
**Figure 5.11** Calibration results and the comparison of simulated and observed biomass of two lines of pearl millet under irrigation and rainfed treatments during the 2008/2009 season:

$\circ$  - GCI 17;  $\bullet$  - Monyaloti.





**Figure 5.12** Calibration results and the comparison of simulated and observed soil water content (SWC) of two lines of pearl millet under irrigation and rainfed treatments during the 2008/2009 season:  $\circ$  - GCI 17;  $\bullet$  - Monyaloti.



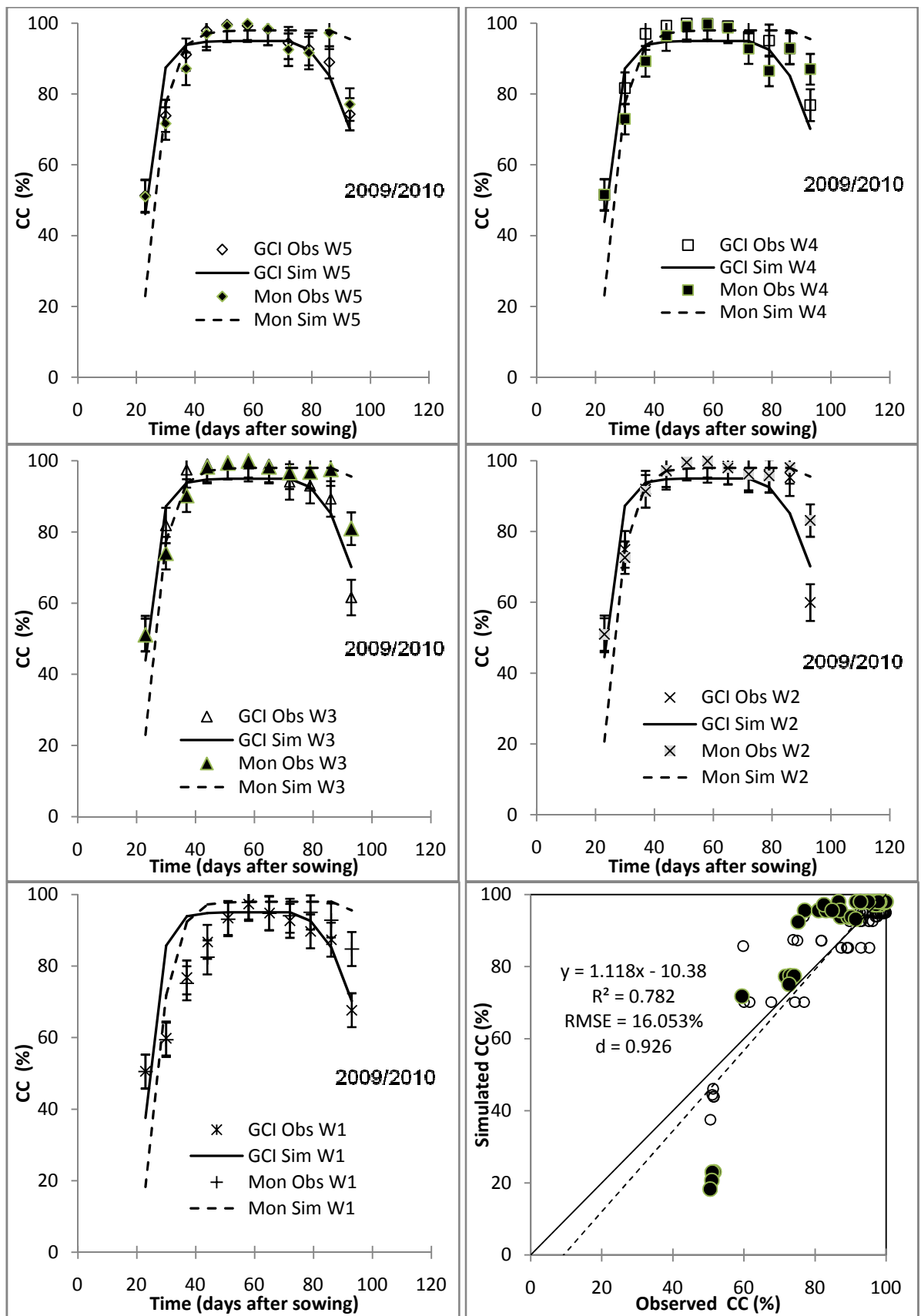
**Figure 5.13** Calibration results and the comparison of simulated and observed cumulative ET of two lines of pearl millet under irrigation and rainfed treatments during the 2008/2009 season:

○ - GCI 17; ● - Monyaloti.

**Table 5.6** The root mean square (RMSE), coefficient of determination ( $R^2$ ) and index of agreement (d) between simulated and observed values of canopy cover (CC), biomass production, soil water content (SWC) and cumulative evapotranspiration (ET) for the calibration and validation of the AquaCrop model for pearl millet

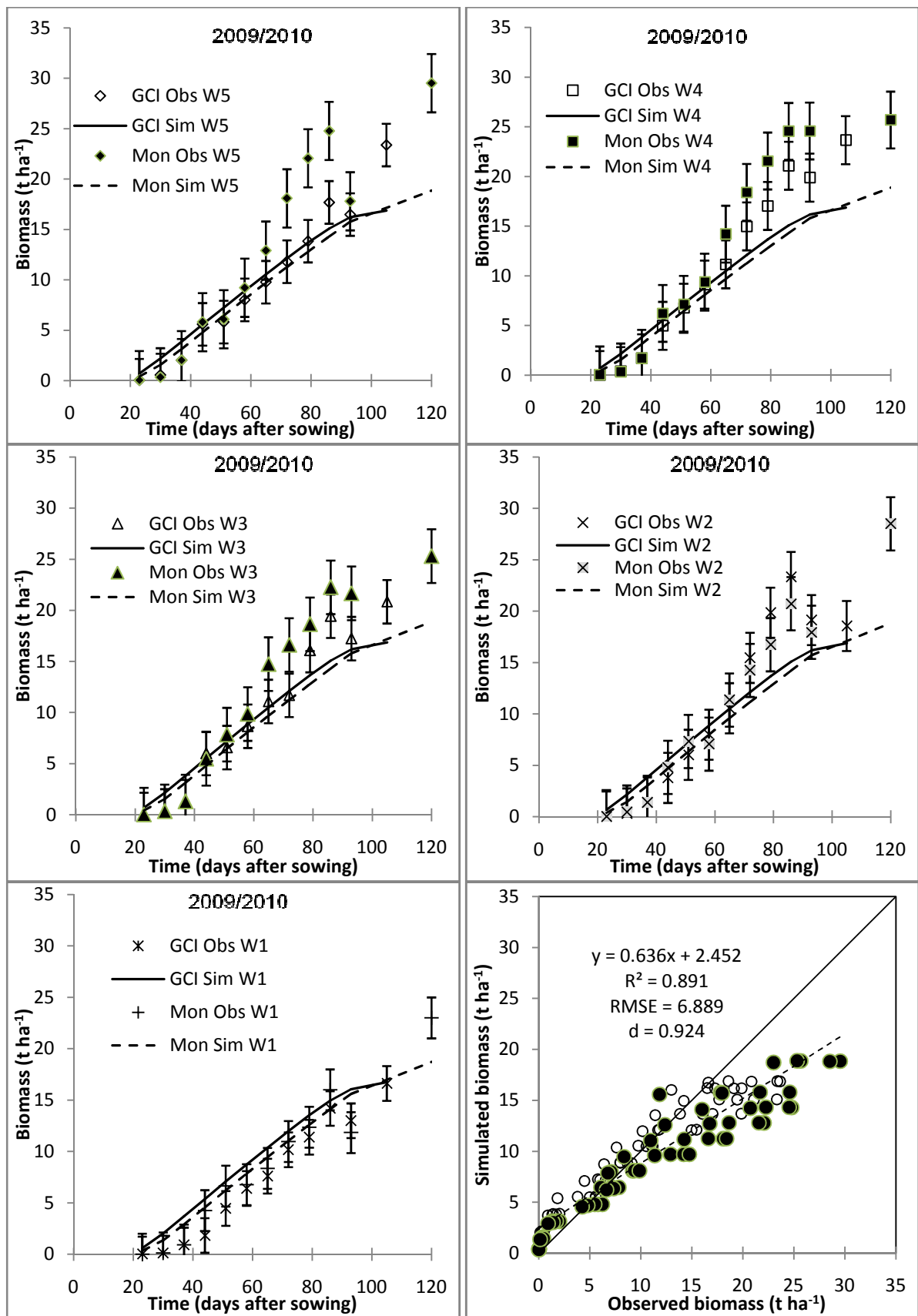
<b>GCI 17</b>	<b>Calibration 2008/2009</b>			<b>Validation 2009/2010</b>		
Parameters	RMSE	$R^2$	d	RMSE	$R^2$	d
Canopy cover CC (%)	13.041	0.906	0.837	8.587	0.814	0.949
Biomass (ton ha <sup>-1</sup> )	1.519	0.963	0.983	3.566	0.917	0.953
SWC (mm)	142.98	0.431	0.540	23.48	0.327	0.747
Cumulative ET (mm)	64.786	0.944	0.976	46.255	0.981	0.975
<b>Monyaloti</b>	<b>Calibration 2008/2009</b>			<b>Validation 2009/2010</b>		
Parameters	RMSE	$R^2$	d	RMSE	$R^2$	d
Canopy cover CC (%)	17.897	0.914	0.783	13.564	0.817	0.910
Biomass( ton ha <sup>-1</sup> )	2.625	0.967	0.968	5.901	0.914	0.904
SWC (mm)	98.657	0.107	0.614	57.63	0.134	0.607
Cumulative ET (mm)	126.876	0.928	0.892	33.868	0.974	0.987

Steduto *et al.* (2011) reviewed the performance of AquaCrop model in simulating growth and development of maize, cotton, quinoa, bambara, barley and teff. They revealed that the model was able to simulate CC, aboveground biomass and crop water use (ET) in good agreement with the observed parameters for all the crops under review. Soil water content, biomass and grain yield were well simulated by AquaCrop during the testing of the model for barley while the model also provided a means of determining irrigation scenarios that can lead to the highest grain yield (Araya *et al.*, 2010). Stricevic *et al.* (2011) concluded that AquaCrop is highly reliable for the simulations of biomass, yield and water demand of maize, sugar beet and sunflower even if available input data were limited. In this study AquaCrop was able to simulate two varieties of pearl millet with different genetic variability. The two have different maturity and physiological forms and the model was able to accommodate these issues. Karunaratne *et al.* (2011) also calibrated and validated AquaCrop for four landraces of bambara groundnut, a crop with high genetic variability, under different water regimes, glasshouse and field conditions in two locations.



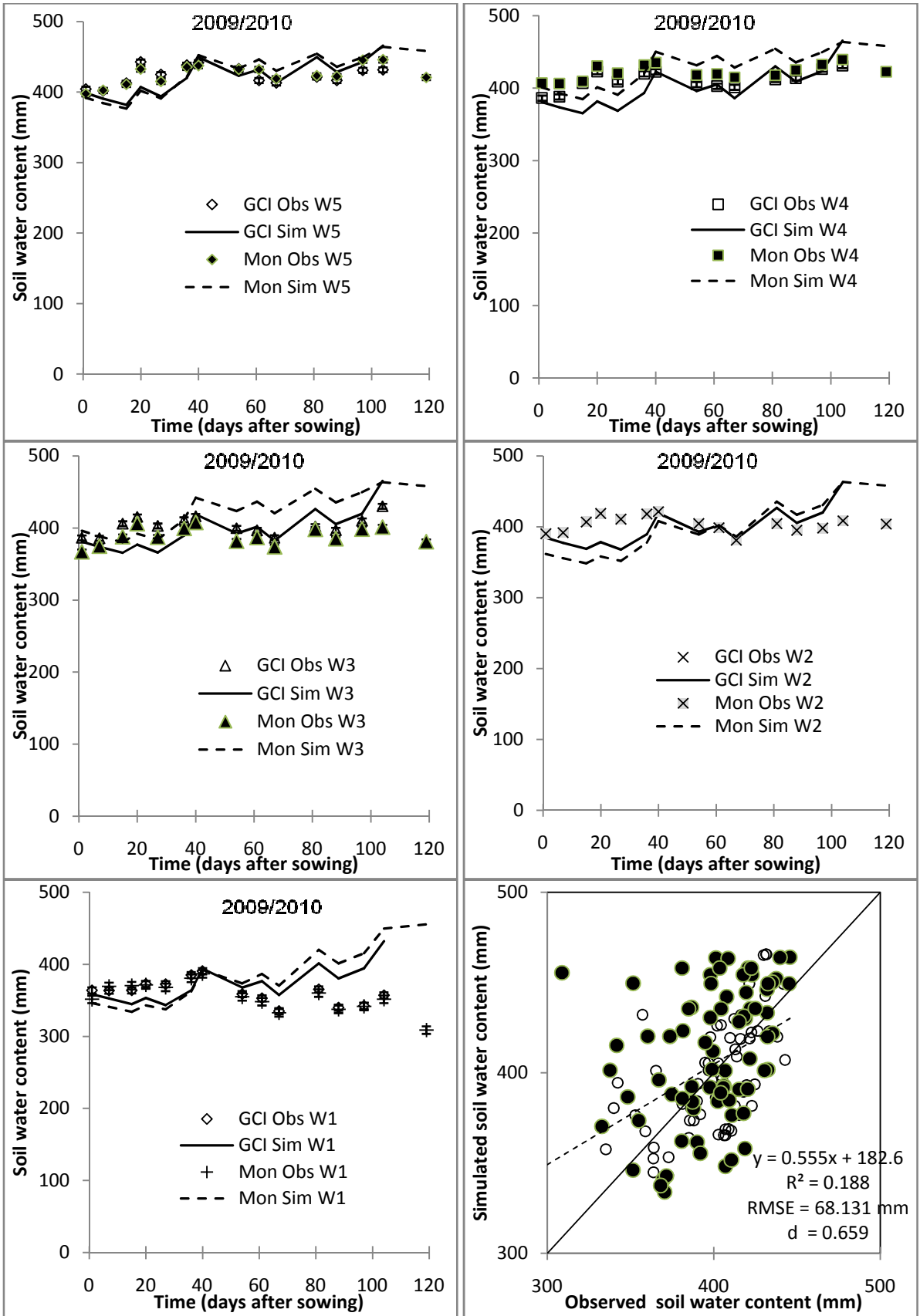
**Figure 5.14** Validation results and comparison of simulated and observed canopy cover (CC) of two lines of pearl millet under irrigation and rainfed treatments of the 2009/2010 season:

○ - GCI 17 ● - Monyaloti.



