WATER-USE AND DROUGHT TOLERANCE OF SELECTED TRADITIONAL CROPS

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EXECUTIVE SUMMARY

At the dawn of agriculture, about 8000 B.C., the population of the world was approximately 5 million. Currently, we have a challenge of feeding about 7.06 billion people in the world. According to the Food and Agriculture Organisation of the United Nations (FAO), by 2075 there will be about 9.5 billion people in the world. This means over 2.5 billion more mouths to feed in a period when substantial changes are anticipated in the wealth, calorific intake and dietary preferences of people in developing countries across the world. Such a projection presents mankind with wide-ranging social, economic, environmental and political issues that need to be addressed today to ensure a sustainable future for all. One key issue is how to produce more food in a world of finite resources.

Today, about 1 in 50 million South Africans suffer from hunger every day. This has a direct negative consequence on their food security. It is encouraging though that in the country, the Water Research Commission (WRC) has for many years now led the way in identifying indigenous crops as having a potential to reduce food insecurity. These efforts, together with those of the Department of Science and Technology, the Department of Agriculture and Forestry and the National Development Plan (especially Chapter 6) of the government of South Africa, are encouraging. In a way, there is a demand for agricultural and other scientists dealing with crop production, food security and human livelihoods to come up with innovative strategies to grow crops under environmental challenges of climate change and limited germplasm.

The agricultural landscape of South Africa in many ways reflects the dominance of modern crops that originated from outside of Africa. Their rise has led to a decline in cultivation and knowledge about indigenous crops. Recent interest in new crops globally and in South Africa (notably through the efforts of the Water Research Commission of South Africa and the Department of Science and Technology), has increased. The complexity of the problem posed by water scarcity, climate change and population growth requires unique solutions, or rather a new way of thinking. Indigenous crops have the potential to fill this gap and be possible future commercial crops. However, what is required to propel these indigenous crops from the peripheries of subsistence agriculture to the promise of commercial agriculture is scientific research that produces databases for use by farmers. Among the essential knowledge base is reliable information about water utilisation by indigenous crops with potential for commercialisation. This information is essential since South Africa is a water-scarce country, whereby the majority of subsistence farmers requiring assistance to transition to small-scale and/or large-scale commercial farmers reside in areas characterised by non-irrigable terrains and low rainfall. Very few of them have access to irrigation water. The progress made on water relations for modern crops suggests that progress can also be made to develop water use models for indigenous crops, which have, hitherto, been left out of this area of research because of lack of basic knowledge about their agronomy.

The initial task of this project was to identify and characterise indigenous and conventional food crops with agronomic potential in South Africa. This was done taking into consideration *inter alia*, (i) what can grow where under water scarce conditions, (ii) water requirements and crop responses to water stress (iii) production yield under water stress conditions. This was done through a detailed review of scientific and grey literature on indigenous and indigenised crops. The review was guided by the need to understand agronomic practices applied to these crops in South Africa and elsewhere, especially under dryland production. The review identified the following the crops as fitting this category: Traditional maize landraces, wild watermelon, wild mustard, cowpeas, amaranth, pearl millet, bambara groundnut, and taro. These crops were selected to include a wide range of crop groups from leafy vegetables, tuber crops, cereal crops and grain legumes.

A series of trials, including controlled, field and rainshelter experiments, were conducted in three provinces of South Africa, namely KwaZulu-Natal, Free State and Gauteng. The overall objective of the experiments was to understand the agronomy of these crops and determine whether or not they were drought tolerant. This included understanding their water use and water productivity. Modelling of selected crops to determine performance under dryland conditions was another secondary objective. The secondary objectives allowed for a more detailed understanding of crop response to natural and simulated drought tolerance. To a limited extent, physiological indices such as seed germination and proline accumulation were also used to link crop characteristics to drought tolerance under field and controlled environment conditions. It was also in this context that a novel approach was used, one which used the variegated nature of landraces as a basis of selecting for drought tolerance. This involved the use of seed colour as a possible selection criterion for drought tolerance in the cereal crops and grain legumes. The studies on crop water use were diverse and represented current trends in determination of yield response to water availability. These included water use efficiency (WUE) and water productivity (WP) as distinct parameters indicating yield response to water availability.

A novel approach of the project was to select at least four crops that could be used to develop a crop model for indigenous crops. This was challenging because most existing models are based on the agronomy of major crops, with known responses to irrigation. To achieve the objective of developing a new model, the FAO's AquaCrop model released in 2009 was selected and tested for the first time on indigenous crops. The advantage of the model is that it is less complex compared with other existing ones with regards to its requirements for parameterisation. In addition, this model was particularly developed for the sole purpose of simulating yield response to water under water limited conditions. Furthermore, AquaCrop represents a new perspective in the understanding of crop water relations from the FAO Irrigation and Drainage Paper No 33, right to Paper No. 56 and now Paper No. 66. Most knowledge in circulation today on crop water use and irrigation scheduling has been largely based and influenced by these publications. The selected crops for this part of the project were amaranth, bambara groundnut, taro, and pearl millet. While the model contained generic files that could be used to describe amaranth, bambara groundnut and pearl millet, its default file for root and tuber crops was not particularly suited for the unique growth pattern of taro – an aroid.

Over a period of five years, this study achieved the overall objective of providing agronomic information about the response of selected indigenous crops, indigenised taro and traditional maize to management under field and controlled environment conditions when water is limited. The specific findings of the study were: (a) Seed coat colour as an important morphological characteristic, (b) Potential drought tolerance in maize landraces exists, (c) Wild watermelon is a potential drought tolerant crop, (d) Wild mustard tolerance to drought is moderate, (e) Cowpea drought tolerance is associated with seed coat colour, (f) Bambara groundnut drought tolerance is associated with seed coat colour, (g) Taro is an important dryland crop of the subtropics, (h) Pearl millet and amaranth studies explained the concepts of water productivity and water use efficiency of underutilised crops, (h) Pearl millet and amaranth studies explained the concepts of water productivity and water use efficiency of underutilised crops. Future studies should combine plant physiology, agronomy and livelihoods to address agronomic potential and food insecurity.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFLP	Amplified Fragment Length Polymorphism,
ARC-ISCW	Agricultural Research Council – Institute for Soil, Climate and Weather
ARC-VOPI	Agricultural Research Council – Vegetable and Ornamental Plants Institute
CCI	Chlorophyll content index
DAP	Days after Planting
DWAF	Department of Water Affairs
FAO	Food and Agriculture Organisation
IWMA	International Water Management Institute
KZN	KwaZulu-Natal
LAI	Leaf Area Index
RAPD	Random Amplified Polymorphic DNA
RSA	Republic of South Africa
SC	Stomatal Conductance
SSR	Simple Sequence Repeats
UKZN	University of KwaZulu-Natal
WAP	Weeks after Planting
WRC	Water Research Commission

CHAPTER 1

INTRODUCTION AND STUDY OBJECTIVES

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1.1 Background

South Africa is one of the 30 driest countries in the world (The Water Wheel, 2007), with an annual average rainfall of less than 500 mm, a significantly lower amount than the world annual average of 860 mm (DWAF, 2002). According to the National Water Act No. 38 (RSA, 1998), South Africa's water resources are scarce and limited in extent. Climate change forecasts have also predicted an increased frequency and intensity in the occurrence of droughts (Petit *et al*., 1999; Hassan, 2006). This is of great concern when viewed within the context of the impacts all this will have on agriculture, and the vulnerability of rural households and the urban poor, regarding food and nutrition security, because the incidence of crop failure will likely increase (Sisulu & Scaramella, 2012). The concern has led to renewed focus on identifying and improving underutilised indigenous and traditional crops for drought tolerance (Mabhaudhi, 2009). In the past decade, the Water Research Commission (WRC) of South Africa has made significant contributions to support research into these crops. This project is one such effort by the WRC to develop and increase the quantity and quality of available information describing drought tolerance and water-use of indigenous food crops.

Underutilised indigenous and traditional crops can be defined as crops that have either originated in South Africa or those that have become "indigenised" over many years (>10 decades) of cultivation as well as natural and farmer selection within South Africa (Schippers, 2002, 2006). In addition, these are crops that have not been previously classified as major crops, have previously been under-researched, currently occupy low levels of utilisation and are mainly confined to small-scale farming areas (Azam-Ali, 2010). Historically, such crops have played an important role in ensuring community and household food security through providing healthy alternatives when the main crop failed or during periods in-between subsequent harvests. Most of these crops are believed to be adapted to a range of ecological niches and may have tolerance to abiotic and biotic stresses, chiefly heat and water stress. This makes them important future crops for small-scale farmers on marginalised lands and an important germplasm source for future crop improvements.

Promotion of neglected underutilised crops, with a view to reinstating them as alternative food sources in agriculture will depend, to a large extent, on availability of information describing their agronomy, water-use and possible drought tolerance. To achieve this, within the limited time framework available, there is need to combine conventional and modern techniques such as crop modelling that will allow for cost-effective generation of quality information. In the absence of extensive agronomic trials, the use of calibrated and validated crop models may assist to generate such information. In sections below, the project was contextualised by describing what underutilised crops are, the diversity they represent, their current status in terms of utilisation as well as their known drought tolerance. This led up to the objectives of the project as stipulated by the WRC.