**Figure 5.15** Validation results and comparison of simulated and observed biomass of two lines of pearl millet under irrigation and rainfed treatments of the 2009/2010 season:

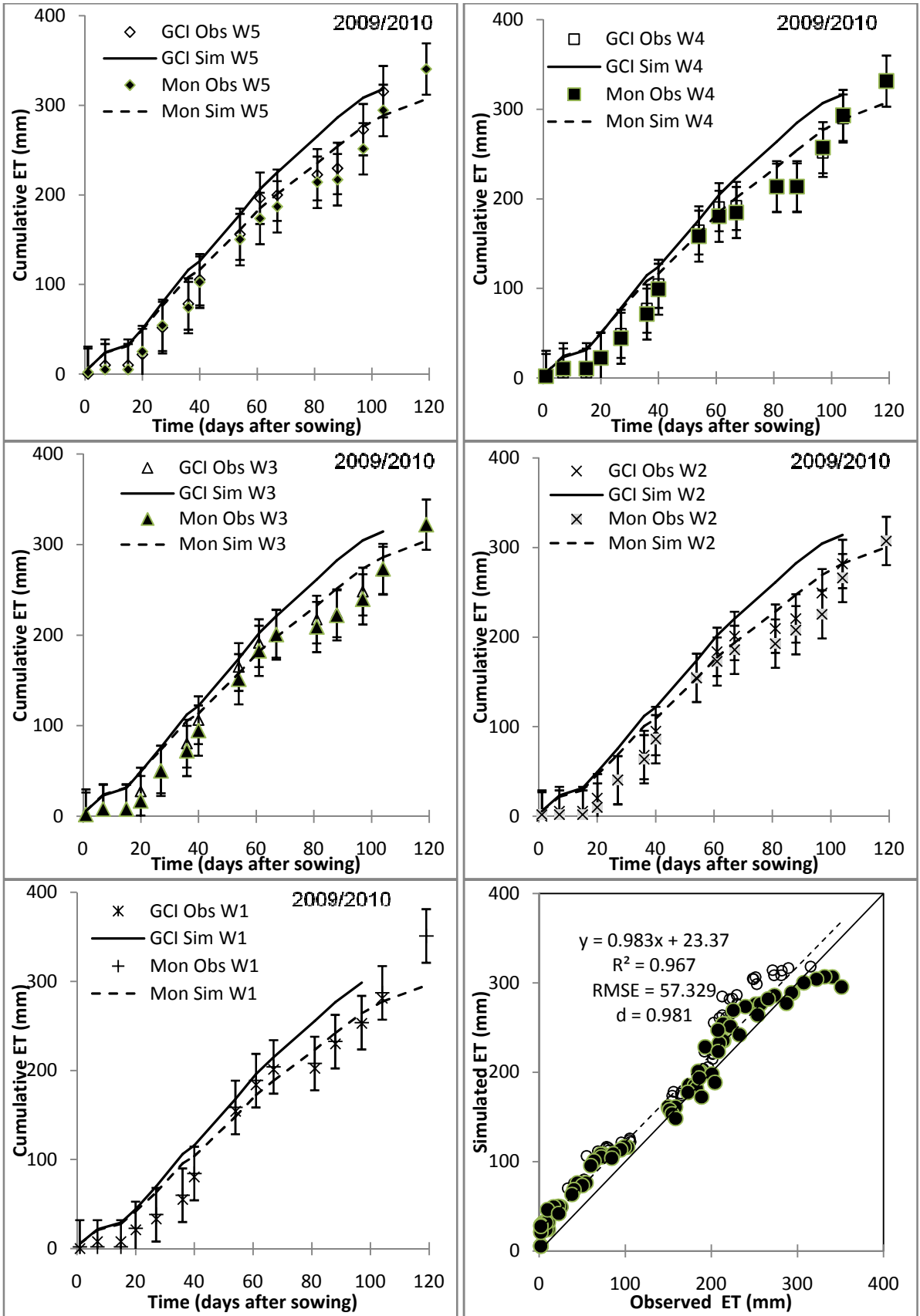
○- GCI 17 ●- Monyaloti.



**Figure 5.16** Validation results and comparison of simulated and observed soil water content (SWC)

of two lines of pearl millet under irrigation and rainfed treatments of the 2009/2010 season:

○ - GCI 17 ● - Monyaloti.



**Figure 5.17** Validation results and comparison of simulated and observed cumulative ET of two lines of pearl millet under irrigation and rainfed treatments of the 2009/2010 season:

○ - GCI 17 ● - Monyaloti.

## **5.4 CONCLUSIONS**

The AquaCrop model was able to simulate canopy cover (CC), biomass production and cumulative evapotranspiration (ET) for the two crops under irrigation and rainfed conditions. However, more work is needed to be done to calibrate the water balance part of the model for the soil water content (SWC) as the performance of the model in simulating this parameter is moderate for the crops and needs to be improved. There is a need to look into the aspect of the model simulating initial canopy cover of transplanted seedlings. The two varieties of pearl millet that were calibrated and validated for AquaCrop presented an opportunity to investigate furthermore the ability of the model to simulate the performance of crops with high genetic variability especially underutilized crops. Therefore, there is need to use datasets from other agro-ecological region to improve the calibration and validation for these crops. The model has the potential to be used as a decision support tool to increase water productivity and to study different scenarios and management conditions of amaranthus and pearl millet cultivations. The ability of the model to simulate more precisely the growth and yield of these two crops with limited inputs and simplicity makes it user friendly and preferable to other more complex crop simulation models.



## CHAPTER 6

### APPLICATION OF AQUACROP FOR PREDICTION OF ADAPTATION OPTIONS FOR AMARANTHUS AND PEARL MILLET PRODUCTION UNDER CLIMATE CHANGE IN SOUTH AFRICA

#### 6.1 INTRODUCTION

The effect of climate change on agriculture is an important issue especially in semi-arid southern Africa. The impact is expected to be severe on water resources and subsequently on agriculture. Various studies on the impact of climate change on agriculture project increasing yield losses in the next hundred years (Challinoret *al.*, 2009; Lobellet *al.*, 2008; IPCC, 2007). Under these semi-arid climates, water is the most limiting factor for crop production. IPCC (2007) projected that, by 2020, between 75 and 250 million of people will be exposed to increased water scarcity due to climate change with a yield reduction of up to 50% from rainfed agriculture in southern African region. Thus, South Africa is also vulnerable to the impact of climate change due to the semi-arid nature of much of the agricultural land in the country. It was also stated that semi-arid and arid areas are particularly exposed to the impacts of climate change concerning water (IPCC, 2001; IPCC, 2007). A study on the potential economic impact of climate change in South Africa shows that there will be decrease in crop yield by 2050 for some crops - especially field crops (Turpieet *al.*, 2002).

These effects of climate change on crop production can be expected because crop production is highly dependent on the climate during the season in which it is grown. Therefore, there is a need for adaptation and sustainability measures against the potential negative impact of the change on crop production. Adaptation to climate change can be defined as changes in a system in response to some force or perturbation which is related to climate (Smithers & Smit, 1997). It can also be defined as adjustments in ecological, social or economic systems in response to actual or expected stimuli and their effects or impacts (IPCC, 2001). Possible adaptation strategies for crop production include change of planting dates, developing of drought resistant varieties, changing of tillage practices and meanings of increasing water use efficiencies of crops, to name but a few. It has been predicted that due to the expected increase in temperatures across Africa, there may be displacement of many of the crops especially in rainfed farming areas (Benhin, 2006). With this potential displacement of crops, there is a need to identify alternative crops that can be used as part of a nationwide adaptation programme for climate change. Drought tolerant crops such as amaranthus and pearl millet are crops that can cope relatively well with adverse conditions such as high temperature that might be expected with climate change. The importance of drought tolerant crops as part of adaptation strategy against the detrimental effects of climate change includes their higher water use efficiency and ability to produce on marginal lands and in semi-arid regions, as well as to tolerate prolonged dry spells.

A better understanding of the response of crops to different environmental conditions will help in selecting better options from different adaptation strategies. Literature reveals that adjusting sowing dates is an easy, simple and powerful adaptation tool for the effects of climate change (Baker & Allen, 1993; Krishnan *et al.*, 2007). Decisions on choice of sowing dates as an adaptation strategy may however be difficult to make without making use of good farm planning management tools. Crop modelling is one of the tools used to develop optimal management strategies. Calibrated crop models can help as support tools for planning, decision making, yield predictions and evaluating the effects of climate change (Steduto *et al.*, 2009). Crop models can be used to formulate and test adaptation and sustainability strategies for the impact of climate change on production of selected crops. This chapter examines the use of AquaCrop model to predict performance of amaranthus and pearl millet under climate change in the Free State, South Africa and to project the available adaptation options in forms of alternative sowing dates.

## 6.2 MATERIALS AND METHODS

### 6.2.1 Study area

Bloemfontein is in a semi-arid region that lies at an altitude of 1353m on latitude 29.1°S and longitude 26.3° E. The summer frost-free period is between October and March with winter between May and August. This area has average maximum and minimum temperatures of 28.7°C and 12.9°C in summer and maximum and minimum temperatures of 19.1°C and below 0 °C in winter (Table 6.1). The hottest days occur during January and the lowest temperatures in July. The average annual rainfall is 540 mm with the driest month being July (Table 6.1).

**Table 6.1** Monthly averages for climate parameters for Bloemfontein (Bloemfontein airport weather station) between 1979 and 2010 (SAWS, 2002)

Month	T <sub>max</sub> (°C)	T <sub>min</sub> (°C)	RH <sub>x</sub> (%)	RH <sub>n</sub> (%)	Precipitation (mm/year)
Jan	30.85	15.20	94	14	81.8
Feb	29.57	14.88	95	18	100.8
Mar	27.30	12.34	96	19	72.3
Apr	24.08	7.54	97	20	37.8
May	21.01	2.38	96	18	14.2
Jun	17.48	-1.68	97	16	9.2
Jul	17.68	-1.85	96	13	8.7
Aug	20.34	1.08	96	10	17.3
Sept	24.13	5.57	93	10	23.6
Oct	26.07	9.37	94	11	51.4
Nov	28.06	11.75	94	12	64.1
Dec	30.17	13.88	94	11	58.63

T<sub>max</sub> – Maximum temperature, T<sub>min</sub> – Minimum temperature, RH<sub>x</sub> – maximum relative humidity, RH<sub>n</sub> – minimum relative humidity.

### **6.2.2 Climatic data and climate change scenarios**

A climate change scenario is defined as a possible future climate constructed for explicit use when investigating the potential consequences of anthropogenic climate change (IPCC, 2001). Downscaled future climate data for the Bloemfontein airport weather station simulating two SRES (Special Report on Emissions Scenarios) scenarios (A2 and B1) consisting average maximum and minimum temperatures and total rainfall were downloaded from the climate information portal of the Climate Systems Analysis Group, University of Cape Town website (<http://cip.csag.uct.ac.za/webclient/introduction>). This website is a source of large suite of observational and projected future climate data for African countries. In the IPCC (2000) report, the A2 scenario was described as a scenario that projected a very heterogeneous world which is self-reliance with preservation of local identities, fertility patterns across regions converge very slowly, which results in continuously increasing global population while economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines. The B1 scenario was described in the same report as a scenario that described a convergent world with the global population that peaks in mid-century and declines thereafter with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. Two global climate models (GCMs) for each SRES were selected out of the ten available GCMs. Global climate models (also known as general circulation models) represent physical processes in the atmosphere, ocean, cryosphere and land surface (IPCC, 2001; Stute *et al.*, 2001). They are numerical models that provide means for numerical experiments of climate transitions during the past, present, and future. These are the most advanced tools for simulating the response of the global climate system to increasing greenhouse gas concentrations (IPCC, 2001; Stute *et al.*, 2001). The two GCMs selected are MPI ECHAM 5 and CSIRO mk3.5. The MPI ECHAM 5 is a European Centre Hamburg Model developed by Max Planck Institute for Meteorology, Germany while CSIRO mk3.5 is a model developed by Commonwealth Scientific and Industrial Research Organization, Australia (IPCC, 2001; Roeckner *et al.*, 2003; Gordon *et al.*, 2010). The CSIRO mk 3.5 has been validated for present and future climates over southern and tropical Africa (Engelbrecht, 2005). The climate change scenarios data were in mean monthly time steps for 20 years, 2046-2065.

### **6.2.3 Crop model**

AquaCrop was calibrated and validated for amaranthus and pearl millet during this study. The detailed of the process of calibration and validation of AquaCrop for the two crops are found in Chapter 5. AquaCrop is suitable for this study as it is simple and requires few input parameters and input data to simulate crops response to water. The model used normalized values of water productivity according to atmospheric evaporative demand and CO<sub>2</sub> concentration therefore making it possible to extend its extrapolation capacity to diverse locations and seasons, including climate change scenarios

(Mainuddin *et al.*, 2010). The desirable ability of the model includes the provision of the mean annual atmospheric CO<sub>2</sub> concentration for a series of past years and the user of AquaCrop can enter a future year's CO<sub>2</sub> for prospective analysis of climate change (Raes *et al.*, 2009). AquaCrop has been used to identify optimal planting dates and predict performance of maize under future climatic change in Zimbabwe (Masanganise *et al.* 2012; Mainuddin, 2010). The daily weather data from 1975 to 2010 for Bloemfontein was used to create climate file for historical years. The mean monthly temperatures (maximum and minimum) and rainfall of the SRES scenarios for the near future (2046-2065) in conjunction with their projected CO<sub>2</sub> from the model were used to create climate files for the climate change scenarios. The baseline years are from 1991 to 2010 while the projected near future years are from 2046 to 2065. The model was run under two management conditions, rainfed and irrigated, for the two crops, baseline years and the climate change scenarios. To determine net irrigation requirements, irrigation conditions were created at allowable depletion of up to 80% of readily available soil water before irrigating back to field capacity.