1.2 Underutilised indigenous and traditional crops

The reduction in genetic diversity caused by focus on few staple crops has resulted in the occurrence of neglected underutilised species (NUS). Unlike most staple crops, NUS are often well-adapted to local growing conditions (Padulosi, 1998), which are often marginal and harsh, thus offering sustainable food production (Idowu, 2009). Within the context of this project, NUS consisted of crops that are indigenous or have been "indigenised" in South Africa. Based on the definitions forwarded by Schippers (2002, 2006), indigenous crops are those that have originated in South Africa while "indigenised" species are those that originated outside of South Africa, but have become domesticated over hundreds of years of on-farm cultivation and selection. Neglected underutilised species that are indigenous to South Africa include many *Amaranthus spp* (Laker, 2007), wild mustard (*Brassica spp*) and other wild edible leafy vegetables (Modi *et al*., 2006) while "indigenised" NUS comprise sweet potatoes (*Ipomoea batata*), wild melon (*Curcubita spp*), taro (*Colocasia esculenta*) and bambara (*Vigna subterranea*). Historically, these crops have provided dietary support to local communities. However, the promotion of "major" crops, even in less suitable areas at times, has relegated them to their current status as NUS.

As already established, South Africa is a water-scarce country; more than 80% of the country is classified as hyper-arid to semi-arid (Bennie & Hensley, 2001). Water availability is a major limiting factor to crop production, threatening food security of vulnerable groups. Although previous studies have classified South Africa as being food secure (De Klerk *et al*., 2004), there is consensus that a large proportion of South Africans are vulnerable to household food insecurity and malnutrition (Steyn *et al*., 2001; Rose & Charlton, 2002; De Klerk *et al*., 2004). In addition, there is concern that none of the major crop plants are adapted for cultivation under water stressed conditions (Baye *et al*., 2001).

The importance of many indigenous species should not be neglected (Prescott-Allen & Prescott-Allen, 1990). Neglected underutilized crop species are often described as "drought tolerant" (Zeven, 1998) and could therefore prove vital in fighting hunger. However, limited information describing basic aspects of their genetic potential, agronomy, water requirements and nutrition remains a hindrance to their development and promotion. Such information may be available in "grey literature" and/or indigenous knowledge systems, both of which are unavailable to scientists. The focus of this project was therefore to develop scientific knowledge describing the genetic potential, agronomy and water requirements of selected NUS in South Africa. The different NUS covered by the project are briefly described below.

1.2.1 Amaranth

Amaranth (*Amaranthus* spp) is an annual C4 crop that grows optimally under warm conditions (Van Heever & Coertze, 1996; Maboko, 1999; Schippers, 2000). In South Africa, amaranth is rarely cultivated because of the belief that it grows naturally, although it has potential to be developed as a cultivated crop (Jansen van Rensburg *et al.,* 2007). The leaves of amaranth have high protein, vitamins and mineral content (Makus & Davis, 1984). Amaranth is considered as a promising crop for cultivation in marginal, arid and semi-arid regions because of its nutritional benefits and ability to adapt to adverse environments (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).

Figure 1.1: *Amarunthus cruentus* growing under field conditions at the University of Free State's Kenilworth Experimental Farm.

Amaranthus spp are known to be tolerant to adverse climatic conditions (Grubben, 2004; Maundu & Grubben, 2004). Amaranth is also known to be moderately tolerant to salinity stress which can help the plant in semi-arid regions as well as areas prone to salinity stress (Omami, 2005). One of the strategies used by the crop to tolerate salinity is efficient use of water. Rapid leaf area development and high stomatal conductance, rapid root and shoot growth after germination are part of the features that ensure the crop uses available soil water efficiently (Liu & Stutzel, 2002). Though, amaranth can cope with adverse conditions, supplementary irrigation and fertilization will increase fresh and dry mass (Akparobi, 2009). The fact that in South Africa cultivation of amaranth is limited in extent and scale means that there is also limited information describing drought tolerance and water-use of local *Amaranthus* spp.

1.2.2 Bambara

Bambara groundnut (*Vigna subterranea)* (Figure 1.2), also known as *Nyimo* in Zimbabwe and *Jugo* beans or *Izindlubu* in South Africa, originated in North Africa and migrated with indigenous people to South Africa. It is an annual legume with a strong well-developed tap root system. Their name originates from Bambara, a district on the upper Niger near Timbuktu. Traditionally, bambara groundnut was cultivated, mainly by women (Mukurumbira, 1985), in semi- and arid regions (Mwale *et al.*, 2007a) where water is usually in short supply, without access to irrigation and/or inorganic fertilizers and with little guidance on improved practices. It is for the sustenance of their families. Within these communities, bambara groundnut played an important role as a protein source (Linnemann & Azam-Ali, 1993). Its protein content (16-25%) is comparable, and in some instances, superior to other established legumes, making it a good complement for cereal-based diets (Linnemann & Azam-Ali, 1993; Mwale *et al.*, 2007a). As a legume, bambara also replenishes nitrogen in the soil through nitrogen fixation, an ability that may be of importance to resource-constrained farmers who may otherwise not be able to afford inorganic nitrogen fertilizers.

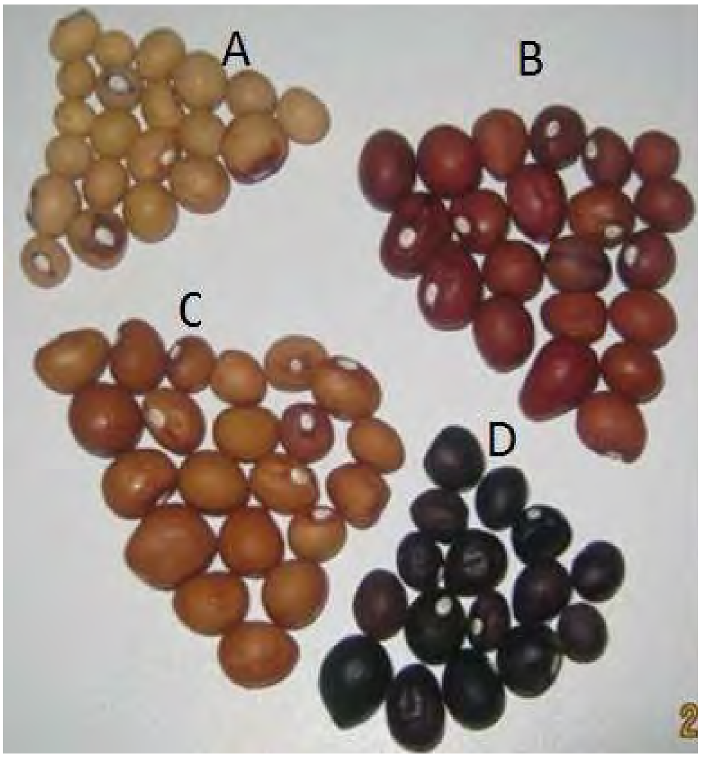

Figure 1.2: Different seed colours occurring in local bambara groundnut landraces; A – Light-brown, B – Red, C – Brown, and D – Black.

However, due to the expansion of groundnut (*Arachis hypogea*) production, bambara groundnut has been relegated to the status of an underutilized crop in most parts of Africa (Swanevelder, 1998). As such, its germplasm improvement and management practices have mainly relied on local experience and resources (indigenous knowledge) (Mukurumbira, 1985). Seeds of bambara groundnut, as with many landraces, also vary in colour (Figure 1.2) with cream, brown, red, mottled and white being dominant (Swanevelder, 1998). Although bambara is widely reported to be drought tolerant, there have been no local studies to verify the presence and extent of such tolerance in local South African landraces of bambara. In this project, seed colour was used as a criterion for selecting bambara for drought tolerance.

1.2.3 Cowpea

Cowpea (*Vigna unguiculata*) (Figure 1.3) is a legume crop that belongs to the *Fabacea*, family formerly known as *Leguminosae* (Verdcourt, 1970). It is one of the oldest crops known to man with its centre of origin and domestication being closely related to pearl millet and sorghum in Africa. Cowpea is an important legume which serves as an important source of protein in the diets of vulnerable populations (El-Jasser, 2011). It is a warm season, annual, herbaceous crop of either an erect, semi-erect (trailing) or climbing growth habit. Cowpea thrives in arid and semi-arid conditions and is produced in areas with optimum rainfall conditions of 400 to 700 mm per annum (DAFF, 2011). Leaves can be consumed as vegetables, while seeds are eaten in the same manner as sugar beans.

Figure 1.3: Cowpea seed (Left: black-eyed cowpea) and a cowpea plant (right) at the flowering stage of growth.

Cowpea has a long taproot, reaching a maximum effective rooting depth of about 2.4 m within eight weeks after planting, which proves beneficial in the event of drought and nutrient mining. Research on cowpea has recently started to emerge; however, it is still considered as a neglected underutilised species based on social and economic restrictions imposed on its production. Although it has been widely reported to be drought tolerant, there is limited South African research confirming such drought tolerance for local cowpea varieties.

1.2.4 Maize landraces

Of the many crops grown in South Africa (SA), maize (*Zea mays* L) (Figure 1.4) is one of the staple foods. Maize (*Zea mays,* L.) belongs to the family Poaceae (Gramineae) and the tribe Maydeae (Sikandar *et al*., 2007). Although maize may have its ancestry outside of Africa, it has been around for so long and has become "indigenised" as a result of hundreds of years of farmer and natural selection. Early Portuguese merchants introduced maize into Africa through their trade networks along the eastern and western coasts of Africa starting in the 16th century. The Dutch introduced maize along the southern African coast in 1658 (Miracle, 1966). The Afrikaans word for maize, "*mielie*" is a translation of the Portuguese word *milho*, meaning grain (Burtt-Davy, 1914).

Figure 1.4: Maize landraces growing in the field at Ukulinga research Farm (left) and maize landrace seed (right) collected from subsistence farmers in KwaZulu-Natal. Maize landraces still show much variation with regard to seed colour.

These varieties formed the now local maize populations or landraces (Figure 1.4). Zeven (1998) defined landraces as crop genetic resources that have evolved continuously under natural and farmer selection practices rather than in the collection of gene banks or plant breeding programs. Historically, landraces were the progenitors of modern crop varieties. Small-scale farmers in traditional farming systems of KwaZulu-Natal and other provinces of South Africa continue to cultivate maize landraces which they have kept from generation to generation. Although these farmers are still planting maize landraces to this day, there has been little or no research to characterize these landraces with respect to drought tolerance and adaptability to water stress.

1.2.5 Pearl millet

Pearl millet is an example of indigenous cereals found mainly in the northern and western part of South Africa. This crop may have been 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). In South Africa, cultivation of pearl millet is majorly at subsistence level by smallholder farmers. It is only grown commercially as forage for animal consumptions in some areas (DAFF, 2011). 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 cultivation is deep, well-drained soil. Pearl millet is easy to cultivate and can be grown in arid and semi-arid regions where water is a limiting factor for crop growth (Naeem *et al.,* 2007). However, it responds very favourably to slight improvements in growing conditions such as supplementary irrigation (Leisinger *et al*., 1995).

Figure 1.5: A field crop of pearl millet growing under field conditions at the University of Free State's Kenilworth Experimental Farm.

Pearl millet is called a "high-energy" cereal as it contains higher oil content than maize grains; its protein and vitamin A content are also higher than maize (International Crops Research Institute for the Semi-Arid Tropics, 2004; National Research Council, 1996). Compared with other staple grains such as maize, wheat and sorghum, pearl millet is less susceptible to pests and diseases (National Research Council, 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 was spreading of sensitive stages of the crop's development in order to avoid the hazards of drought that occur during the season. In the case of early relief of drought, recovery of leaf growth supports good grain filling in productive tillers in order to limit the yield losses in the main shoot of pearl millet (Winkel *et al.,* 1997).

1.2.6 Taro

Taro [*Colocasia esculenta* (L.) Schott] (Figure 1.6) belongs to the family *Araceae*, sub-family *Aroideae* (Lebot, 2009). It is one of the few edible species in the genus *Colocasia* (Ezumah, 1972) and is the most widely cultivated species in it (Vinning, 2003). Leaves and corms (Figure 1.6) of taro are edible and are a rich source of carbohydrate, vitamins A and C, and protein. In South Africa, taro is a traditional "indigenised" crop that like many traditional crops is neglected and underutilized.

Its Zulu name is *amadumbe* and the crop is most common along the coastal areas and hinterland of KwaZulu-Natal (KZN) province (Modi, 2004). There has been an increase in taro production owing to improved access to niche markets. However, there have not been local studies investigating the drought tolerance and water-use of some of the landraces currently being cultivated. With improved information availability, taro production as well as its commercialisation may be expanded beyond current levels.

Figure 1.6: Two taro landrace varieties from KwaZulu-Natal: Left) Var. *esculenta* – dasheen with one main corm and a *huli* used as planting material and, Right) Var. *antiquorum* – eddoe with numerous side cormels.

1.2.7 Wild mustard

Wild mustard [*Brassica juncea* (L.) Czern & Coss and *Brassica nigra* (L.) W.D.J. Koch] (Figure 1.7) is an indigenous leafy vegetable of South Africa and belongs to the family of *Brassicaceae* or *Crucefereae* (Dixon, 2007). It is cultivated under diverse environmental conditions and is of great importance to the nutrition and livelihoods of rural South Africans. Wild mustard, like many other indigenous leafy vegetables, provides essential vitamins, trace elements (iron and calcium) and other nutrients that are important for good health (Chweya & Eyzaguirre, 1990). The seeds also have high oil and protein content (Burton *et al*., 1999), although this is dependent on environmental conditions (Walton, 1999).

Figure 1.7: Wild mustard landraces growing in the field at Ukulinga Research Farm, Pietermaritzburg. The crop picture was taken at flowering prior to harvesting.

B. juncea has been reported to establish quickly, thus achieving optimum ground cover. According to Woods *et al*. (1991), this growth characteristic is a good stress avoiding mechanism especially in water limited environments. Current information on the crops husbandry is locked up in indigenous knowledge systems and similar to wild watermelon; there has been very limited scientific research on the crop. Hence wild mustard has obtained a place as one of South Africa's' neglected underutilized species.

1.2.8 Wild watermelon

Wild watermelon (*Citrullus lanatus* L.) (Figure 1.8) is a native crop of southern Africa. David Livingstone, an early explorer of Africa, described it as abundant in the Kalahari Desert, where it is believed to have originated. There, the ancestral melon grows wild and is known as the Tsamma melon (*Citrullus lanatus* var *citroides*) (Whitaker & Davis, 1962). It is a vine-like plant or a climber and trailer herb, with edible fruits and leaves. The former name *Citrullus vulgaris* (vulgaris meaning "common" Shosteck, 1974) is now a synonym of the accepted scientific name for watermelon, *Citrullus lanatus*. It is regarded as the most morphologically diverse species in the genus *Cucumis* (Kirkbrde, 1993). Varieties differ widely in fruit size, morphology and taste, as well as vegetative traits and climatic adaptation. Wild and early watermelons were extremely bitter, but this was eliminated quickly under cultivation with the selection of seed and cross-pollination.

Wild watermelon is a member of the *Cucurbitaceae* family, is a vine-like plant or a climber and trailer herb, with edible fruits. It has a long history of cultivation and is grown throughout the world as a staple food (edible seeds and flesh), and for animal feed (Bawa & Bains, 1977; Ahmed, 1996 cited by Wani *et al*., 2006). The rind is utilized for products such as pickles and preserves as well as for extraction of pectin (Hasan, 1993; Godawa & Jalali, 1995 cited by Wani *et al*., 2006), whereas seeds are a potential source of protein (Oyenga & Fetuga, 1975; Teotia & Ramakrish-na, 1984) and lipids (Lazos, 1986). The fruits are a popular and important source of water in the diet of the indigenous people in the Kalahari Desert during dry months of the year when no surface water is available.

Figure 1.8: Wild watermelon growing in the field at Ukulinga Research Farm, Pietermaritzburg. The picture was taken when the crop had started flowering and forming yield.

The plant itself has been observed to be drought tolerant (Akashi *et al*., 2001). According to Miyake and Yokota (2000) wild water melons keep their photosynthetic apparatus intact during prolonged drought. This would suggest that there are mechanisms present which make the plant tolerant to water deficits and excessive light energy falling on the leaves (Kawasaki *et al*., 2000). However, wild water-melon is still considered as a neglected and underutilized species; within the context of South Africa, there is a dearth of information on agronomy and possible drought tolerance of local landraces.

1.3 Crop responses to water stress

Plant or crop responses to water/drought stress vary and are dependent on the intensity and duration of the stress (Chaves *et al*., 2002). Such responses are often described as being complex (Blum, 2011) and research is yet to fully elucidate all of them. An understanding of crop responses to water stress is important and fundamental to selection and breeding of drought tolerant crops. This is especially true in the case of NUS where there is a dearth of such information. The major crop responses to water stress are discussed below.

1.3.1 Stomatal conductance

Jaleel *et al.* (2009) defined drought stress as the moderate loss of water which results in stomatal closure and limitation of gas exchange. Stomatal conductance is the rate of diffusion of carbon dioxide (CO_2) in and out of the leaf, which by extension represents opening and closure of stomata. It has previously been stated that closure of stomata (reduced stomatal conductance) is the first response of almost all plants to water stress (Mansfield & Atkinson, 1990; Cornic & Massacci, 1996). Plant stomata close in order to reduce transpirational water loses. Chaves *et al*. (2002) give a detailed description of stomatal closure in water stressed plants. Closure of stomata in response to stress has been associated with abscicic acid (ABA) signalling from drying roots (Gowing *et al*., 1990; Davies & Zang, 1991). Field trials on several crops such as maize (Tardieu *et al*., 1991), grapevine (Correira *et al*., 1995; Stoll *et al*., 2000) and clover (Socias *et al*., 1997) concurred with this hypothesis. In this study, stomatal closure was viewed as a crop response to decreasing soil water content.