#### **6.2.4 Adaptation scenarios**

For the purpose of this study, the focus was on change of transplanting or/and planting dates as it affects production and the water use of the two crops under the stipulated climate change scenarios. The current recommended planting date for amaranthus for Bloemfontein area is during October and November (van den Heever & Coertze, 1996) and that of millet is mid-November and early December (ARC- Grain Crops Institute, Potchefstroom, personal communication with Dr Nermera Shargie). The recommended planting dates for each crop, for both the past and future climatic data and growing periods of crops were taken into consideration to select optimal planting dates and these dates were used to run the model (Table 6.2). Ten proposed planting dates were tested from September to mid-January at two weeks intervals. These ranges of selected planting dates were based on the climate datasets due to the thresholds temperatures affecting crop development. The base temperatures for amaranthus and pearl millet are 7°C and 8°C while their upper temperatures are 30°C and 32°C respectively. There was only one genotype available for amaranthus but two lines of pearl millet were used during the course of this study. Therefore, the choice between different varieties of a particular crop as an adaptation strategy against climate change can only be examined in pearl millet. The two lines of pearl millet are of short and medium season varieties with different levels of drought tolerance.

**Table 6.2** Planting dates scenarios as an adaptation option for the two crops

		Amaranthus		Pearl millet			
				GCI 17		Monyaloti	
Proposed	Code	RPD	Growing period	RPD	Growing period	RPD	Growing period
01-Sep	PD1	October - November	100 days	Mid November - early December	105 days	Mid November - early December	120 days
15-Sep	PD2						
01-Oct	PD3						
15-Oct	PD4						
01-Nov	PD5						
15-Nov	PD6						
01-Dec	PD7						
15-Dec	PD8						
01-Jan	PD9						
15-Jan	PD10						

RPD - Recommended planting dates

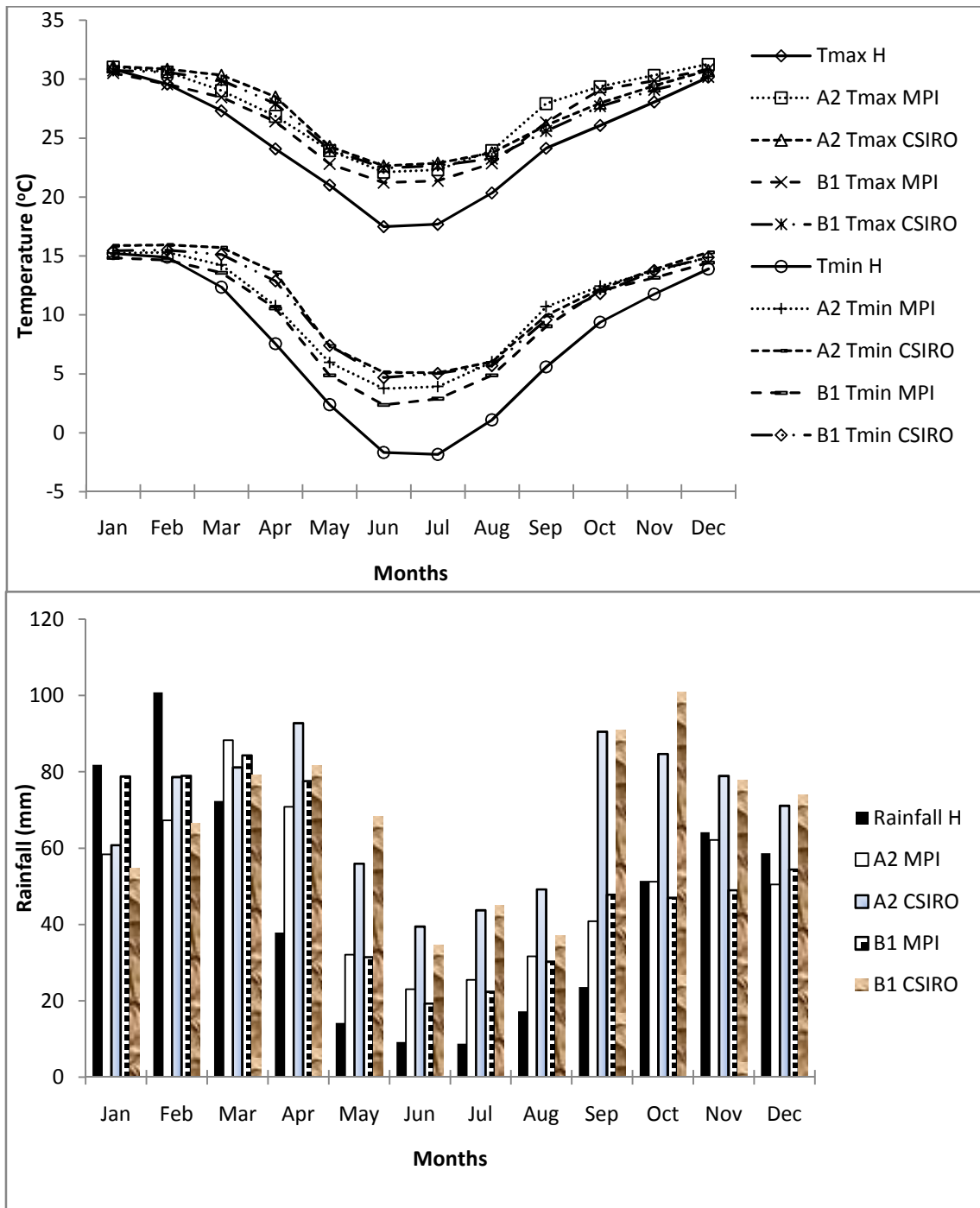
## 6.3 RESULTS AND DISCUSSION

### 6.3.1 Past and future climate

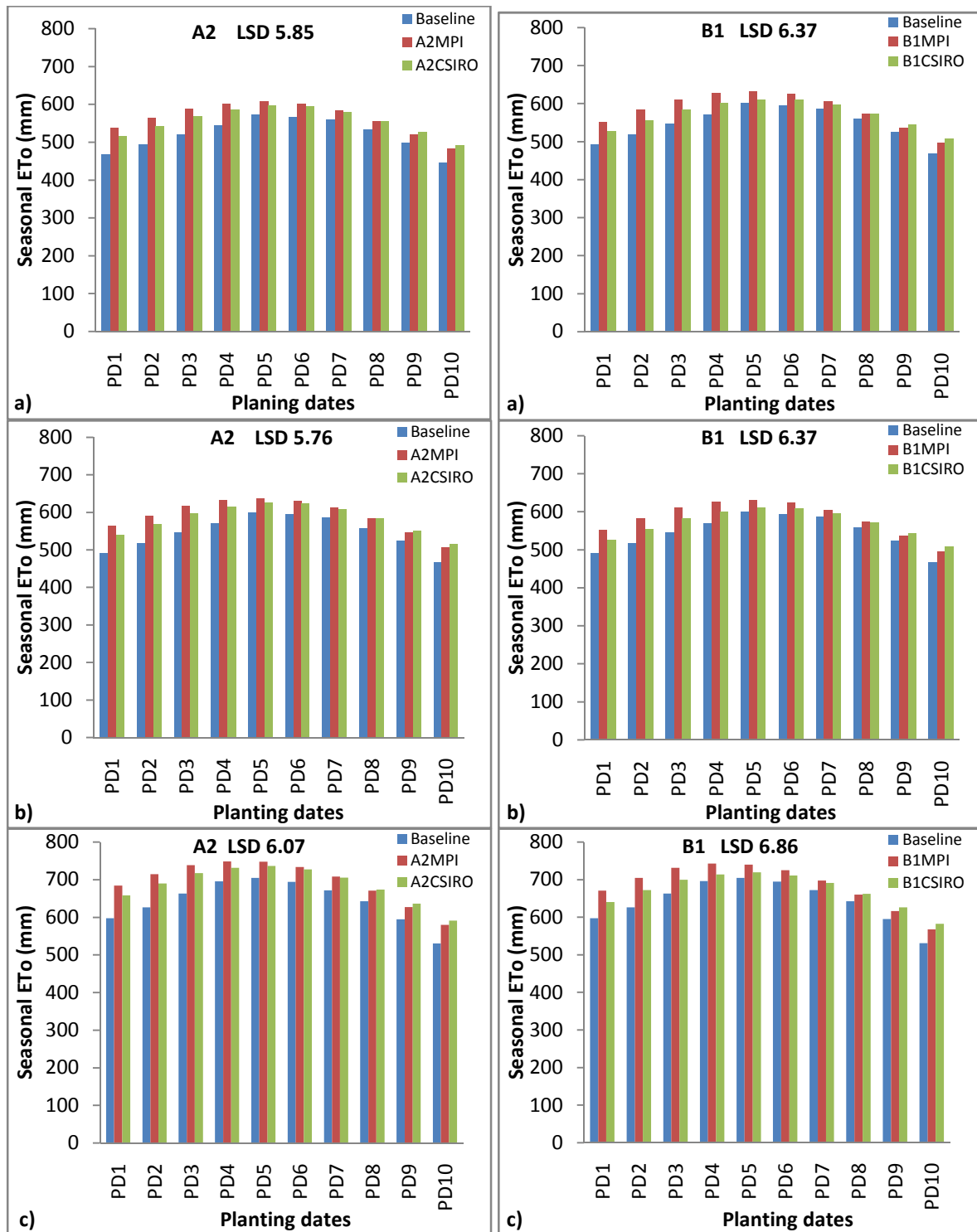
For both scenarios, the temperatures are supposed to increase in the near future and the largest increases are found during the winter period, June and July (Figure 6.1), where the increase can be more than 5°C in both maximum and minimum temperatures. Temperature increase in summer is predicted to be minimal and could be as little as 0.18°C. Rainfall prediction varies throughout the year for both scenarios and both GCMs (Figure 6.1). The CSIRO model predicted the highest rainfall for both of the scenarios in the first half of the summer (October – December). The amounts of rainfalls predicted by CSIRO model are also higher than the amount of historical rainfalls for these months. The two scenarios also predicted higher winter rainfall from both GCMs. Total seasonal rainfalls predicted by MPI ECHAM 5GCM are 602mm and 622mm for A2 and B1 scenarios compare to 828 mm and 812mm predicted by CSIRO mk3.5 GCM for the two scenarios respectively.

In both scenarios, baseline years recorded the lowest ETo for all the planting dates in both scenarios irrespective of the crop. Therefore higher atmospheric evaporative demand is expected with climate change. This could be due to higher temperatures (maximum and minimum temperatures) predicted by the two GCMs in both scenarios for the near future. Figure 6.2 shows that there is influence of planting dates on the seasonal reference evapotranspiration (ETo) for both scenarios and GCMs. MPI ECHAM 5 GCM predicted higher ETo for more than half of the proposed planting dates (PD1 – PD7) while CSIRO mk3.5 GCM predicted higher ETo for the rest of the proposed planting dates. This is due to the reason that MPI ECHAM 5 model predicted higher temperature than CSIRO mk3.5 model for the near future years. Planting dates of PD4 and PD5 (15 Oct & 1 Nov) will produce the highest ETo in the near future in both scenarios and GCMs. This signifies that the total atmospheric evaporative demand through the season will be very high if transplanting or planting is done on these

dates under both scenarios. Figure 6.2 also shows that seasonal reference evapotranspiration is different for different growing period of crops. Amaranthus and GCI 17, improved line of pearl millet, will experience lower ETo over their growing period (100 and 105 days) compare to Monyaloti which is a medium season variety (120 days). Reference evapotranspiration (ETo) is very important as it describes the evaporative demand of the atmosphere independently of crop type, crop development and management practices (Allen *et al.*, 1998). It is also referred to as the evaporation drying power of the atmosphere. It is important to know when and how to irrigate for efficient water use and optimum crop production. ETo can be used with crop coefficients of particular crops to design irrigation scheduling and water management (Hargreaves, 1994; Allen *et al.*, 1998). Other models such as Irrigation Scheduling Alfalfa (ISA) model in United States and model for establishing irrigation requirements and scheduling strategies in Southern Africa (SAPWAT) also makes use of ETo and crop coefficient values to estimate crop evapotranspiration (Snyder & Bali, 2008; van Heerden *et al.*, 2009).



**Figure 6.1** Mean monthly maximum and minimum temperatures and monthly total rainfall of historical (1979-2010) and predicted climates (2046-2065) under A2 and B1 scenarios. H = Historical, MPI = MPI ECHAM 5 and CSIRO = CSIRO mk3.5 models.



**Figure 6.2** Seasonal reference evapotranspiration (ETo) as affected by different planting dates and growing seasons predicted under A2 and B1 scenarios compare with the baseline. MPI = MPI ECHAM 5 and CSIRO = CSIRO mk3.5 models. ((a) Amaranthus; (b) Pearl millet line - GCI 17; (c) Pearl millet line - Monyaloti).