Closure of stomata decreases the flow of CO_2 into the leaves, followed by a parallel decline in net photosynthesis, and ultimately plant growth. There is however ongoing debate as to whether drought mainly limits photosynthesis due to closure of stomata or metabolic impairment (Sharkey, 1990; Tezara *et al*., 1999). However, general consensus has been that stomatal closure is the main reason for decreased photosynthesis under mild to moderate water stress (Cornic &

Massacci, 1996; Chaves *et al*., 2002, 2003; Yokota *et al*., 2002). Collinson *et al*. (1997) ascribed drought resistance in bambara, in part, to effective stomatal control. Sivan (1995) studied drought tolerance in two taro varieties of dasheen and eddoe types, as well as tannia (*Xanthosoma sagittifolium*) and observed that stomatal conductance declined under water stress relative to the well-watered treatment.

1.3.2 Chlorophyll content

Debate still is ongoing as to whether water stress mainly limits photosynthesis through stomatal closure or metabolic impairment (Lawson *et al*., 2003; Anjum *et al*., 2003). The capture of light, used in photosynthesis, and production of reducing powers is the preserve of photosynthetic pigments – mainly the chlorophylls a and b. Farooq *et al*. (2009) showed that these pigments are sensitive to water stress. In separate experiments conducted on barley (Anjum *et al*., 2003) and by Farooq *et al*. (2009), water stress was shown to induce changes in the ratios and quantities of chlorophyll a and b as well as carotenoids. Chlorophyll content was shown to decrease in sunflower plants subjected to water stress (Kiani *et al*., 2008).

Assessing alterations in pigment composition and content has now become an effective means of evaluating plant responses to stresses (Chen *et al*., 2007). In separate reports by Estill *et al*. (1991) and Ashraf *et al*. (1994), chlorophyll b increased in two lines of okra, while chlorophyll a was unaffected; the overall effect was a reduction in the Chlorophyll a: b ratio in both okra lines in response to water stress. Mensha *et al*. (2006) reported decreased chlorophyll content in sesame subjected to water stress. In India, Sahoo *et al*. (2006) observed decreased chlorophyll stability index in a taro hybrid subjected to water stress using polyethylene glycol (PEG). Recently, Vurayai *et al*. (2011b), working on pot trials, reported that water stress did not have a significant effect on chlorophyll content index (CCI) of bambara landraces; they concluded that CCI was not reduced by water stress at all stages of growth. However, they recommended that their observations be evaluated further under field conditions.

1.3.3 Plant growth and development

Plant growth is the irreversible increase in the size of the plant. It includes stages from germination, emergence, vegetative growth up to and including reproductive growth. Plant growth is achieved through cell division (mitosis), expansion and finally differentiation. The processes of cell growth are some of the most sensitive ones to water stress due to reduction in turgor pressure (Taiz & Zeiger, 2006). In short, cell growth and consequently plant growth, is a turgor driven process. Thus, under water stress, turgor pressure is low, resulting in reduced cell division, expansion and differentiation; the observed effect of which is reduced plant growth.

According to Harris *et al*. (2002), the first and foremost effect of water stress is reduced germination and emergence. Kaya *et al*. (2006) stated that drought stress severely reduced germination and seedling stand. Water stress has been reported to reduce seedling establishment in several NUS – maize landraces (Mabhaudhi & Modi, 2010, 2011); wild mustard (Mbatha & Modi, 2010); wild water melon (Zulu & Modi, 2010). Poor seedling establishment, as a result of water stress, leads to low yield due to reduced stand, and in most cases no amount of effort and/or expense later in the crop development can compensate for this deleterious effect (Mabhaudhi & Modi, 2010).

Water stress impairs mitosis, elongation and expansion, resulting in reduced plant height, leaf number and area and generally reduced crop growth (Nonami, 1998; Kaya *et al*., 2006; Hussain *et al*., 2008). Water stress has previously been reported to reduce plant height in potato (Heuer & Nadler, 1995) and soya bean (Specht *et al*., 2001; Zhang *et al*., 2004. Bhatt & Rao (2005) associated the reduction in plant height with a reduction in cell expansion. Leaf development is crucial to photosynthesis and dry matter production. Similar to plant height, water stress has been reported to affect leaf number and area in many crops, including soybean (Zhang *et al*., 2004), cowpea (Manivannan *et al*., 2007a), wheat and maize (Sacks *et al*., 1997) and sunflower (Manivannan *et al*., 2007b).

With regards to NUS, water stress was also shown to reduce plant height, leaf number and area in maize landraces (Mabhaudhi & Modi, 2010, 2011); wild mustard (Mbatha & Modi, 2010); wild water melon (Zulu & Modi, 2010). Elsewhere, Sahoo *et al*. (2006) subjected a taro hybrid to water stress using PEG. They observed significant differences in plant growth parameters of height, leaf number and area in response to water stress. Furthermore, growth responses of Bambara landraces to water stress have been previously studied (Collinson *et al*., 1996, 1997; Mwale *et al*., 2007b; Sinefu, 2011; Vurayai *et al*., 2011a). They all reported reduced plant growth (plant height, leaf number, leaf area, leaf area index) in response to water stress. However, work on Bambara groundnut still requires more research since all research has been done on landraces; landraces have a lot of a variation within and amongst themselves. In a study on drought tolerance of a dasheen and eddoe taro varieties by Sivan (1995), water stress was shown to reduce leaf number, and leaf area of both cultivars; the greatest decrease in leaf area was in the eddoe type cultivar. Reduction in leaf number and area was attributed to premature senescence of old leaves.

In principle, the root is the only plant part responsible for sourcing water which is used by the plant. Therefore, the importance of the root system with regards to a plant's ability to tolerate stress has been well established (Jaleel *et al*., 2009). Hypothetically, under water stress, the root will grow until a plant's demand for water is met; however, genetic variations may limit potential maximum rooting depth (Blum, 2005). Several studies have reported increased root growth in plants subjected to water stress – sunflower (Tahir *et al*., 2002), *Phoenix dactylifera* (Djibril *et al*., 2005), *Populus sp* (Wullschleger *et al*., 2005). Increased root growth under stress has been associated with an increased root: shoot ratio; under stress, plants will allocate more assimilate to root growth (sourcing more water) while limiting stem growth (loss of water).

Increased root: shoot ratio (dry matter) has been reported in bambara groundnut (Collinson *et al*., 1996; Vurayai *et al*., 2011a). Sivan (1995) also reported increased root: shoot ratio, on a dry matter basis, in dasheen and eddoe cultivars of taro; the eddoe cultivar was shown to increase root: shoot ratio in response to both moderate and severe water stress. However, Blum (2005) argued that the increase in root: shoot dry matter ratio in response to stress may not necessarily be due to increased dry matter partitioning to the roots, but rather reduced partitioning to the leaf as well as leaf senescence. Blum (2005) further argued that root length may increase under stress at a reduced total root mass. However, despite differences in perception, a well-developed root system allows for enhanced capture of soil water; an important drought adaptation response (Vurayai *et al*., 2011a).

1.3.4 Yield

Yield refers to the harvestable portion of the crop. The objective of every farmer is to fetch high yields (Jaleel *et al*., 2009) under all conditions, more so under drought stress. The objective of many breeding experiments is to develop a crop that will produce high yields under all environmental conditions (Blum, 2005), including drought. However, crop yields show considerable variation under drought stress conditions (Jaleel *et al*., 2009).

According to Farooq *et al*. (2009), many yield-determining plant processes are affected by water stress. Farooq *et al*. (2009) provided a detailed table highlighting percentage yield reductions for a wide variety of crops in their review of effects of plant drought stress on crop growth. Water stress has been reported to reduce yields in cotton (Pettigrew, 2004), pearl millet (Yadav *et al*., 2004), and in barley (Samarah, 2005). Studies have also shown yield reduction in response to water stress in legume crops such as soya beans (Frederick *et al*., 2001) and black beans (Nielson & Nelson, 1998). The effect of water stress on yield of bambara groundnuts has also been studied; reports showed reduced yield in response to water stress (Mwale *et al*., 2007a, b; Sinefu, 2011; Vurayai *et al*., 2011a). Despite popular belief that taro is a water loving plant, Sahoo *et al*. (2006) reported minimum yield reduction in a taro hybrid subjected to PEG induced water stress. They concluded that the development of drought tolerant taro cultivars was possible. Therefore, evaluating responses of previously unstudied taro landraces to water stress may aid in identifying genotypes with drought tolerance.

1.4 Mechanisms of drought tolerance

A plant's chosen mechanism to coping with stress is based on the choice of responses it adopts in responding to developing water stress. Based on this combination, and the magnitude and timing of stress (Blum, 2005), a plant may escape, avoid, and/or tolerate stress.

1.4.1 Drought escape

Drought escape is mainly associated with occurrence of phenological stages. Plants that escape drought achieve this by having a short growing season, allowing them to complete their growth cycle before water stress becomes terminal. According to Araus *et al*. (2002), flowering is an important adaptation related to drought escape. They further stated that escape occurs when crop phenology, such as time to flowering, is closely synchronised with periods of water availability, particularly when the growing season is characterised by terminal drought (Farooq *et al*., 2009). The only negative to drought escape is that yield is generally correlated with length of crop duration; hence shortened growth duration will result in decreased yield.