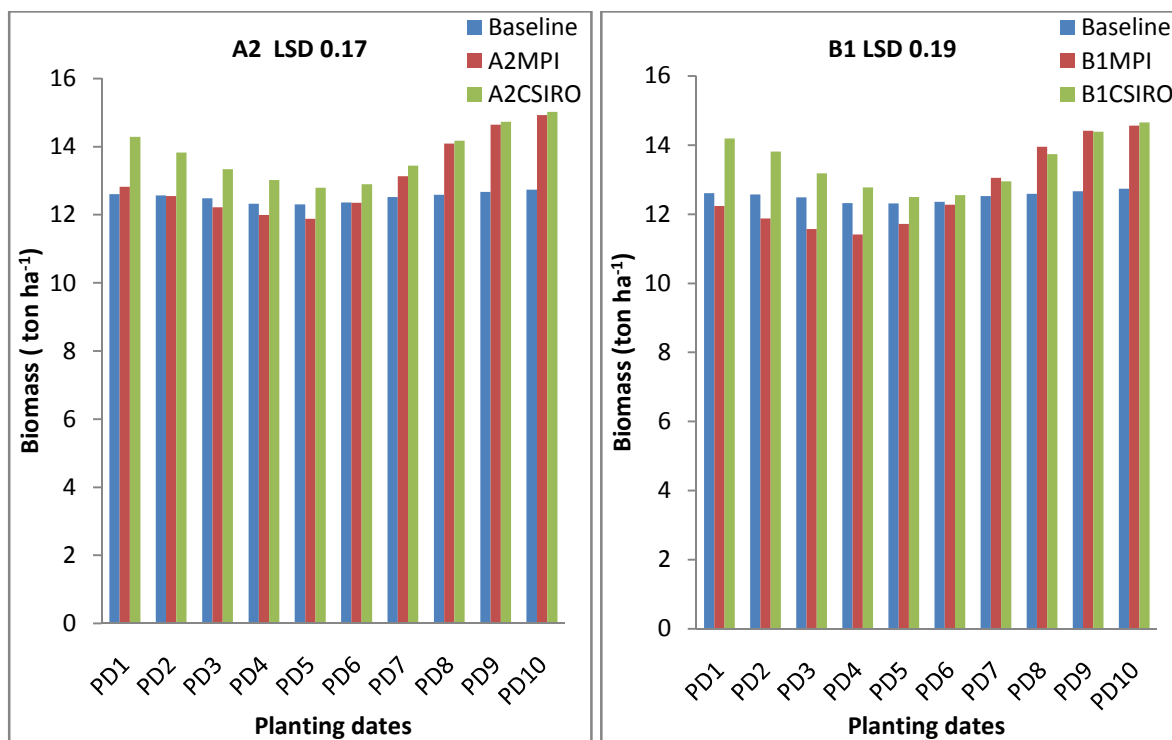
## 6.3.2 Amaranthus

### 6.3.2.1 Biomass

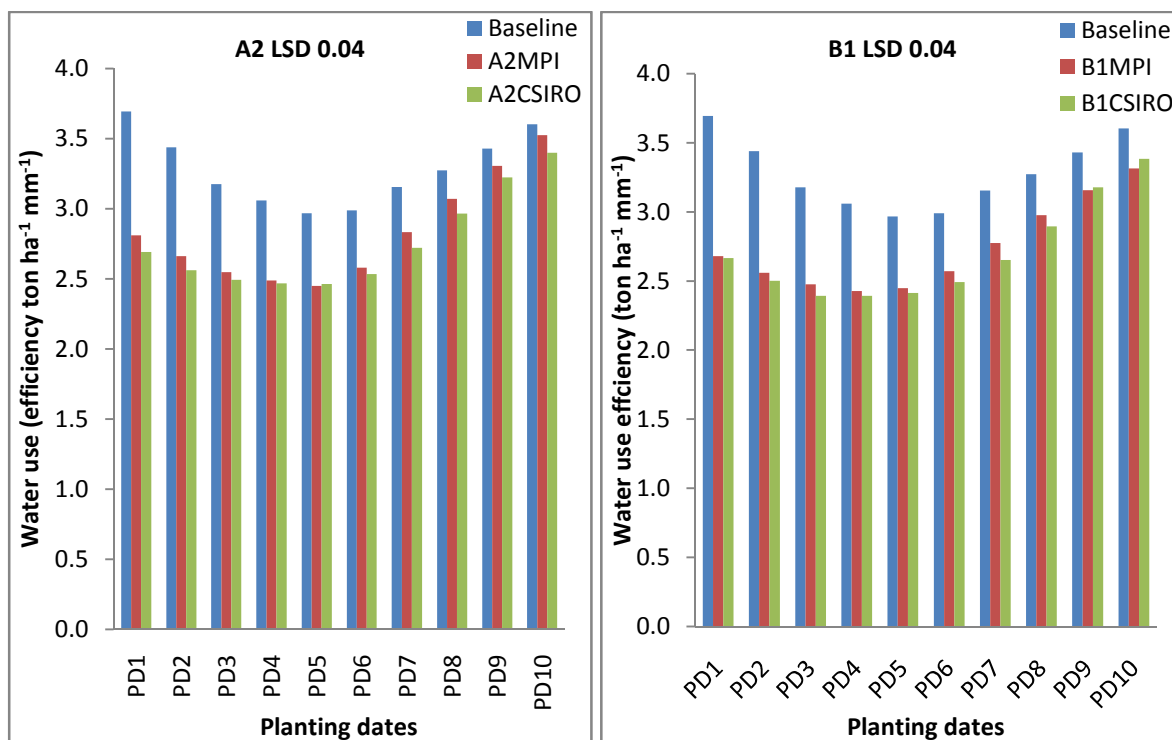
Biomass production will represent both final biomass and yield of amaranthus as the crop is cultivated as a leafy vegetable. Impact of predicted climate change on amaranthus biomass production is shown to be positive (Figure 6.3). The biomass will increase under the near future time slice for all the transplanting dates under the CSIRO GCM climate change predictions. The highest biomass of 15.02 t ha<sup>-1</sup> predicted is found under the A2 scenario if the crop is transplanted on PD10 (15 Jan) while the lowest biomass, 11.42 t ha<sup>-1</sup> was found under the B1 scenario if the crop is transplanted at the beginning of the summer on PD4 (15 Oct). For the same planting date, the biomass of baseline condition is higher than that of the lowest predicted biomass with a difference close to 1 t ha<sup>-1</sup>. Under the two scenarios, transplanting on PD 9 and PD10 will produce the highest biomass for the 2046-2065 climate from both GCMs. Comparing scenarios and transplanting dates, more biomass will be produced under A2 than B1 scenario while transplanting done on PD9 and PD10 will be advantageous under both scenarios. Increase in rainfall predicted under the two scenarios by both GCMs might have provided the means for the increase in biomass production. However, higher ETo for planting dates of PD4-PD5 shows that these periods might require more water to satisfy the atmospheric demand during the transplanting and this will expose the seedlings, which will have small canopy, to drier and warmer condition probably imposing stress and might slow down the growth and development of the crop. Large portion of the rainfall incident at these periods might be lost to the environment due to evaporation rather than transpiration.

### 6.3.2.2 Water use efficiency (WUE)

Compared to baseline years, the water use efficiency (WUE) of amaranthus is lower under the climate change predictions (Figure 6.4). The variation of WUE of amaranthus across transplanting dates follows the same trend found in the biomass predictions, with lower values during the mid-season planting dates, which had overall higher temperatures. Mid-season will require more water to perform as much as the early and late season. However, water is used more efficient at early and later transplanting date (PD1) under baseline conditions, while it is used most efficiently at later transplanting dates (PD10) under the predicted near future years under both scenarios. The baseline condition produced the highest WUE of 3.69 t ha<sup>-1</sup> mm<sup>-1</sup> followed by A2CSIRO and B1CSIRO with 3.52 and 3.38 t ha<sup>-1</sup> mm<sup>-1</sup>. Transplanting on PD4, PD5 and PD 6 will produce low WUE for amaranthus despite the fact that ETo was high during this period. Locations, seasons and planting dates that favour low evaporative demand of the atmosphere often enhance water use efficiency which translates to yield per unit evapotranspiration (Sadras *et al.*, 2007).



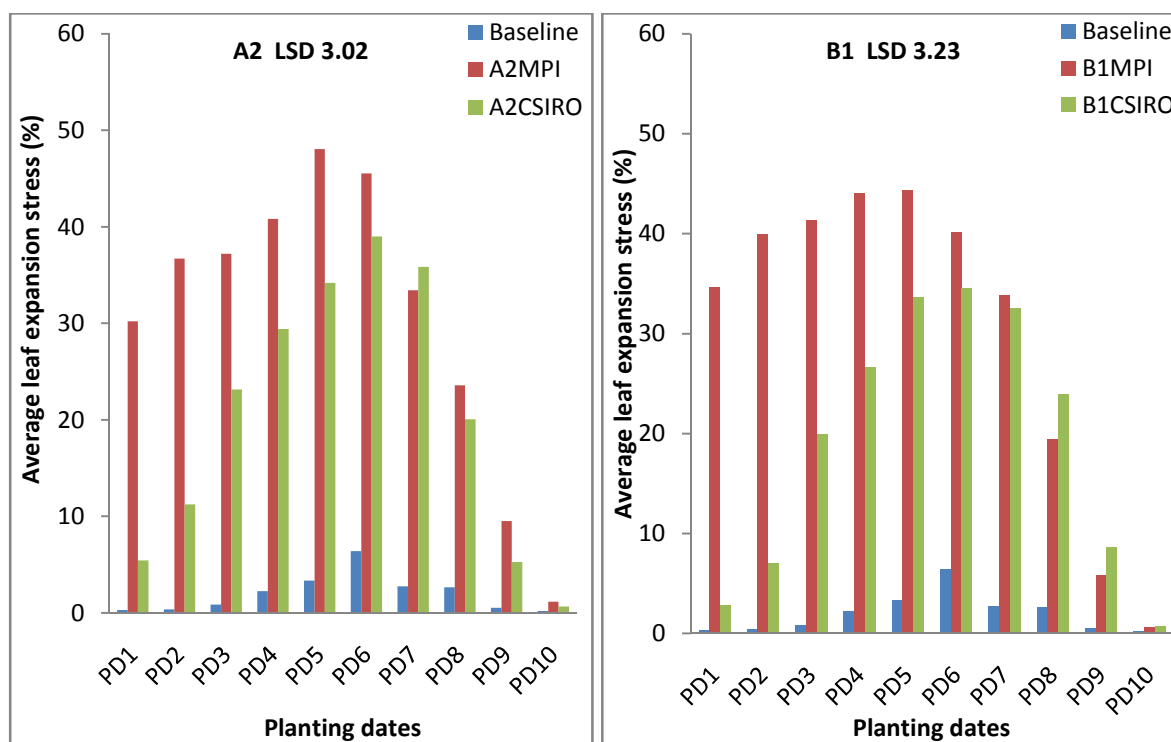
**Figure 6.3** Effect of climate change on biomass production of amaranthus under the two scenarios and baseline conditions. MPI = MPI ECHAM 5 and CSIRO = CSIRO mk3.5 models.



**Figure 6.4** Water use efficiency of the amaranthus under climate change scenarios. MPI = MPI ECHAM 5 and CSIRO = CSIRO mk3.5 models.

### 6.3.2.3 Average leaf expansion stress

When running AquaCrop on the rainfed mode, the level of leaf expansion stress can be used to explain the difference between crop production under the baseline conditions and near future climate scenarios. Restriction of leaf growth is one of the indicators of stress conditions such as water, salinity and heat stress in crops (Taleisnik *et al.*, 2009). AquaCrop uses leaf expansion as one of the response functions to gauge the effects of water stress (Steduto *et al.*, 2012). Average leaf expansion stress follows the same pattern of reference evapotranspiration (Figure 6.5). For the baseline and CSIRO mk3.5, leaf expansion stress peak is found during mid-season plantings. The predicted leaf expansion stress of MPI ECHAM 5 model did not have a normal distribution with more or higher values of leaf expansion stress for the earlier planting dates and then lower values of leaf expansion stress for the crops grown at planting dates after the mid-season to rather lower values for the later plantings. There is high indication that average leaf expansion stress will be imposed in the near future under both scenarios will be very much higher than that experienced under the baseline climate conditions. Comparing average leaf expansion stress and ETo, it will be observed that high stress as high as 48% is experienced at the planting dates (PD5) with high ETo of MPI ECHAM 5 GCM prediction under A2 scenario. Amaranthus will experience high leaf expansion stress not less than 34% if transplanted on PD6 under B1 scenario predicted by CSIRO mk3.5 model. For the same planting date, the stress was not higher than 6.4% under the baseline condition. Irrespective of the scenarios and baseline conditions, leaf expansion stress that will be imposed on amaranthus will be less than 1% if transplanting is done on PD10. There is direct relationship between leaf expansion rates and yield. Any stress causing reduction in leaf expansion has a detrimental effect on crop productivity. Radiation interception and transpiration surface or leaf area of a crop is determined by the leaf expansion and growth which is directly proportional to crop yield and productivity (de Luca *et al.*, 2001). Sadras *et al.* (1993) noted that leaf expansion rate was reduced in sunflower under high evaporative demand compared to the moderate evaporative condition. Disturbed leaf expansion due to stress consequently reduced radiation interception and this limits the transpiration in a water stressed crop (Sadras *et al.*, 1993). High leaf expansion stress resulted from high evaporative demand which leads to reduced transpiration rate, radiation interception consequently reduced the yield.



**Figure 6.5** Average leaf expansion stress as imposed by baseline conditions and predicted near future climates. MPI = MPI ECHAM 5 and CSIRO = CSIRO mk3.5 models.

#### 6.3.2.4 Irrigation water requirement

The amount of irrigation water required for optimum production of amaranthus for proposed planting dates are statistically different (Table 6.3). The lowest irrigation water amount required for optimum production in amaranthus can be achieved if the crop is planted on PD10 and the highest amount of water required could be found between the planting dates of PD3 and PD6 under baseline conditions and both predicted climate scenario. However, under both scenarios, irrigation requirements for planting dates under climates predicted by MPI ECHAM 5 model is higher than that of CSIRO mk3.5 model for the first half of the proposed planting dates. This observation might be due to high temperature coupled with low rainfall predicted by this model. This is a reflection of influence of evaporative demand and its use to determine irrigation requirement of crops. High evaporative demand condition requires high irrigation due to water loss to the environment through water depletion from soil surface by the evaporation process.

**Table 6.3** Irrigation requirements (mm) for amaranthus as affected by climate change for baseline condition and predicted near future climates

	<b>Baseline</b>	<b>A2MPI</b>	<b>A2CSIRO</b>	<b>B1MPI</b>	<b>B1CSIRO</b>
PD1	135.26	230.50	156.90	245.55	135.85
PD2	153.80	230.55	159.45	251.50	169.75
PD3	276.98	236.85	209.75	233.55	199.60
PD4	263.69	240.16	218.53	252.53	221.21
PD5	238.08	244.95	224.68	229.84	226.42
PD6	217.00	232.63	216.79	182.58	203.47
PD7	191.44	182.63	191.84	160.95	193.32
PD8	142.78	136.68	121.47	114.58	152.11
PD9	140.67	98.68	108.00	86.32	124.63
PD10	114.33	69.10	77.75	54.75	94.35
LSD	12.84	36.21	39.74	43.21	43.93

Values in the same column not sharing the same letter differ significantly at LSD (P=0.05).

#### 6.3.2.5 Water use efficiency (WUE) of irrigated amaranthus

Water use efficiency (WUE) of amaranthus is significantly different for all the different planting dates (Table 6.4). The differences are as expected considering different irrigation requirement for different planting dates and the scenarios. Baseline condition has the highest WUE throughout all the proposed planting dates. This shows that increase in biomass expected in the near future years will consume more water from rainfall and irrigation. Across the baseline condition and the two climate change scenarios, transplanting on PD9 and PD10 will produce higher WUE compared to PD 5 and PD6 that are with low WUE. For baseline condition, the highest WUE is recorded for transplanting done on PD1 ( $3.69\text{t ha}^{-1} \text{mm}^{-1}$ ) but for both climate change scenarios and GCMs the highest WUE predicted is for transplanting that will be done on PD10 (A2MPI = 3.53, A2CSIRO = 3.40, B1MPI = 3.32 and B1CSIRO =  $3.38\text{t ha}^{-1} \text{mm}^{-1}$ ). Therefore, for climate change scenarios, planting on PD10 will exhibit highest WUE across all the proposed planting dates.