1.4.2 Drought avoidance

The essence of drought avoidance is to reduce water loss while enhancing or maintaining uptake by the roots. Drought avoidance involves crop responses such as stomatal regulation, enhanced capture of soil moisture through an extensive and prolific root system (Turner *et al*., 2001; Kavar *et al*., 2007). Several root characteristics such as biomass, length, depth and thickness (volume) are thought to contribute to final yield under drought stress (Subbarao *et al*., 1995; Turner *et al*., 2001; Kavar *et al*., 2007) due to improved water capture. Additionally, reduced water loss by the plant can be achieved by morphological changes: reduced plant height, leaf number, leaf area and leaf area index (LAI) contribute to reducing water loss by the plant (Mitchell *et al*., 1998) thereby assisting the plant to avoid drought. Blum (2004) also associated drought avoidance with reduced season duration due to reduced leaf number; reduced season duration is also characteristic of drought escape, suggesting that the mechanisms do not work in isolation. However, as with drought escape, the crop responses that are employed to avoid drought are at the expense of dry matter production hence yield.

1.4.3 Drought tolerance

Drought tolerance has been defined as the plant's capacity to maintain metabolism under water stress (Blum, 2005). It includes osmotic adjustment (accumulation of metabolites, osmoprotection (e.g. proline) and the antioxidant defence systems (Farooq *et al*., 2009). Blum (2005) gave a detailed account of increasing evidence suggesting a relationship between high osmotic adjustment and maintenance of biomass and yield under stress. Unlike escape and avoidance, the *modus operandi* of drought tolerance does not show any solid evidence of a yield reduction (Blum, 2005). However, drought tolerance as an effective crop drought-resistance mechanism is rare; it mainly exists in seed embryo and is lost after germination (Blum, 2005). Nonetheless, it is an important crop mechanism for dealing with stress.

1.5 Crop modelling

A crop model is a simplified representation of a real system (Hillel, 1977; De Wit, 1982). Sinclair and Seligman (1996) defined crop modelling as the dynamic simulation of crop growth by numerical integration of constituent processes with the aid of computers. Uses of crop models span from the farm level to regional levels. Models can assist as decision support tools for planning (Steduto *et al*., 2009), decision making, yield forecasting, evaluating effects of climate change as well as for identifying research gaps. According to Singels *et al*. (2010), models are also useful in the integration of knowledge and data across disciplines; multidisciplinary research has recently been advocated as the way forward in terms of research. With regards to decision support, Steduto *et al*. (2009) suggested two classes of support – strategic (land-use, climate change, sustainability) and tactical (cultivar selection, fertilisation, plant populations, etc.) while Singels *et al*. (2010) added a third class – operational support (irrigation scheduling, weeding, etc.).

The variety of applications of crop models has made them an essential tool in agricultural systems. South Africa has also been part of the global advancement in modelling; over the years, South Africa has developed several of its own models – ACRU (Schulze, 1975), BEWAB and SWAMP (Bennie *et al*., 1988, 1997, 1998), CANEGRO (Inman-Bamber, 1995; Inman-Bamber & Kiker, 1997) and CANESIM (Singels & Donaldson, 2000), PUTU (De Jager, 1974; Kaiser & De Jager, 1974), SAPWAT (Crosby & Crosby, 1999), SAPWAT 3 (Van Heerden *et al*., 2009), and SWB (Annandale *et al*., 1999). In addition, several other international models have been successfully used in South Africa. These include CERES and CROPGRO which are housed in DSSAT (IBSNAT, 1993; Jones *et al*., 1998; Uehara & Tsuji, 1998). Singels *et al*. (2010), in their review of the history of crop modelling in South Africa over 25 years (1983-2008), reported that, given South Africa's limited manpower and resources, the scope of model development and application was plausible. However, more still needs to be done in order to bring South Africa at par with global developments and trends. Such efforts would involve working on new local and international models, adapting them to South African conditions, and modelling underutilised and indigenous crops.

1.5.1 Approaches to modelling

Several authors (Bouman *et al*., 1996; Passioura, 1996; Monteith, 1996; Boote *et al*., 1996; Fischer *et al*., 2000; Hammer *et al*., 2002) have reviewed the different approaches to modelling, as well as their advantages and limitations. These included regression or empirical models, stochastic models, parameter models, and deterministic models. This review will focus on deterministic models.

Deterministic or mathematical models attempt to mimic, in as much as is feasibly possible within calculation time, the actual processes known to occur in the soil-plant-atmosphere-continuum (SPAC) (Savage, 2001). They attempt to explicitly represent causality between variables (Whisler *et al*., 1986) and their observed behaviour based on the physical laws controlling flow of mass and energy that can be described mathematically (Hillel, 1977; Savage, 1993; Savage, 2001). Hence their increased accuracy and precision. A distinction between deterministic models can be drawn between a mechanistic and functional approach (Hillel, 1977;

Wagenet, 1988; Passioura, 1996; Savage 2001). For the purposes of this study, we shall focus more on the mechanistic and functional approaches.

1.5.1.1Mechanistic approach

The mechanistic approach has also been described as a *scientific* approach to describing knowledge. Its aim is to improve our knowledge and understanding of the crop with regards to crop growth and development, physiology, and responses to environmental changes (Steduto *et al*., 2009).

1.5.1.2 Functional approach

This has also been described as an engineering approach to solving problems and is selected to fit observed field and laboratory measurements (Monteith, 1996). They attempt to provide sound management advice to farmers or predictions to policymakers (Passioura, 1996). It must be however noted that the distinction between these two approaches is seldom as lucid. In practise, and to varying degrees of emphasis, most models may contain aspects of the two approaches and serve both purposes (Karunaratne, 2009; Singels *et al*., 2010).

1.5.2 An overview of major crop models

Azam-Ali *et al*. (1994) stated that at the core of any crop model, lies a set of equations designed to estimate production rate of biomass from captured resources such as carbon dioxide, solar radiation and water. Steduto (2003) categorised modelling biomass production into three approaches: carbon-driven, radiation-driven and water-driven models.

The so-called school of De Wit is credited for the carbon-driven biomass production approach (De Wit, 1965; De Wit *et al*., 1970). The latter base crop growth on carbon assimilation by the leaf via photosynthesis (Todorovic *et al*., 2009) and includes WOrld FOod Studies (WOFOST; Van Diepen *et al*., 1989; Boogard *et al*., 1998) as well as other Wageningen crop models (Bouman *et al*., 1996; Van Ittersum *et al*., 2003) and the American CROP GROwth model (CROPGRO; Boote *et al*., 1998, 2002). Van Ittersum *et al*. (2003) provide a detailed and particularly interesting review of the Wageningen models since De Wit (1958) to date.

Radiation-driven crop models rely on conversion of intercepted solar radiation to radiation use efficiency (RUE) as the basis for calculating biomass (Monteith, 1977). Intermediary steps such as leaf quantum efficiency per unit of CO_2 fixed, photo- and dark respiration rates, are thought to be incorporated into RUE (Monteith, 1977). This reduces their level of complexity and input requirements compared with carbon-driven modules. Models such as the Crop environment Resources Synthesis (CERES; Ritchie *et al*., 1985; Jones & Kiniry, 1986; Jones *et al*., 2003), Erosion Productivity Impact Calculator (EPIC; Jones *et al*., 1991), and Simulator mulTIdisciplinary for Crop Standard (STICS; Brisson *et al*., 2003) (adapted from Todorovic *et al*., 2009).

Water-driven crop models are based on an approach postulated by several authors from as early as 1958 (De Wit, 1958) to most recently (Hanks, 1983; Tanner & Sinclair, 1983; Hsiao & Bradford, 1983; Steduto, 1996; Steduto & Albrizio, 2005). Biomass accumulation is a function of transpiration and a water productivity (WP) parameter. Water-driven models are less complex with few input requirements (Steduto *et al*., 2007, 2009). Their main advantage of water-driven models compared to radiation-driven models, lies in the normalisation of the WP parameter for climate (both ETo and atmospheric CO_2) thus giving them wider applicability in space and time (Steduto & Albrizio, 2005; Hsiao *et al*., 2007; Steduto *et al*., 2007). Notable models, which come to mind include CropSyst (Stockle *et al*., 2003), which has both RUE and a vapour pressure deficit (VPD)-driven component and the FAO's newly released model – AquaCrop (Steduto *et al*., 2009; Raes *et al*., 2009). CropSyst requires 40 parameters to run it while AquaCrop requires 33 crop input parameters to run it (Todorovic *et al*., 2009).

The focus of this project was on describing drought tolerance of indigenous food crops. Therefore, emphasis was on yield response to water such that a water-driven model was most suited for this project. Although several water-driven models have been used to predict yield response to water, only AquaCrop has recently been used for underutilised crops. Therefore, within the context and scope of this project AquaCrop was selected to simulate the yield response to water of at least four of the selected NUS studied in the project.

1.6 Conclusion

It is possible that the key to future food security may very well lie in the untapped potential of neglected underutilised crops. Therefore, it is imperative that we study locally available neglected underutilised crops and evaluate them for drought tolerance using agronomic techniques as well as modern techniques such as crop modelling, which allow for rapid evaluation of production scenarios. Since a crop's ability to tolerate drought is dependent on a complex or dynamic variety and combination of responses and mechanisms, the project sought to evaluate the dynamics of drought tolerance in selected NUS within the context of South Africa. An understanding of morphological mechanisms involved in the responses of these NUS is fundamental to their identification as drought tolerant crops. Such an understanding of morpho-anatomical responses would contribute significantly towards breeding for drought tolerance and making available developed varieties of these NUS. The use of crop modelling as a technique may also aid in the interpretation of agronomic field data. Well-calibrated and validated models could also assist as selection tools for drought tolerance in these NUS thus reducing on time and resources needed to fill the knowledge gap on these NUS.

1.7 Objectives

The contractually specified objectives of the project were:

1.7.1 General objective

To develop comprehensive knowledge of water use characteristics of drought tolerant food crops with a specific focus on indigenous/ indigenised crops for application in South Africa. Through that knowledge, food production in rural areas would be increased, thereby alleviating food insecurity.

1.7.2 Specific objectives

1. To identify and characterise indigenous and conventional food crops with application potential in South Africa in terms of (among others): a. what can grow where under water scarce conditions, b. water requirements and crop response; c. marketable yield; and d. economic value adding chains.
2. To assess and rank the indigenous and conventional food crops placing specific emphasis on: a. drought tolerance; b. crop adaptability; c. economic importance and potential; d. information gaps in relation to water use characteristics, for purposes of selecting crops for empirical measurement and modelling of water use.
3. To determine empirically the water use characteristics of at least 4 selected crops (over at least two growing seasons) in order to perform crop growth modelling using available South African or international models with emphasis on response to water.
4. To develop, verify and empirically validate the crop growth model.

Chapter 2

Drought tolerance of selected local maize (*Zea mays* L.) landraces compared to two commercial hybrids under rainfed conditions

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2.1 Introduction

Drought, through low and erratic rainfall distribution, is a major feature of South African climate. Since maize is sensitive to drought (Farre *et al*., 2000), there exists much variation in dryland maize yields (Benhil, 2002). Although sensitivity to water stress varies according to crop developmental stages (Doorenbos & Kassam, 1979), water stress occurring at any time can reduce final yield; the extent of yield reduction being dependent upon intensity of water stress (Heinegre, 2000). Under dryland conditions, farmers usually plant early, in late spring, or at the onset of the rain season, with a few planting late due to resource constraints. Under these conditions, water stress can occur at any time during crop growth.

The late spring crop is often exposed to water stress at the establishment stage. Water stress at this stage can limit yield by reducing emergence (Mohammadkhani & Heidari, 2008). The optimum planted crop usually experiences mid-season drought. The occurrence of drought at the vegetative stage reduces plant height and leaf size (Khan *et al*., 2001). Impact on yield will thus be the result of reduced canopy size available for photosynthesis (Heinegre, 2000). For the late planted crop, drought usually coincides with the reproductive stages as the rains peter out. Water stress during tasseling limits yield by reducing cob prolificacy and size (Heinegre, 2000). Drought stress may also delay silk emergence until pollen shed is nearly or completely finished resulting in yield reductions due to loss of kernel number (Lauer, 2003). Water stress after silking, during grain-filling, may result in a shortened grain-fill period thus lowering kernel weight. If soil water content is depleted during grain-fill, grain abortion may occur (Coffman, 1998). Under dryland conditions, choice of planting date becomes a strategic decision for managing water stress associated yield losses.

Selection of planting dates is a management component of maize cropping systems which can significantly influence maize yield stability and potential (Norwood, 2001). Sheperd *et al*. (1991) reported that early planting contributed significantly to higher yields. Otegui and Melon (1997) concurred by reporting that early planting placed tasseling and silking ahead of the risk of water stress. They argued that late planting resulted in less biomass production, reduced kernel set and low grain yield. Otegui *et al*. (1995) had previously reported that optimum planting dates gave higher yields than early and late planting dates. Delayed plantings were generally accompanied by increased temperatures during the growing season which accelerated crop development and decreased accumulated solar radiation (Otegui & Melon, 1997).

Local farmers who still grow maize landraces depend on rainfed agriculture, making them vulnerable to yield variations. While hybrids have been tested and selected for different planting dates and field conditions, there have been no similar studies for local maize landraces. This study sought to evaluate the responses of landraces, in terms of growth parameters and yield components, to planting date associated water stress compared with two hybrids SC701 and SR52. The choice of hybrids used in this study was based on the fact that smallholder and subsistence farmers in KwaZulu-Natal generally prefer these two hybrids.

2.2 Materials and Methods

2.2.1 Experimental site, planting material and field layout

Three field experiments were planted at the University of KwaZulu-Natal's Ukulinga Research Farm in Pietermaritzburg (29°37'S; 30°16'E) under dryland conditions. The experimental design was a split-plot design arranged in a completely randomised design with planting date as a main factor and variety as sub-factor, replicated three times. There were three planting dates; 28 August, 2008 (early), 23 October, 2008 (optimum) and 9 January, 2009 (late). Two colour variations of local landraces, white (Landrace A) and dark red (Landrace B) were used in the study, together with two hybrids, SC701 and SR52. The plant population was 26 667 plants per hectare.

Plant height was measured from the soil surface to the base of the tassel. Leaf number was counted for leaves with at least 50% green area up till flowering. Days to tasseling (DTT) were counted as number of days from sowing to when 50% of the population had tasselled. Yield components were measured at harvest. Weather data was obtained from an automatic weather station (AWS) located about 100 m from the trial site. Soil water content was determined gravimetrically by sampling from the 30 cm profile and calculated as follows;

Soil water content = [(wet soil – dry soil) /dry soil] %

2.2.2 Crop management

Weeding was done mechanically. Fertiliser application was based on soil analysis recommendations; 20 kg phosphorus (P) per hectare and 180 kg nitrogen (N) per hectare. Kemprin (Cypermethrin @ 12 mℓ/10 ℓ) was used to control aphids.

2.2.3 Data analysis

Data were analysed using ANOVA in GenStat® Version 11. Means were separated using least significant differences (LSD) at 5%.

2.3 Results

Average monthly rainfall amounts measured for the period September to December 2008 showed less than 1mm of rainfall recorded (Fig 2.1). Temperatures during this period were also low; September had the lowest average temperature of less than 10°C (Fig 2.1). This period coincided with the first and second planting dates. Rainfall increased considerably over the period January to May 2009 (Fig 2.1).

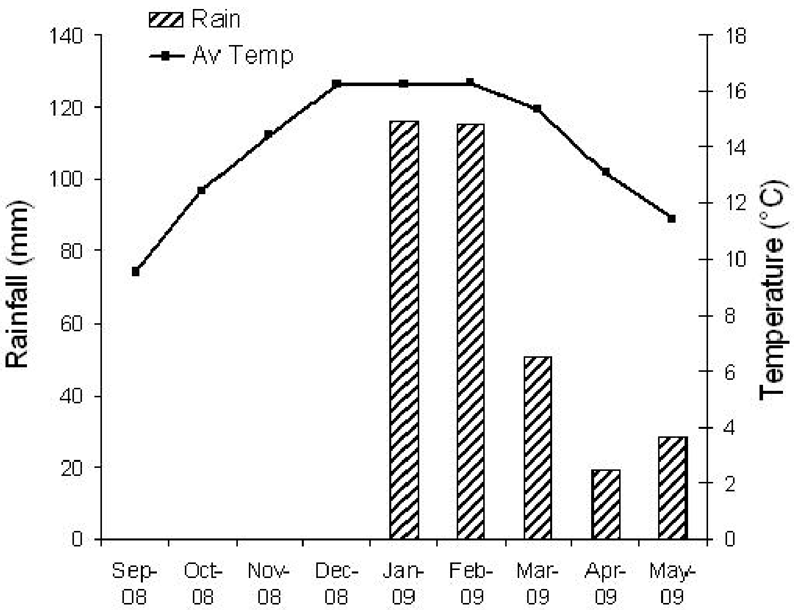

Figure 2.1: Monthly average rainfall and temperature (°C) recorded at Ukulinga during September 2008 to May 2009.

Planting date had a significant effect (P<0.001) on final emergence. There were significant differences (P<0.05) between varieties, although the interaction between planting date and variety was not significant (P>0.05) (Table 2.1). Landrace A and Landrace B had the highest emergence in the early planting, respectively, with SC701 and SR52 being equal (Table 2.1). Emergence decreased for all varieties in the optimum planting date (Table 2.1). Although emergence increased in the late planting, it was less than emergence in the early planting, with the exception of Landrace A which equalled the early planting (Table 2.1). Based on mean values, for all varieties, emergence decreased by 48% and 5% in the optimum and late plantings, respectively, when compared to the early planting. Emergence of hybrids was 6% and 18% lower than landraces in the optimum and late planting, respectively.

Table 2.1: Growth of landraces (Land A and B) and hybrids (SC701 and SR52) for three different planting dates.