#### 6.3.2.6 Change in biomass

Change in the projected biomass production for the near future years in reference to the baseline years are expressed in percentages. The biomass will increase by 14.68% if amaranthus is transplanted on PD10 in the near future years under A2 scenario predicted by MPI ECHAM 5 GCM, while it will only increase with 12.55% under the same condition under B1 scenario (Figure 6.6). The MPI ECHAM 5 model predicted decrease in biomass with planting dates (PD1-PD5) under A2 scenario. This may be due to the fact that average monthly rainfall predicted by this model decreases with time, from September until January (Figure 6.1). The maximum decrease in biomass is recorded under B1 scenario with -7.98% at PD4. Therefore, with the increase and decrease in biomass production compared to baseline condition, there is impact of climate change on amaranthus due to change in

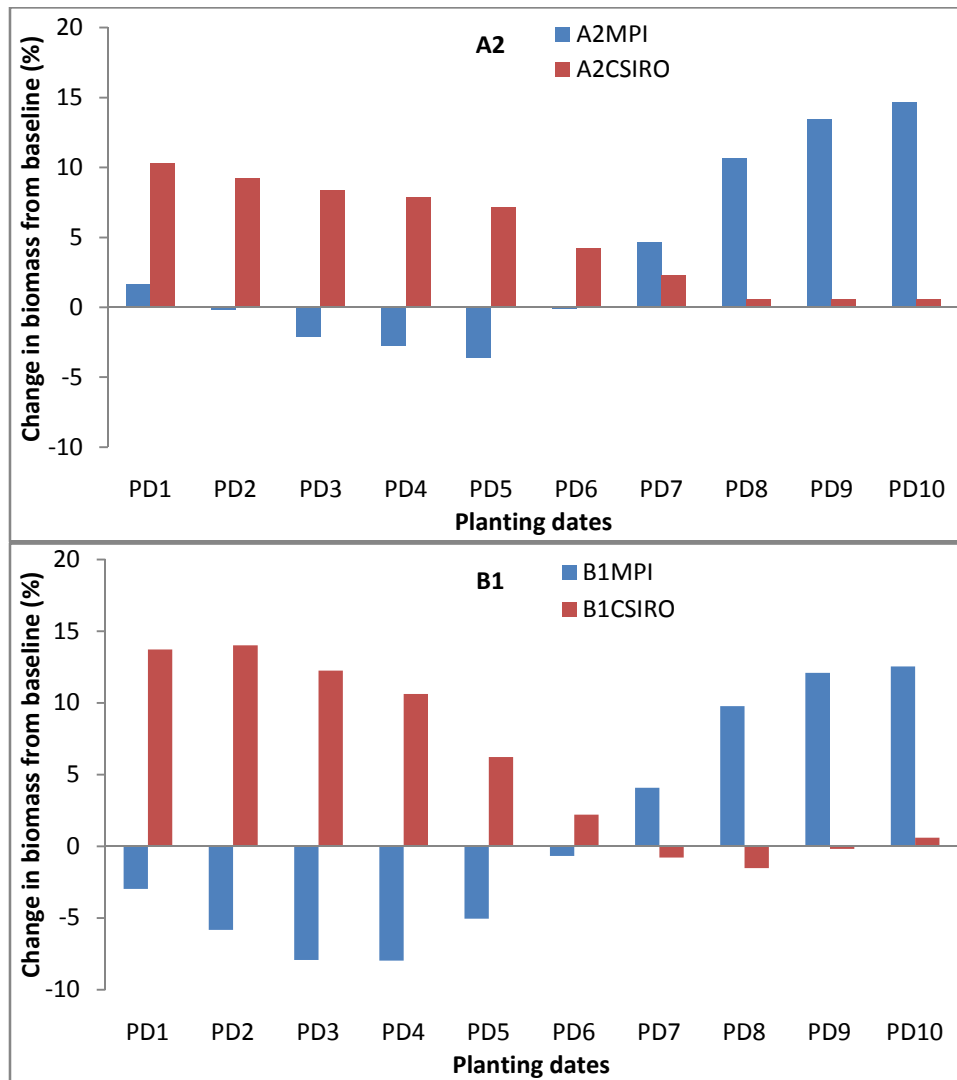
temperature and rainfall. On the contrary, Mainuddin *et al.* (2010) and Eastham *et al.* (2008) both reported no significant impact of climatic variations on maize production in Thailand.

**Table 6.4** Water use efficiency ( $\text{t ha}^{-1} \text{mm}^{-1}$ ) of irrigated amaranthus as affected by climate change for baseline condition and predicted near future climates

	<b>Baseline</b>	<b>A2MPI</b>	<b>A2CSIRO</b>	<b>B1MPI</b>	<b>B1CSIRO</b>
PD1	3.69	2.92	2.72	2.80	2.69
PD2	3.44	2.8.0	2.62	2.71	2.54
PD3	3.18	2.72	2.59	2.66	2.49
PD4	3.06	2.70	2.60	2.65	2.52
PD5	2.97	2.70	2.63	2.68	2.57
PD6	2.99	2.81	2.71	2.78	2.66
PD7	3.16	3.00	2.86	2.92	2.79
PD8	3.27	3.16	3.04	3.04	2.98
PD9	3.43	3.34	3.25	3.18	3.20
PD10	3.60	3.53	3.40	3.32	3.38
LSD	0.04	0.12	0.13	0.12	0.13

Values in the same column not sharing the same letter differ significantly at LSD (P=0.05).

There is no difference in predicted biomass production under the two scenarios but shifting transplanting dates a month backward and forward shows an increase in biomass production. Increase in biomass production for the projected future climate compared to baseline condition may be due to the higher rainfall projected for the near future by these two scenarios. Availability of adequate water during transplanting is very important in cultivation of transplanted crops so as to help seedlings with recovery, formation of roots, and to minimise or and prevent water stress (Mainuddin *et al.*, 2010). Projected increase in temperature might be another reason for the predicted increase in biomass of amaranthus. Amaranthus as a C4 crop uses energy and water more efficiently than other crops (Gowik & Westhoff, 2011). For C3 and C4 crops adapted to similar climates, leaves of C4 plants have a higher photosynthetic rate at the optimum temperature than the C3 plants (Vu & Allen, 2002). On the other hand, high temperature might be responsible for the predicted high average leaf expansion stress of projected near future years compare to the baseline condition.



**Figure 6.6** Change in projected biomass of amaranthus from baseline condition as affected by climate change scenarios.

With increase in temperature, the evaporative demand also increases and invariably leads to water stress in the absence of adequate water or high evaporative loss. Therefore, water stress is expressed in the form of a leaf expansion stress index. Considering the recommended planting dates for Bloemfontein, of October – November, delaying transplanting dates for amaranthus until the first half of January will be beneficial to the crop production. During this period, the crop will produce higher yield, with higher water use efficiency, lower leaf expansion stress and if irrigation is required, a smaller amount of irrigation water will be needed. In an investigation by Dharmarathna *et al.* (2012) to study the effect of changing planting date as a climate change adaptation strategy for rice production in Sri Lanka under A2 and B2 scenarios, the rice yield was found to increase if the transplanting date should be delayed for one month. Masanganise *et al.* (2012) predicted increase in yield with delayed planting for three cultivars of maize in north-eastern Zimbabwe. All these are in accordance with the findings of this study.

### 6.3.3 Pearl millet

#### 6.3.3.1 Biomass

Biomass production under both scenarios and baseline conditions are significantly different for the two lines of pearl millet (Figure 6.7). Effect of climate change on the short season line (GCI 17) will be positive while it will be negative for medium season line. The model predicted that the biomass production of GCI 17 (short season variety) will increase while that of Monyaloti (medium season variety) will decrease under the two climate scenarios. Short season varieties are able to reach maturity in time escaping drought and heat stress under warmer climatic conditions. Planting on PD10 will produce biomass of 13.15 t ha<sup>-1</sup> of GCI 17 while it will be 14.29 t ha<sup>-1</sup> of Monyaloti under A2 scenario. The average highest biomass of GCI 17 produced is found under A2 scenario with 13.15 t ha<sup>-1</sup> while that of Monyaloti will be 14.54 t ha<sup>-1</sup> under B1 for the same planting date (PD10). Irrespective of the planning dates, CSIRO mk3.5 model predicted higher biomass than MPI ECHAM 5 under the two scenarios. The CSIRO mk3.5 model predicted more rainfall than MPI ECHAM 5 model which might be the reason for its better performance. Asfaw and Lipper (2012) observed in their review that there will be more yield benefits under scenarios of increased than decreased rainfall. Although, there will be a decrease in biomass of Monyaloti with climate change but the lowest biomass produced will still be higher than 14 t ha<sup>-1</sup> under both scenarios and planting dates. GCI 17 did not produce as much as the lowest biomass produced by Monyaloti under climate change for the two scenarios. The reason for huge differences in the biomass production of the two lines of pearl millet might be due to genetics and different water productivity of the two lines (see chapter 5). Though, Monyaloti is a local variety it has higher water productivity than GCI 17 which is an improved variety. Some authors in the literature call for short season varieties of crop for cultivation to maximise production as an adaptation measure under climate change (Masanganise *et al.*, 2012; Tinge *et al.*, 2008). This was demonstrated by GCI 17, a short season variety, in this study.

#### 6.3.3.2 Grain yield

The trend of biomass production is similar to the grain yield that will be produced by the two lines of pearl millet in the near future. Under the two climate change scenarios, grain yield will be increasing for GCI 17 but decreasing for Monyaloti (Figure 6.8). This is expected as the model calculates the yield of the crop by multiplying biomass with the harvest index of the crop (Raes *et al.*, 2009). Lower grain yield might be caused by shift in the growth stages of the crops caused by high temperature which might lead to shortening of crop duration (Khaliq, 2008.). This calls for choice of short season variety and drought tolerant crops as measures against drought and climate change. However, the effect of planting dates on grain yield will be minimal for the two lines of pearl millet under the projected climate change. The average grain yield of GCI 17 and Monyaloti planted on PD10 under A2 scenario are 6.84 and 7.25 t ha<sup>-1</sup> compare to the baseline yield of 6.61 and 7.64 t ha<sup>-1</sup> respectively. Under the projected climate of MPI ECHAM 5 model for the two scenarios, grain yield of the two



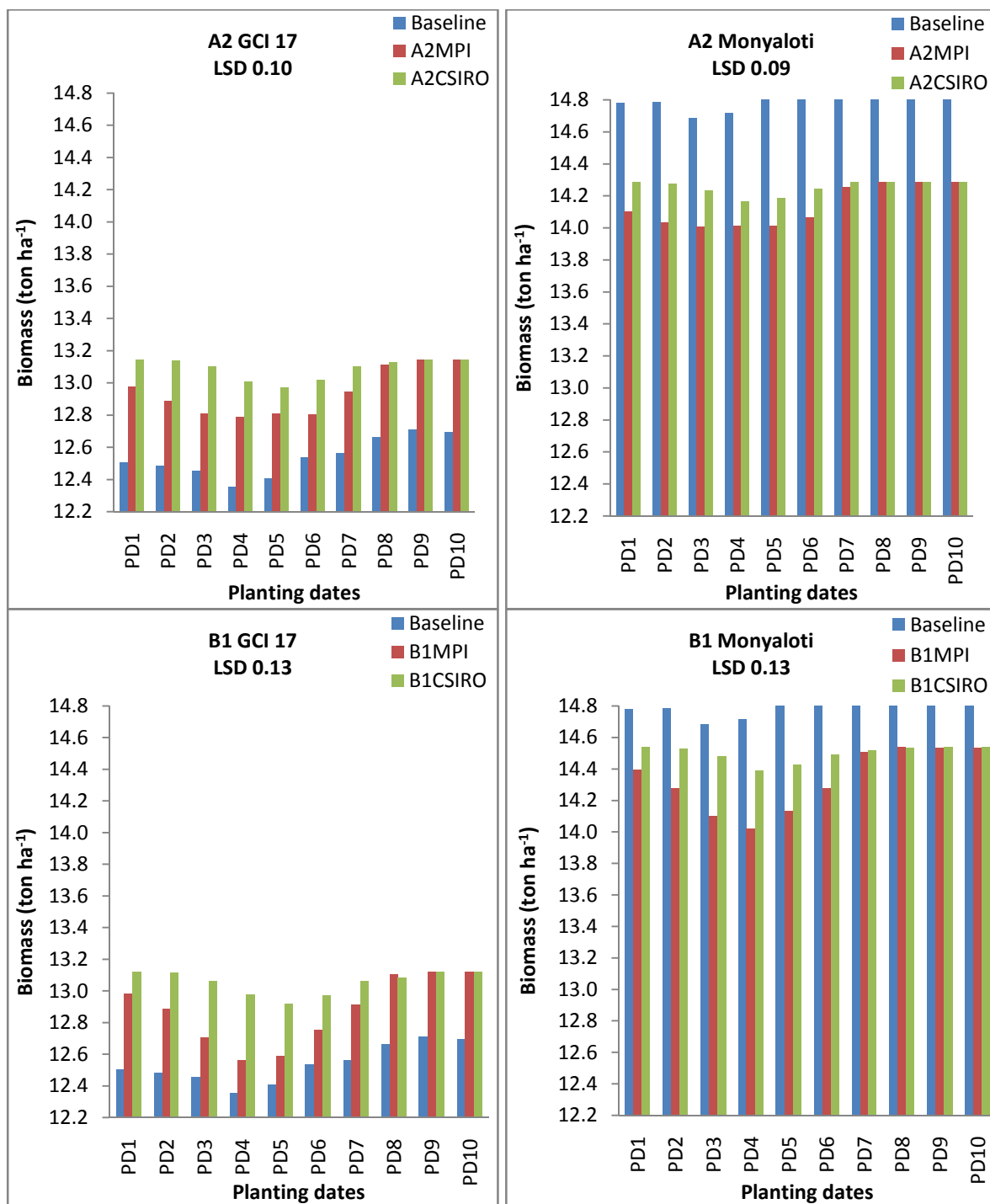
lines of pearl millet planted on PD 4 and 5 of near future will be the lowest compare to the rest of the dates under the climate change scenarios. The amount of rainfall predicted by MPI ECHAM 5 model is lower than that of CSIRO mk3.5 model for both scenarios. Delay in planting dates has been suggested and observed as a means of adaptation strategy by many authors. Khaliq (2008) predicted increase in maize grain yield if planting is delayed up to 30 days in 2020 in all locations, in Pakistan, where their study was carried out. In contrast to the findings of this study, the author also found out that early planting of maize will reduce average grain yield under climate change in 2050. Early planting of GCI 17 in the near future will still produce higher grain yield compare to the baseline condition but delay in planting till PD9 and PD10 will produce higher and equal yield for the two GCMs under both scenarios. Higher grain yield of GCI 17 as a result of delay in planting could be due to the fact that the high rainfall predicted will coincide with flowering period which will reduce water stress that might have been detrimental to the grain formation of the crop.