Planting Date	Variety	Emergence (%)	Plant Height (cm)	Leaf Number	DTT[v] (DAS[w])
Early	Land A	93.3a	92.9e	11.88bc	105a
	Land B	86.7ab	88.1e	11.91bc	102.67a
	SC701	74.7bcd	99.3e	12.35bc	105a
	SR52	74.7bcd	168.4de	11.57bc	105a
Mean		**82.3[a]**	**97.2[b]**	**11.93[b]**	**104.42[a]**
Optimum	Land A	40e	141.1bc	12.78ab	81.67b
	Land B	48e	143.6bc	12.67abc	81.67b
	SC701	38.7e	172.3a	12.89ab	84b
	SR52	44e	163.9ab	13.67a	81.67b
Mean		**42.7[c]**	**155.2[a]**	**13[a]**	**82.25[b]**
Late	Land A	93.3a	158.8ab	11.67bc	63d
	Land B	78.7bcd	130.4cd	10.74c	63d
	SC701	72cd	146.1ab	11.4c	67.67c
	SR52	69.3cd	142.7bc	10.83c	63d
Mean		**78.3[b]**	**144.5[a]**	**11.16[a]**	**64.17[c]**
$LSD_{(P=0.05)}$ P.Date		**6.79**	**13.97**	**0.662**	**2.288**
$LSD_{(P=0.05)}$ PD x Var		**13.58**	**27.95**	**1.324**	**4.575**

Note: [v]DTT = days to tasseling; [w]DAS = days after sowing. *Numbers with different letters in the same column differ at LSD (P=0.05).

There were significant differences (P<0.001) between planting dates, with respect to both final plant height and leaf number (Table 2.1). With the exception of Landrace A, all other varieties attained maximum plant height in the optimum planting, followed by late and early planting, respectively (Table 2.1). Maximum leaf number was attained in the optimum planting, followed by early and late planting, respectively (Table 2.1). Although earlier planted crops were shorter than late planted crops, they had more leaves (Table 2.1). There were no differences (P>0.05) between varieties as well as no significant interaction (P>0.05) between planting date and variety.

Time to tasseling (DTT) were significantly affected (P<0.001) by planting date (Table 2.1). Early planting took the longest number of days to tassel (≈104 DAS). Landrace A, SC701 and SR52 tasselled at the same time while Landrace B tasselled earlier. On average, the optimum and late plantings tasselled 22 days (≈82 DAS) and 26 days (≈40 DAS) earlier than the early planting. For both optimum and late planting, Landrace A, Landrace B and SC701 tasselled at the same time while SR52 took longer to tassel (Table 2.1).

Highly significant differences (P<0.001) between planting dates and varieties were observed with regard to ear prolificacy (EP) (Table 2.2). Landrace A and Landrace B had the highest EP, respectively, in the early and optimum planting, with Landrace A having at least 3 ears per plant (Table 2.2). Ear prolificacy decreased in the late planting for landraces. For all three planting dates, landraces had, on average, at least 2 ears/plant compared to 1 ear/plant in hybrids (Table 2.2).

There were highly significant differences (P<0.001) for ear length between varieties. In all three plantings, ears of SC701 and SR52 were significantly longer than ears of Landrace A and Landrace B. Ears of hybrids were, on average, 37% longer than ears of landraces. Although ear length of landraces increased in the successive plantings (14% and 22% increments in the optimum and late plantings compared to the early planting), ears of landraces remained smaller than ears of hybrids (Table 2.2).

Although planting date had no effect (P>0.05) on ear mass, there were highly significant differences (P<0.001) between varieties (Table 2.2). Ear mass of SC701 and SR52 was significantly higher than ear mass for landraces in the early and late planting. The difference was more pronounced in the early planting; ears of hybrids weighed, on average, a staggering 165% more than ears of landraces. The difference was reduced to an average of 54% more weight in the optimum and late plantings due to the weight gain recorded in ears of landraces; ears of landraces increased weight by 33% and 42%, on average, in the optimum and late plantings, respectively, compared to the early planting (Table 2.2).

Kernel rows per ear (KRE) increased with successive planting dates, albeit not significantly (P>0.05) (Table 2.2). There were, however, significant differences (P<0.05) between varieties. Landrace B was similar to SC701 in the early planting, while SR52 had the most KRE. In the optimum planting, Landrace B was similar to SR52, with SC701 having the most KRE. Landrace A improved in the late planting and was similar to SR52, while SC701 still had the most KRE. Based on mean values, hybrids had an average of 11 KRE compared to 9 KRE in landraces.

Kernel number per ear (KNE) differed significantly ($P<0.05$) between planting dates. There were highly significant differences ($P<0.001$) between varieties. For all three plantings, SC701 and SR52 had more KNE than landraces. Kernel number per ear increased, overall, with successive planting dates in hybrids and landraces, with the exception of SR52 and Landrace B which decreased in the optimum and late planting, respectively (Table 2.2).

Grain mass per plant was not significantly affected ($P>0.05$) by planting date, although it increased with successive planting dates, in line with increments recorded in KRE and KNE (Table 2.2). There were highly significant differences ($P<0.001$) between varieties. SR52 and SC701 had the highest grain yield per plant, respectively, in the early and optimum planting. Grain yield increased with successive planting dates in Landrace A and Landrace B, although it still remained lower than SC701 and SR52. The greatest differences were observed in the early planting; average grain mass per plant of hybrids was more than double (140%) that of landraces (Table 2.2).

Dry matter accumulation (100 GM) showed significant differences ($P<0.05$) between planting dates and varieties (Table 2.2). SC701 and SR52 had the highest 100 GM, respectively, in the early and optimum planting. Landrace A was similar to SR52 in the optimum planting. Landrace B increased with successive planting dates while Landrace A, SC701 and SR52 decreased with successive plantings. Consequently, Landrace B had the second highest 100 GM in the late planting (Table 2.2). Overall, compared to the early planting, 100 GM decreased with successive planting dates, by 7% and 16% in the optimum and late planting dates, respectively.

Results for total grain yield (t/ha) were consistent with results for yield components measured (ear length and mass, KRE and KNE) (Table 2.2). There were no differences ($P>0.05$) between planting dates, but highly significant ($P<0.001$) differences between varieties were observed (Table 2.2). The interaction between planting date and variety was not significant ($P>0.05$). For both Landrace A and Landrace B, grain yield increased with successive plantings, with highest grain yield being achieved in the late planting (Table 2.2); the opposite was true for SR52. SC701 achieved highest grain yield in the late planting (Table 2.2). SR52 was consistent in all three plantings (>5 t/ha) (Table 2.2).

Table 2.2: Yield components of landrace (Land A and B) and hybrids (SC701 and SR52) for three different planting dates.

Planting date	Variety	EP[x]	Ear length (cm)	Ear mass (g)	KRE[y]	KNE[z]	Grain mass/ Plant (g)	100 Grain Mass (g)	Grain Yield (t/ha)
Early	Land A	3.1a	14.05bc	122b	8.41bc	169cd	83.9bc	50.36cd	2.23b
	Land B	2.157a	11.29d	88.4bc	9.35b	153d	76.9bc	45.17d	2.07b
	SC701	1.2c	19.3a	278.5a	9.63b	294b	174.7ab	64.1a	4.67ab
	SR52	1.083c	19.03a	279.8a	10.28ab	354ab	210.5a	62.23ab	5.6a
Mean		**1.885[a]**	**15.92[b]**	**192.2[a]**	**9.42[b]**	**243[a]**	**136.5[a]**	**55.47[a]**	**3.64[a]**
Optimum	Land A	3.333a	14.56bc	150.8b	9.38b	239bcd	121.9b	50.15cd	3.27ab
	Land B	1.611b	14.35bc	131.1b	10.04ab	281bc	112.3b	46.03d	3.00b
	SC701	1.444b	18.19ab	209.8ab	11.24a	337ab	170.4ab	55.78abc	4.57ab
	SR52	1.167c	20.3a	220.3ab	10.27ab	345ab	191.3ab	53.83bc	5.07ab
Mean		**1.889[a]**	**16.85[ab]**	**178[a]**	**10.23[ab]**	**300[ab]**	**149[a]**	**51.45[ab]**	**3.98[a]**
Late	Land A	1.067c	15.91bc	164.2b	10.07ab	306b	139.4b	44.62d	3.73ab
	Land B	1.229c	14.98bc	134.3b	9.27b	266bcd	129.0b	46.30d	3.47ab
	SC701	1c	20.74a	242.1a	12.13a	441a	190.5ab	45.60d	5.07ab
	SR52	1.111c	19.11a	223a	10.73ab	379ab	187.5ab	49.47cd	5.00ab
Mean		**1.102[b]**	**17.68[a]**	**190.9[a]**	**10.55[a]**	**348[a]**	**161.6[a]**	**46.5[b]**	**4.32[a]**
LSD$_{(P=0.05)}$ P.Date		**0.4097**	**1.588**	**49.88**	**1.093**	**59.4**	**34.63**	**4.711**	**0.923**
LSD$_{(P=0.05)}$ PD x Var		**0.8195**	**3.176**	**99.75**	**2.186**	**118.8**	**69.26**	**9.422**	**1.846**

Note: [x]ear prolificacy; [y]kernel rows per ear; [z]kernel number per ear. Numbers with different letters in the same column differ at LSD (P=0.05)

2.4 Discussion

Contrary to reports that early planting resulted in reduced or poor and unsynchronised emergence due to a lack of soil water in the seedbed at planting (Mwale *et al*., 2003), early planting resulted in the highest emergence. Under conditions of low soil water content, Landrace A and Landrace B out-emerged hybrids. Optimum planting had the lowest emergence. Emergence increased in the late planting due to increased soil water content and warmer temperatures. Germination and especially emergence is far more rapid and uniform at soil temperatures of 16-18°C (Arnon, 1972).