#### 6.3.3.3 Water use efficiency

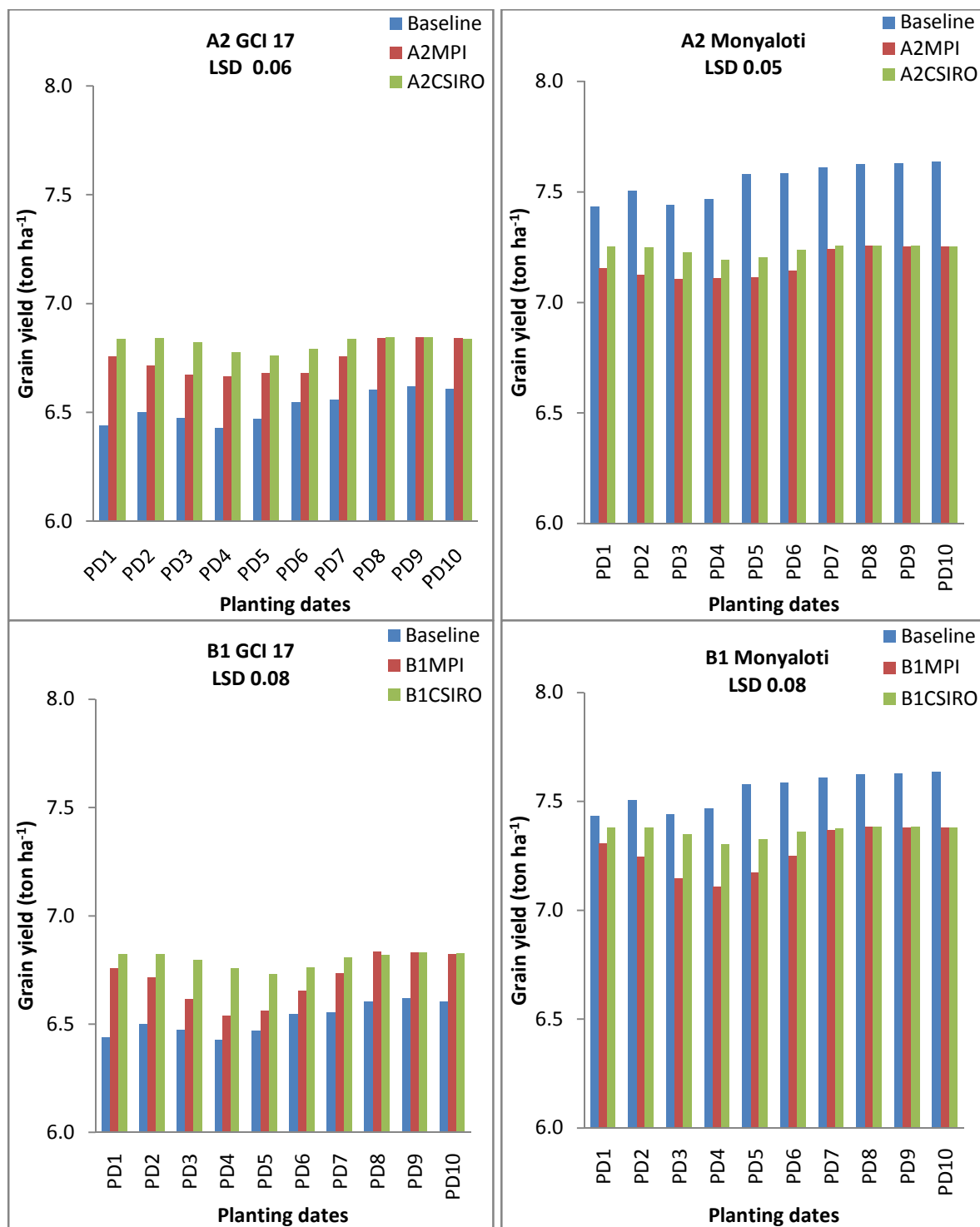
In terms of biomass and grain yield of the two lines of pearl millet, water use efficiency (WUE) of the crop is higher under the baseline condition than the projected climate change scenarios (Figure 6.9). The difference in WUE of GCI 17 under the baseline condition and the projected climate change scenarios are getting reduced as the planting dates shift from PD1 towards PD10. The huge differences in WUE of Monyaloti under baseline condition and projected climate change scenarios are not unexpected as the biomass and grain yield decreases even under a climate that was predicted with high rainfall. Monyaloti has higher WUE of  $2.75 \text{ t ha}^{-1} \text{ mm}^{-1}$  while GCI 17 has WUE of  $2.65 \text{ t ha}^{-1} \text{ mm}^{-1}$  under the same baseline condition. GCI 17 used water more efficiently at the planting date PD1 than any other planting dates while Monyaloti has the best WUE at planting date PD10.

#### 6.3.3.4 Average leaf expansion stress

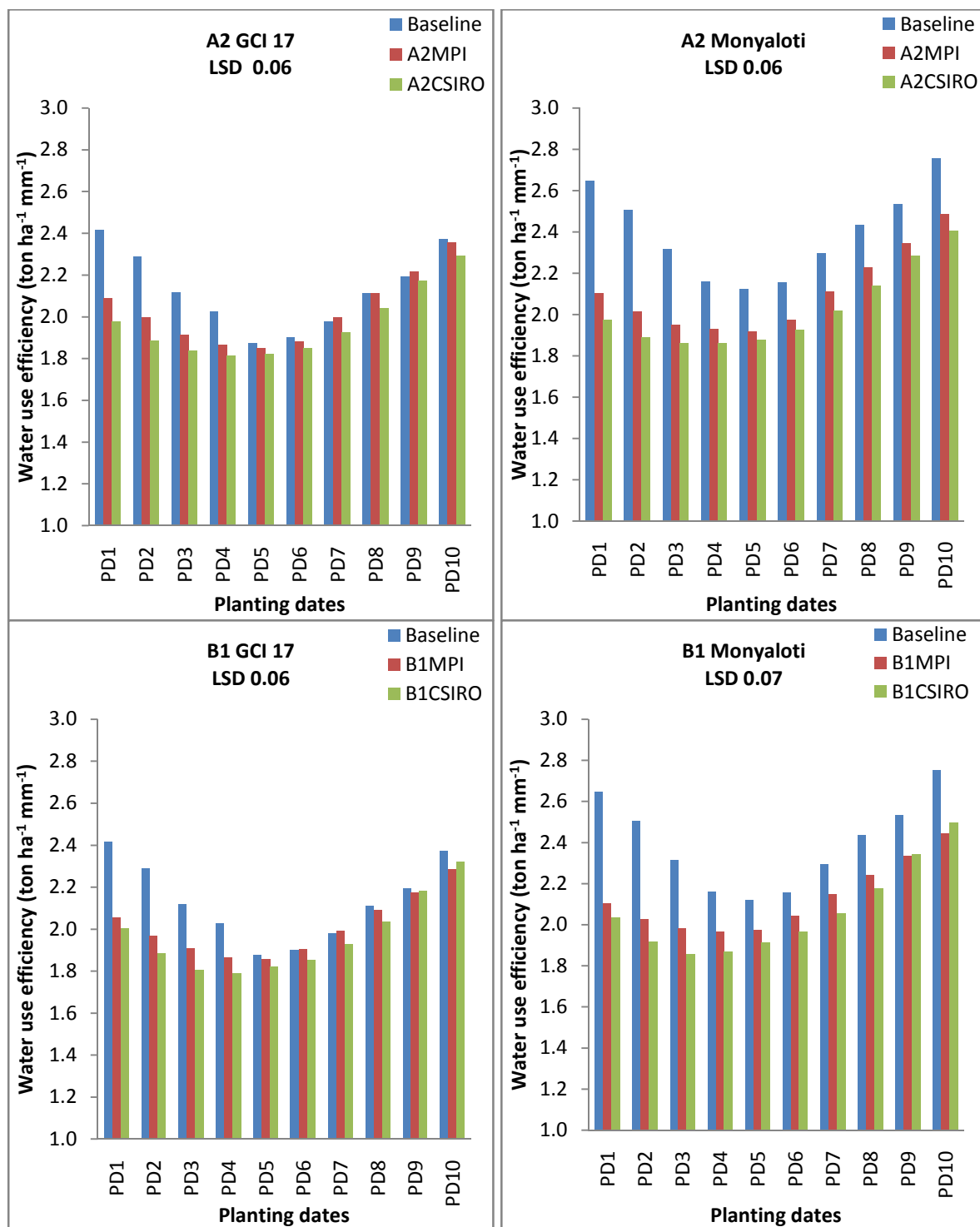
The study of how stress affects leaf development and influences crop growth and development is very important. Presence of stress in plant can be in the form of restriction of expansion of leaf or leaf reaching the stage of senescence prematurely which translates into different effects such as retarded growth and yield reduction in crops. Increased rate of leaf senescence may control duration of grain filling under water stress conditions (de Souza *et al.*, 1997). Figure 6.10 illustrates that GCI 17 experiences more stress than Monyaloti. The stress is more pronounced under baseline conditions for the two lines of pearl millet. However, the highest leaf stress that will be experienced by the line will be under B1 scenario at 0.95% at planting date of PD6. The highest average leaf stress under baseline condition for Monyaloti is 0.90% at planting date of PD6. The leaf expansion stress that will be experienced by Monyaloti under projected climate change scenarios are less than half of predicted leaf expansion stress for GCI 17. High leaf expansion stress recorded for the plantings dates of PD6 and PD7 could be initiated by high evaporative demand during this period.



**Figure 6.7** Effect of climate change on biomass production of the two line of pearl millet under two climate change scenarios. MPI = MPI ECHAM 5 and CSIRO = CSIRO mk3.5 models.



**Figure 6.8** Effect of climate change on grain yield of two line of pearl millet under two scenarios. MPI = MPI ECHAM 5 and CSIRO = CSIRO mk3.5 models.



**Figure 6.9** Water use efficiency of the two lines of pearl millet under climate change scenarios. MPI = MPI ECHAM 5 and CSIRO = CSIRO mk3.5 models.

Drought tolerance level is the main reason for the difference observed between GCI 17 and Monyaloti for average leaf expansion stress. Monyaloti is more drought tolerance than GCI 17 (see Chapter 5). It is suitable to report that MPI ECHAM 5 predicted the highest average leaf expansion stress for the two lines of pearl millet under both scenarios. This could be due to high temperature and low rainfall forecast by this model. It was observed that too low or too high temperature can retard the rate at which plants develop and grow (Ong & Monteith, 1985).

#### 6.3.3.5 Irrigation water requirement

The net irrigation water required for the two lines of pearl millet reflects the rainfall pattern for baseline and the predicted climate change (Table 6.5). Under the two scenarios, CSIRO mk3.5 model predicted higher rainfall under the two scenarios which resulted in lower irrigation required compared to MPI ECHAM 5 model. On an average, Monyaloti require less water than GCI 17 as a result of its higher WUE (see Figure 6.10). The planting date that requires least amount of water for irrigation is PD10 irrespective of the two lines of pearl millet, scenarios and GCMs, it seems that under the new planning in mid-January will be efficient.

#### 6.3.2.6 Water use efficiency (WUE) of irrigated pearl millet

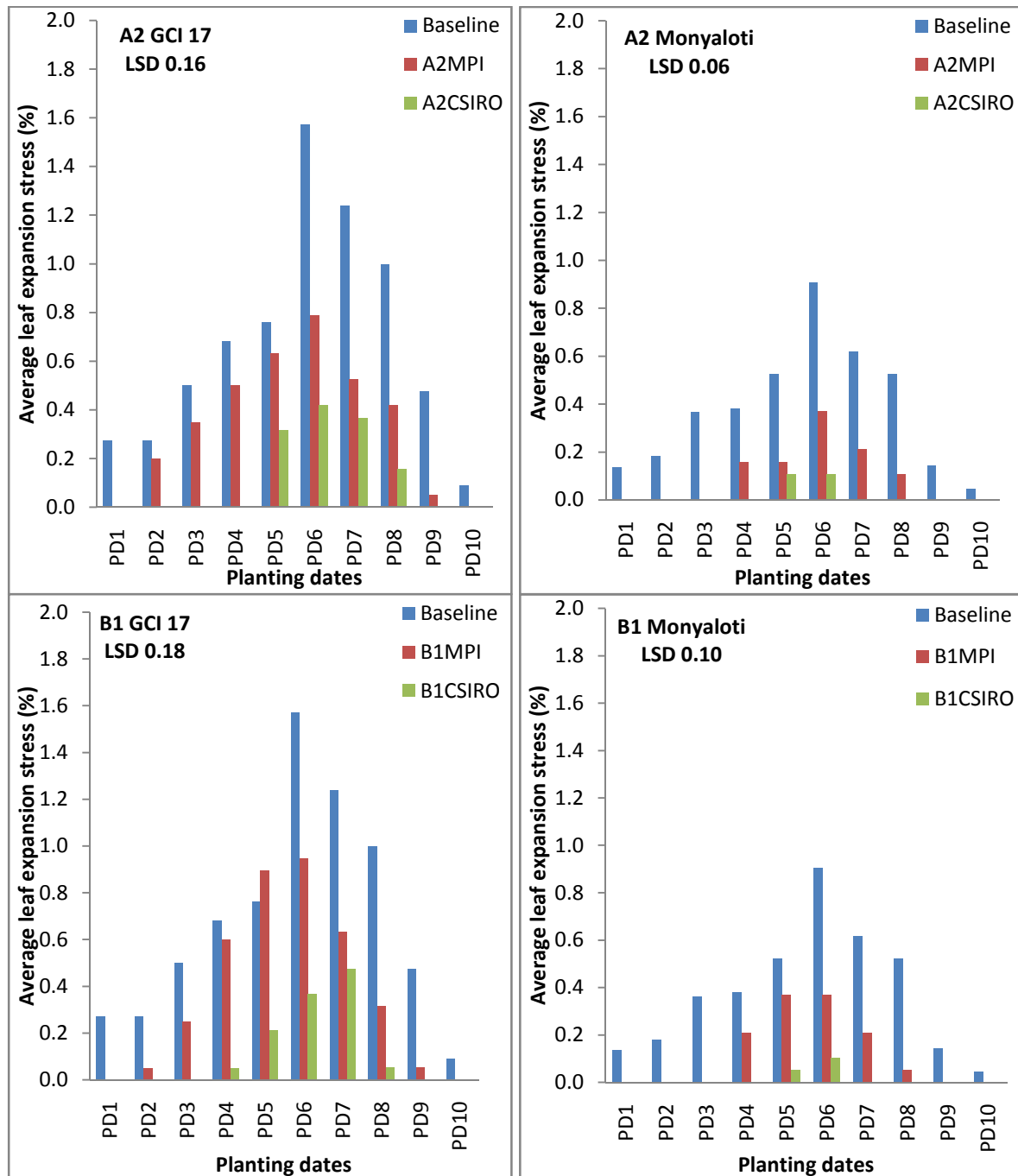
Table 6.6 shows that water use efficiencies (WUE) are significantly different for all the planting dates and low for planting GCI 17 on early season planting, PD4-PD7. The WUE is low as expected for the scenarios with predictions of high rainfall. The WUE of Monyaloti is higher than that of GCI 17 under baseline condition. However, the CSIRO GCM predicted the highest WUE ( $2.5 \text{ t ha}^{-1} \text{ mm}^{-1}$ ) under the B1 scenario at the planting date of PD10 compare to other GCM and scenario.

#### 6.3.3.7 Change in biomass

Due to reduction in biomass production of Monyaloti under projected climate change scenarios, the change in biomass production is negative for all the planting dates. Figure 6.11 shows that percentage increase in biomass production for GCI 17 under A2 scenario can be as high as 5% while the decrease is as much as -6% for Monyaloti under the same scenario. Higher increase in biomass predicted in GCI 17 could be due to the fact that it will be able to complete its life cycle under climate change. Masanganise *et al.* (2012) suggested planting of short season maize variety in part of Zimbabwe as an adaptation measure under climate change to maximise maize production. Planting on PD10 did not give a significant difference of increase from planting on PD 8 and PD9 for GCI 17. Planting on PD5 recorded the largest decrease in biomass under both scenarios for Monyaloti.

### 6.3.3.8 Change in grain yield

Respective increase and decrease in biomass production of GCI 17 and Monyaloti transformed into the same trend for grain yield. Change in grain yield will be positive for GCI 17 and negative for Monyaloti in the near future under the two scenarios (Figure 6.12). The change in grain yield for Monyaloti planted on PD5 will be as large as -5% under both scenarios.



**Figure 6.10** Average leaf expansion stress as imposed by baseline conditions and predicted near future climates on the two lines of pearl millet. MPI = MPI ECHAM 5 and CSIRO = CSIRO mk3.5 models.

**Table 6.5** Irrigation requirements (mm) for the cultivation of the two lines of pearl millet as affected by climate change for baseline condition and predicted near future climates

	GCI 17					Monyaloti				
	Baseline	A2MPI	A2CSIRO	B1MPI	B1CSIRO	Baseline	A2MPI	A2CSIRO	B1MPI	B1CSIRO
PD1	96.43ab	137.00bc	34.60d	162.80bcd	34.50ef	91.83abcd	127.25a	42.70d	145.00ab	34.05e
PD2	84.50abc	127.60ab	93.35dc	170.20ab	51.40ef	99.56bcde	126.40a	50.95cd	152.50ab	42.35de
PD3	102.29abcd	135.30bc	109.95ab	160.60a	85.15def	108.00cde	134.20a	101.10bcd	159.42a	84.90cde
PD4	137.64abc	168.10abc	126.65ab	159.55ab	101.95bcd	135.22cde	133.16a	115.74a	159.63a	107.11abc
PD5	128.71a	160.00a	125.05a	160.00ab	125.89ab	125.61abc	134.32a	125.42a	133.84a	107.84ab
PD6	120.07ab	161.32ab	134.74a	134.68ab	126.63ab	90.50ab	134.89a	108.53a	117.32ab	108.95ab
PD7	103.86abc	135.84ab	127.68a	118.26abc	137.05ab	61.61bcde	100.11a	91.79a	73.11b	119.95ab
PD8	66.14bcd	101.47abc	101.95a	73.84cd	101.79a	65.83de	55.58a	56.05ab	65.26c	65.26a
PD9	74.79d	56.11c	75.26ab	37.63ef	56.32abc	48.94de	18.89b	19.11d	19.05c	9.42bcd
PD10	44.89cd	18.05d	18.25d	18.20f	9.10cde	27.21e	9.15b	0.00e	9.20d	0.00e
LSD	45.62	36.8	44.33	19.53	45.49	45.8	37.38	42.65	35.17	44.32

Values in the same column not sharing the same letter differ significantly at LSD (P=0.05).

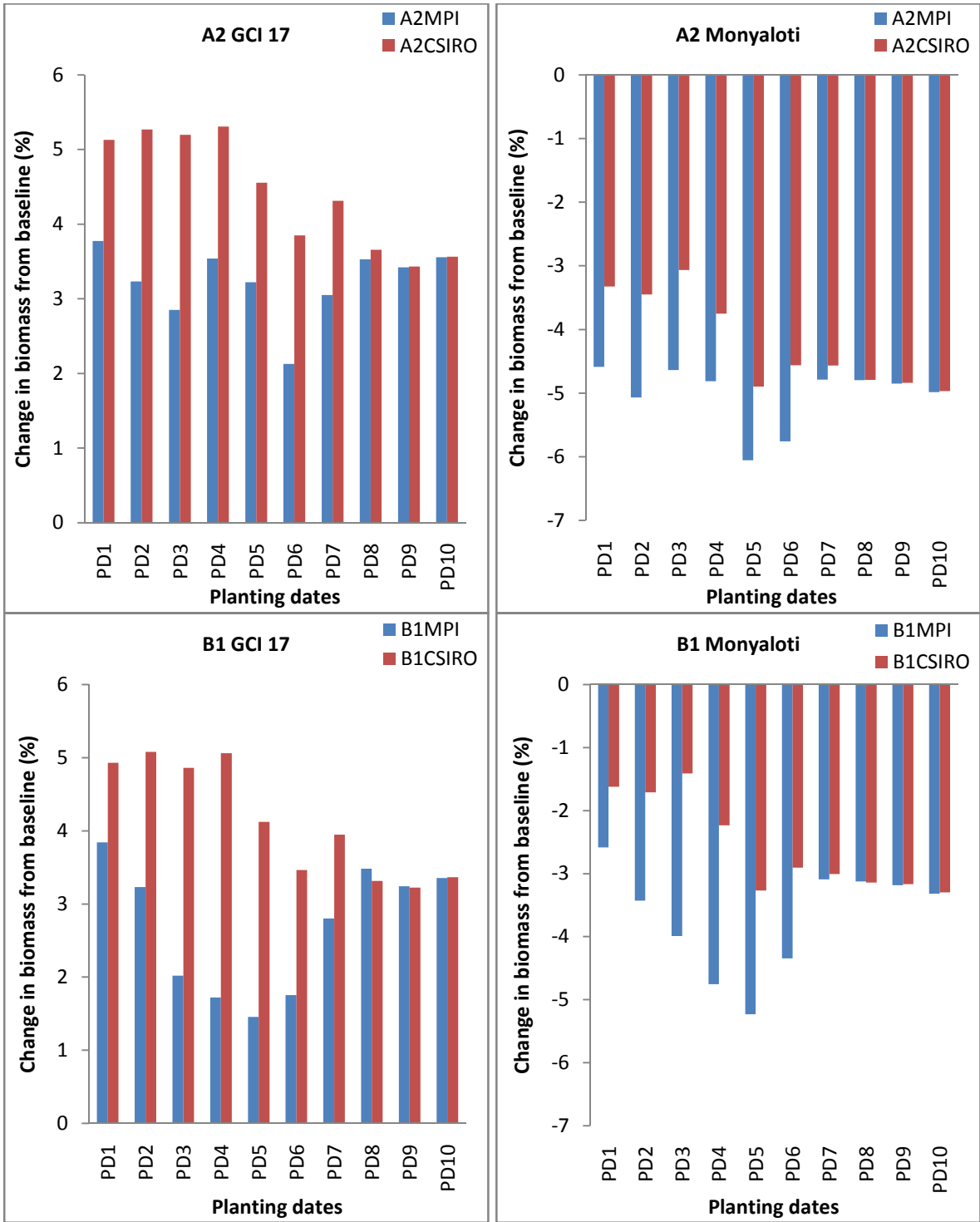
**Table 6.6** Water use efficiency ( $t\ ha^{-1}\ mm^{-1}$ ) of irrigated two lines of pearl millet as affected by climate change for baseline condition and predicted near future climates

	GCI 17					Monyaloti				
	Baseline	A2MPI	A2CSIRO	B1MPI	B1CSIRO	Baseline	A2MPI	A2CSIRO	B1MPI	B1CSIRO
PD1	2.36ab	2.10b	1.98bc	2.06a	2.00a	2.58abc	2.11b	1.97ab	2.11ab	2.04a
PD2	2.23a	2.01b	1.89bc	1.98cd	1.88cd	2.44a	2.02c	1.89cd	2.03cd	1.92c
PD3	2.07ab	1.93c	1.84de	1.93ef	1.81ef	2.26ab	1.96c	1.86de	2.01de	1.86de
PD4	1.98bcd	1.88c	1.82e	1.89fg	1.80f	2.17ab	1.94de	1.87e	1.99e	1.87e
PD5	1.88cd	1.86d	1.83e	1.88fg	1.83f	2.12ab	1.93de	1.88e	1.99e	1.92de
PD6	1.89d	1.90d	1.86e	1.92g	1.86f	2.15c	1.98e	1.93de	2.05e	1.97de
PD7	1.98d	2.01d	1.93de	2.00g	1.93ef	2.29c	2.11de	2.02cde	2.15de	2.06cd
PD8	2.11cd	2.12c	2.04cd	2.09de	2.04de	2.43bc	2.23c	2.14c	2.24c	2.18c
PD9	2.18bc	2.22b	2.17b	2.18c	2.18c	2.52abc	2.34b	2.28b	2.33b	2.34b
PD10	2.36ab	2.36a	2.29a	2.29b	2.32b	2.71ab	2.49a	2.41a	2.45a	2.5a
LSD	0.2184	0.0837	0.0842	0.0773	0.088	0.2254	0.0909	0.0907	0.087	0.097

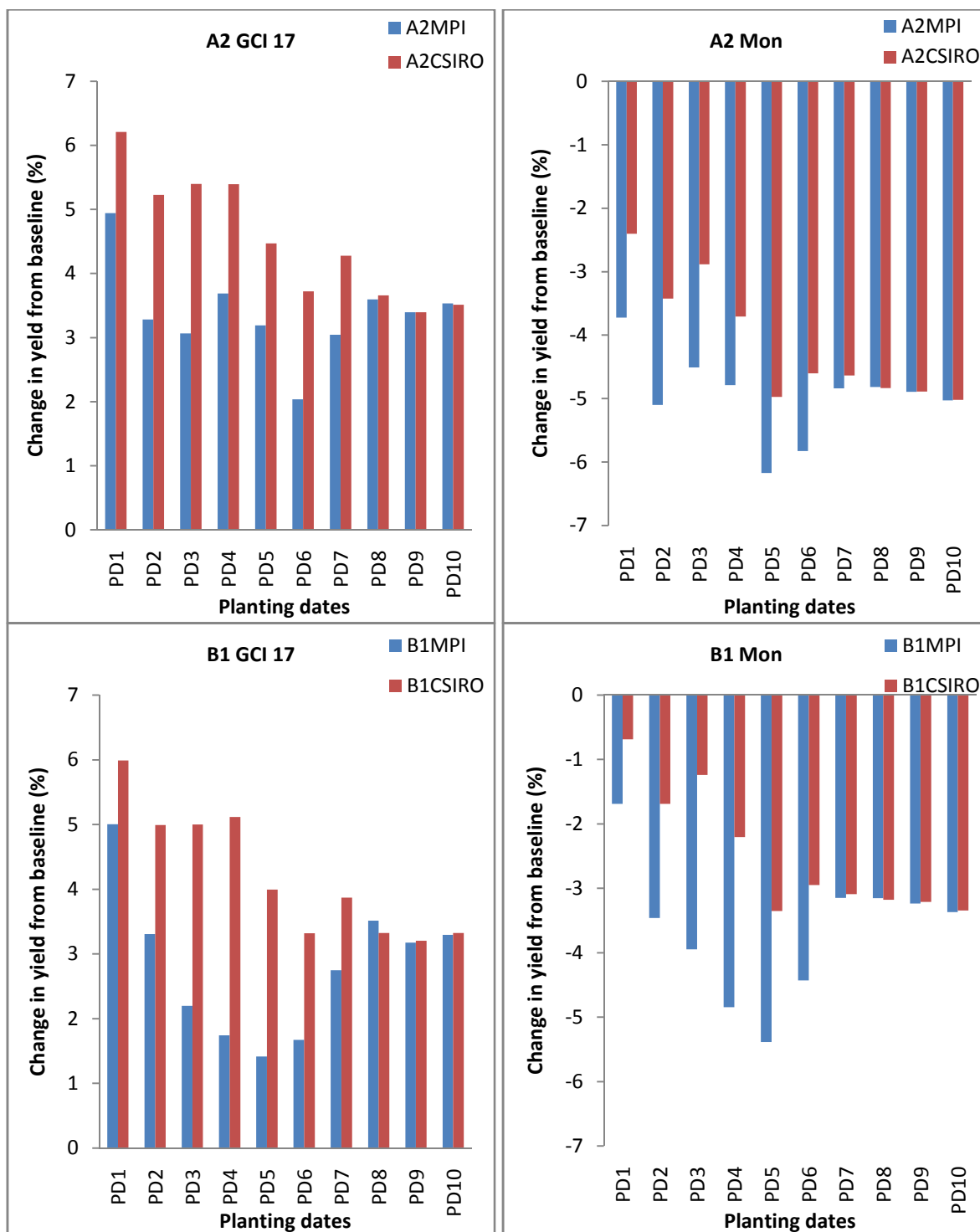
Values in the same column not sharing the same letter differ significantly at LSD (P=0.05).

Differences in performances of the two lines of pearl millet maybe primarily due to their maturity period. GCI 17 matures early and has the ability to avoid dry spells by attaining reproductive stage very early. However, the level of drought tolerance and water productivity (WP) can be used to explain net irrigation requirement in the two lines of pearl millet. Monyaloti is more drought tolerant and has higher WP than GCI 17 (see Chapter 5 for crop characteristics used for creating crop file in the model). AquaCrop has been used in many studies to predict crops performance under climate change. Crops performances under observation include irrigation requirement, evapotranspiration (ET), WUE and most especially yield. Mainuddin *et al.* (2010) used AquaCrop to assess impact of climate change on different crops cultivated in Mekong Basin of Thailand. They observed that under two climate scenarios (A2 and B2), yield of crops under investigation were higher in A2 than B1 scenario. Based on the results from the model predictions, they were able to make recommendations on adaptation strategy for crops under observation for climate change scenarios. Masanganise *et al.* (2012) also used AquaCrop to test the response of maize to climate change. It was concluded that there will be positive impact of climate change on maize production in Zimbabwe and growers were advised to stagger their planting to meet the onset of rain as an adaptation strategy. Results of an investigation by Immerzeel and Droogers (2009) using AquaCrop to study the impact of global climate change on the agriculture on the Bunyala plains, Kenya reveals that elevated CO<sub>2</sub> will influence a substantial impact on crop growth and increase the yield substantially.





**Figure 6.11** Change in projected biomass of the two lines of pearl millet as affected by climate change scenarios MPI = MPI ECHAM 5 and CSIRO = CSIRO mk3.5 models.



**Figure 6.12** Change in projected grain yield of the two lines of pearl millet as affected by climate change scenarios MPI = MPI ECHAM 5 and CSIRO = CSIRO mk3.5 models.

## **6.4 CONCLUSIONS**

Assessment of impact of climate change should be considered as one of the most important application of AquaCrop. The model was able to forecast the trend of performances of amaranthus and pearl millet in terms of biomass production, grain yield, water use efficiency (WUE), and net irrigation requirement. In terms of the response of the two crops to the climate change, amaranthus will respond positively. Improved variety (GCI 17) of pearl millet will increase in biomass, grain yield and WUE while the local variety (Monyaloti) production will decrease in terms of biomass, grain yield and WUE. The simulation results help to identify possible adaptation means for the two crops. For each of the crops, amaranthus and pearl millet, a delay in starting the season (transplanting or planting) to meet the period when the evaporative demand will be lower and thus have more available water under climate change in form of rainfall, will give a favourable result. In order to choose a better line of pearl millet for cultivation under climate change, it is recommended that economic evaluation is also carried out due to the fact that as the improved variety increase under climate change, the increase is projected to be as high as the yield from local variety which is predicted to be decreasing. Another issue is that Monayloti line of pearl millet can be prescribed as forage crop for animal husbandry. This could be a source of forage for animal husbandry under climate change as the decreased biomass is still higher than the increased biomass of GCI 17.

## CHAPTER 7

### GENERAL CONCLUSION AND RECOMMENDATIONS

South Africa is a water scarce country with more than 50% of the available water being used for agricultural purposes. Therefore, water, which is one of the major factors determining food production, is not readily available throughout most of a growing season. Water availability is always considered as a major part of the determinant for the choice of crops to be cultivated in any agroecological zone. Amaranthus and pearl millet, are underutilized indigenous crops – a leafy vegetable and cereal respectively, and are suitable for cultivation in central South Africa because they have drought adaptation attributes. These crops possess potentials to contribute to food security and alleviate poverty through income generation, sustained production with low inputs and increase diversity in the diet. Understanding crop response to water will help in optimising crop water use efficiency in terms of crop growth and development. Therefore, studies were carried out on a field under a line source sprinkler irrigation system, in the greenhouse with a pot experiment and at the lysimeter facility to characterize the water use of amaranthus and pearl millet and to model the growth and yield of these two crops.

In terms of the effect of water application on growth and development of amaranthus, the study revealed that amaranthus under full irrigation needed to accumulate more thermal time to complete its growth and development cycle, than the plants with lower water application. During the first season, plants from the rainfed had the lowest thermal time accumulation to maturity while in contrast during the second season similarly treated plants had the highest thermal time accumulation. It is suspected that the ability to complete growth stages and development with less accumulated thermal time could be a means of coping with the effects of water stress, as the first season for amaranthus recorded a water use than that measured during the second season. Therefore, during the second growing season when the seasonal evaporative demand was higher, the plant restricted growth to avoid excessive water loss. Growth of amaranthus as affected by water application was contrary to expectation that fully irrigated plants will produce better than those receiving less water. Fully irrigated plants produced shorter plants with less leaves and branches. The observation was that plants that received the least irrigation produced larger canopies and more dry mass than the fully irrigated plants. However, there was no clear difference between the water treatments for most of the growth analysis parameters. But the rainfed plants that were assumed to be under water stress exhibited lower specific leaf area which means thicker leaves than the rest of the treatments. This was recognised as a stress coping mechanism in crops to maintain a good photosynthetic factory while restricting water loss.

In pearl millet, it was observed that irrigation affects growth and development positively. Irrigation application was observed to enable the pearl millet crop to complete development in a shorter time during the first season than the rainfed crop. However, the improved line (GCI 17) after accumulating more thermal time, was able to show an avoidance mechanism as a means of water stress tolerance, as it appears that the plant might have delayed growth until a favourable condition resumes. Irrigation did not have any effect on growth parameters such as number of leaves and number of tillers per plant. This could be explained based on the genetic differences of the two lines. However, irrigation positively influenced the plant height in both lines of pearl millet in this experiment. Although, Monyaloti is taller than GCI 17, the plots with large amounts of irrigation applied to both lines produced taller plants while the shortest plants were found in the rainfed plots. Flowering or emergence of the panicle was also affected by water treatments. The flower emerged earlier on the irrigated plots than on the rainfed plots for both lines of pearl millet and during both seasons, thus showing a delay in the reproductive phase to avoid the water stress period. To confirm that irrigation assists growth and development of pearl millet, both lines produced higher leaf area index and biomass when irrigated than the rainfed plots during each season. However, there was no very clear picture to explain growth rates of the two lines of pearl millet as affected by gradient of water applications. This could be due to the fact that there were insufficient sampling dates during the cropping season.

One of the main aims of this study was to investigate the water use of the two crops which was done through physiological and agronomic means. The two crops under investigation exhibited an ability to tolerate water stress which influence the mechanisms of their water uptake and invariably reduced water use. In the field, amaranthus was able to manage water stress through the closure of stomata which was recorded as low stomatal conductance in rainfed plots. Stomatal closure reduces water loss as a response to water deficit in soil-crop-atmosphere continuum. This mechanism was also seen in the pot trial for amaranthus where water stressed plants recorded lower stomatal conductance and reduced relative water content compared to the well watered plants. The ability of the crop to respond to water deficit as seen in this study was supported by other results reported in the literature. A relationship between stomatal conductance and soil water was also determined to represent soil water depletion and the resultant stomatal closure. The total soil water content of the field at 387mm per 1800mm was determined as the threshold point for stomatal conductance of amaranthus in response to water stress. In terms of water use of amaranthus, it was observed for the two seasons that the optimum daily water uptake was between 1.2 and 6.5 mm day<sup>-1</sup>. Weather conditions, available water and crop size are the determinants of this rate of water use. High evaporative demand can increase demand of a crop for water. One of the factors affecting evapotranspiration in crops is canopy cover. Amaranthus with a larger canopy will be able to cover more area and reduce evaporative water loss from the soil surface. Seasonal water use of amaranthus in the field situation was 437 mm for the first

season and 533 mm for the second season for fully irrigated plots while rainfed plots recorded 307 mm and 360 mm water use for the 2008/2009 and 2009/2010 seasons respectively. The difference in water use could be attributed to different evaporative demand recorded for different seasons. Application of water has an influence on production of fresh and dry mass of amaranthus whether considering the weekly harvest of total aboveground plant or serial harvesting done at a specific height for the same plants at regular intervals. It was observed that while water application can increase the production of amaranthus, it must also not be too much to cause nutrient leaching which would result in a lower biomass production of the crop. This was due to the fact that the plots receiving the lowest amount of irrigation water, produced higher fresh and dry mass of amaranthus during both seasons while production in the fully irrigated plots was low for the two seasons. This affected the water use efficiency of the crop so that even in the second season, rainfed plots had the highest water use efficiency for both fresh and dry mass. However, plants in the well watered pots in the greenhouse transpired more water than the stressed plants due to better growth and development which was reflected as higher fresh and dry mass but with little difference in water use efficiency compared to stressed plants.

Pearl millet demonstrated a response to water stress with lower leaf water potential and lower stomatal conductance. During the lysimeter trial, water stress treatments show that more suction will be needed to remove water from the leaf at low stomatal conductance. A relationship was determined between the leaf water potential and stomatal conductance. The crop adjustment to the severe water stress condition was observed in pearl millet with a crop under severe water stress condition having lower leaf water potential than the plants under mild water stress at the same stomatal conductance. In contrast to the observation from the amaranthus field trials, where the daily evapotranspiration of the two lines of pearl millet were different for the two seasons. In the first season, the active range of daily ET was between 2 and 8 mm day<sup>-1</sup> while it was 1 and 6 mm day<sup>-1</sup> for both lines of pearl millet in the second season. The difference could also be attributed to different evaporative demand during the two seasons. The two lines of pearl millet had different total water use during each season. Overall, in the 2008/2009 season, GCI 17 had water use of 309 mm while Monyaloti water use was 414 mm. The water use of GCI 17 for the second season was 401 mm and that of Monyaloti was 457 mm. The soil water content and amount of rainfall were higher in the second season (2009/2010) which might be the cause of higher water use during the second season compare to the first season for the two lines of pearl millet. However, the local variety exhibited higher water use efficiency than the improved line for both seasons. Monyaloti also recorded higher water productivity in producing biomass during lysimeter trials compared to GCI 17. In both lines of pearl millet, imposition of water stress induced higher water productivity especially in GCI 17 plants stressed at grain filling stage. This could be a means of coping with water stress as was reported in the literature. Less water is used and water productivity increased as more biomass is produced per unit volume of transpired water. Crops were

able to reduce water use under water stress as a means of coping with water stress thus increasing the water use efficiency.

Data from the field experiment, greenhouse and lysimeter trials were used in modelling the two crops response to different water regimes. In amaranthus, simulating canopy cover was a challenge and this could be related to the planting method which was transplanting. The transplanted seedlings might not be able to recover at the same rate because of transplanting shock which might slow down the canopy cover development. This was especially noticeable in simulation of canopy cover of the rainfed crop. Apart from this, biomass and cumulative evapotranspiration were well simulated with a good index of agreement by the calibrated AquaCrop model. However, AquaCrop could be improved to include the option of serial cuttings or harvesting so as to more closely simulate the harvesting of green leafy vegetables. Simulation of canopy cover, biomass production and cumulative evapotranspiration of pearl millet performed adequately well. The good performance in simulating these crop parameters was illustrated by the high index of agreement. In both crops, simulating soil water content performed poorly which was suspected to be due to the use of values of maximum rooting depth for the two crops obtained from the literature. The AquaCrop model has the potential to be used as a decision support tool to increase water productivity and to study different scenarios and management conditions of amaranthus and pearl millet cultivations. The ability of the AquaCrop model to simulate more precisely the growth and yield of these two crops with limited inputs and simplicity makes it user friendly and preferable to other more complex crop simulation models.

The model was used to assess impact of climate change on the production, and predict effects of adaption options for amaranthus and pearl millet following the calibration and validation process. The crop parameters that were used to assess the impact involve biomass, water use efficiency, irrigation water requirement under climate change, leaf expansion stress and change in biomass with climate change. A series of planting dates was investigated as a means of adaptation under climate change and the above output parameters were predicted with the model. For pearl millet, the choice of a preferable line was also an adaption option during the prediction exercise with AquaCrop model. AquaCrop predicted higher evaporative demand for the future climate dataset under all the scenarios compared to present climate. However, there will also be an increase in biomass production, lower water use efficiency, more leaf expansion stress and higher water requirement under most of the climate change scenarios for amaranthus cultivation. The model predicted an increase in biomass and grain yield for GCI 17 and a lowering for Monyaloti. This observation could be due to different growing season length of the two lines of pearl millet. For both lines of pearl millet, water use efficiency and leaf expansion stress will be lower under the climate change scenarios than the baseline conditions resulting in a larger amount of irrigation water being required. It can be deduced from the results of the model predictions, that a delay in transplanting amaranthus and planting pearl millet for

two months under the climate change scenarios will be more beneficial, as it avoids the period of high evaporative demand..

This study revealed that the two crops (amaranthus and pearl millet) can adjust to water limited conditions through manipulation of their growth and development. Growth restriction was observed in amaranthus to avoid water stress conditions while pearl millet used avoidance and escape mechanism to reduce the effect of water stress. These mechanisms in pearl millet can be observed with rapid vegetative growth and prolonged flowering duration of rainfed plants in both lines of pearl millet. The coping mechanism for both crops under water stress condition helps in reducing water use and at the same time increasing the water use efficiency while the beneficial impact of irrigation on their production is feasible. These attributes exhibit the possibilities of cultivating these two crops in central South Africa, a semi-arid region of the country. This should be a step towards promoting the cultivation of the two crops in this part of the country and can be recommended as an alternative crop for farmers because of its low input requirements. AquaCrop was able to adequately simulate the growth and development of the two crops with a limited number of inputs. This model will help in accurately quantifying water requirements for these crops under different environmental conditions. It is also a good decision support tool as it was seen in its application to predict the production of the two crops under climate change.

In future, further research should include investigation on effect of interaction of nutrient and irrigation on amaranthus production which might reveal the reasons for the observed response of amaranthus according to the quantity of applied water. Choice of planting dates should be re-visited to be able to make recommendations in accordance with the seasonal forecasts. For AquaCrop, more studies are needed on root development of the two crops so as to input an actual value for the rooting depth parameter of the model. This might help in simulating water balance of the two crops in the field situation. The better simulation of early canopy expansion for transplanted seedlings is another area where future research can focus to improve the representation in AquaCrop. As it was done for pearl millet, more varieties or genotypes should be included in calibration and validation exercises with the model for amaranthus. The calibration and validation of AquaCrop for these two crops can also be improved by employing datasets from other agroecological region.



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