Plant height and leaf number are established growth parameters and indices of water stress tolerance. Reduction of leaf number under water deficits is a result of reduced leaf appearance rate and reduced plant height as well as accelerated leaf senescence (Carberry *et al*., 1993a, b; Belaygue *et al*., 1996; Marcelis *et al*., 1998; Gupta *et al*., 2001; Pic *et al*., 2002). Early planting resulted in the shortest plants since it coincided with the driest period. The vegetative stage of the optimum planting coincided with increasing soil water content and temperature, resulting in plants expressing their genetic potential. Plant height and leaf number decreased slightly in the late planting in response to decreasing soil water content and temperature. Aldrich *et al*. (1975) associated late planting with a shortened season; this may have limited plant growth.

Early planting took the longest time to tassel followed by optimum and late planting, respectively. Early planting has been reported to enjoy a longer growing season when compared to optimum and late planting (Aldrich *et al*., 1975; 1986). Tasseling in the early and optimum planting coincided with increased rainfall and soil water content whilst the late planting coincided with decreasing temperatures, rainfall and soil water content. This pattern was consistent with that suggested by Otegui and Melon (1997). Both hybrids and landraces were similar, with respect to DTT, confirming that landraces were late maturing varieties.

Contrary to reports by Otegui and Melon (1997) that early planting gave the highest yield; early planting had the lowest grain yield. This was due to few kernel rows and low kernel number, despite plants having high EP. Ear size and EP are genotype specific and are already determined at the onset of tasseling. Landrace A and Landrace B had the highest EP, respectively, compared to SC701 and SR52 in all three planting dates. Early planted crops had the highest biomass accumulation as shown by 100 GM. Otegui *et al*. (1995) found that planting early allowed plants to fully utilise solar radiation due to a prolonged season duration resulting in more assimilate for grain-filling.

Grain yield increased in the optimum planting date, buoyed by corresponding increases in kernel rows and kernel number. Landraces recorded the greatest increase in yield, followed by SC701, while SR52 slightly decreased. Otegui *et al*. (1995) reported that higher grain yields from optimum planting dates were a result of greater kernel number and higher cob number. Despite having the shortest growing period, late planting resulted in the highest grain yields for landraces and SC701. Ear size increased together with kernel rows and kernel number. Variation in planting date has been shown to influence kernel numbers (Harris, 1984). According to Green *et al*. (1985), results of planting dates may vary and it is not unusual for late planted crops to out-yield the optimum planting. However, despite the gains made by landraces, they still had lower yields than hybrids in all three plantings.

2.5 Conclusion

While the selected hybrids used for this study cannot be described as drought tolerant hybrids, they were superior to the landraces. Although landraces were prolific, they had smaller ears with fewer kernel rows, lower kernel number and lighter kernels, resulting in lower grain yield compared to hybrids. Planting date selection may be a useful tool for managing maize landrace production under dryland conditions. Early planting resulted in the lowest yields. Maize landraces achieved highest yields in the late and optimum planting dates, respectively. This was due to increased vegetative growth (plant height and leaf number) during the late and optimum planting dates. Hybrids performed better than landraces and showed more consistency over time, with respect to plant growth and yield; this may be attributed to their superior genetic makeup. Landraces exhibited drought tolerance during crop establishment and emerged well in the early planting. The fact that landraces showed drought tolerance during the establishment stage and their high ear prolificacy suggests that they may possess characteristics that may be useful to future breeding experiments. The fact that despite being low yielding, landraces still remain popular in rural areas suggests that there is a need to study them even further. Such a study could look at other desirable characteristics, other than drought tolerance, that may explain their continued presence within these communities.

Chapter 3

Drought tolerance of wild watermelon

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3.1 Introduction

Wild watermelon has been cultivated in Africa for thousands of years as a staple food (edible seeds and as a cooked vegetable), a dessert food (edible flesh), animal feed and alcohol fermentation. Its fruits are a popular and important source of water (comprising of about 90% water) in the diet of the indigenous people of the Kalahari Desert during dry months of the year when no surface water is available. The fruit is cut open at the one end and the first piece of flesh is eaten. Leaves and young fruits are utilized green, and because of its high content of pectin it is popular as a constituent of jams, jellies and vegetables (Van Wyk & Gericke 2000). In the Kalahari, the fresh fruits are also used as stock feed in times of drought (Van Wyk & Gericke, 2000). It is possibly due to the fact that it originates from a very dry area that wild watermelon is thought to be drought tolerant.

Akashi et al. (2001) showed evidence that wild watermelon plants that inhabited the Kalahari Desert exhibited were extremely drought tolerance. The plants were able to keep their photosynthetic apparatus intact during prolonged drought under conditions of high solar radiation. This therefore suggested that there were mechanisms present which allowed the plant to tolerate oxidative stress arising from excessive light energy falling on the leaves (Miyake & Yokota, 2000, and Kawasaki et al., 2000). Little is known about the drought tolerance of local wild water melon landraces. Despite its importance and potential as a food crop, studies of drought tolerance in local wild watermelon germplasm were scarce in literature. Therefore, the objective of this study was to determine seed performance and drought tolerance in local germplasm of wild watermelon.

3.2 Materials and methods

3.2.1 Plant material

Seeds of wild watermelon were donated by subsistence farmers and used to produce fresh seed lots during the 2006/07 season at Pietermaritzburg, KwaZulu-Natal (29°35′S; 30°25′E). Three varieties differing in terms of seed coat colour (red, brown, and dark-brown) were germinated according to international seed testing rules for melons (ISTA, 1999).

3.2.2 Field experimental design

A field trial was performed at Ukulinga Research Farm of University of KwaZulu-Natal, Pietermaritzburg under dryland conditions with no supplementary irrigation. The experimental design was a split-plot design arranged in a completely randomized design. There were three planting dates (early, mid, and late season planting), which were the main factors, and three seed varieties (sub-factors) differing in terms of seed coat colour (red, brown, and dark-brown). The inter-spacing and intra-spacing were of the equal size of 3 m for all trials. All the trials were given equal amounts of an organic fertilizer (40 g of Gromor® Accelerator). Weed control was done by hand-hoeing.

3.2.3 Growth analysis and yield determination

Emergence was determined by counting the number of emerged seedlings every week for three weeks. A plant was counted as having emerged when the cotyledon had emerged from the soil surface. By the fourth week plants started to produce true leaves not cotyledons. Thereafter, measurements of leaf number, vine number and vine lengths were taken until plants had reached flowering. Flowering was defined as when at least 50% of the experimental plants in a given plot had flowered.

Fruits were harvested when plants had reached physiological maturity. This was defined as when at least 50% of leaves and vines in about 50% of the experimental had senesced. After harvesting, fruits were graded according to their size and mass (in kg) into three categories – large, medium and small.

3.2.4 Seed germination and vigour after harvesting

After harvesting was done and fruits having been categorised as described above, the best looking fruits from different plots were selected. Thereafter, the fruit were cut open in order to obtain the fresh seeds. Following this, the seed were again characterised on the basis of seed colour into three major groups (red, brown and dark). The separated seeds were then used in a standard germination test (ISTA, 1999) for eight days to determine their seed quality based on germination percentage, seedling length and mass.

3.2.5 Data analysis

GenStat® Statistical Package Version 9 (VSN International, UK) was used to perform analysis of variance. Least significant differences (LSD) were used to determine differences between treatments at the 5% level of significance ($P = 0.05$).

3.3 Results and discussion

Results of emergence showed that, over-all, percentage emergence was very poor. It was below 80% across all planting dates (Table 3.1). There were no significant differences ($P < 0.05$) in planting dates and seed colour with respect to emergence. However, planting at the optimum date (2^{nd} planting date) resulted in comparatively higher percentage emergence compared with early and late planting (Table 3.1 and Figure 3.1). Improved emergence observed for the optimum planting date which was planted in November, may have been due to improved soil water availability because of summer rainfall received during that month. Early planting had the lowest percentage emergence compared with optimum and late planting. The early planted crop was planted in September, typically before the onset of the rainy season in KwaZulu-Natal. As such, the crop was planted into a dry seedbed; additionally, there was no rainfall received during the whole month of September. This could explain our observations of delayed and poor emergence.

Another possible explanation for the poor emergence observed for the early planted crop have been due to lower soil temperatures, which delayed seedling emergence.

Table 3.1: percentage emergence of wild watermelon planted over three planting dates – Early (September), Optimum (November) and Late (January) – at Ukulinga Research Farm during 2008/09 planting season.

	Early Planting	**Optimum Planting**	**Late Planting**
	------------------------------ Emergence (%) ------------------------------		
Plot 1	4	8	7
Plot 2	0	4	8
Plot 3	4	6	8
Plot 4	7	6	4
Plot 5	5	6	3
Plot 6	4	5	0
Plot 7	3	7	1
Plot 8	3	5	4
Plot 9	3	7	5
Total	**33**	**54**	**40**
%	**40.74**	**66.67**	**49.38**
Average	**3.67**	**6.00**	**4.44**
STDev	**13.13**	**21.35**	**15.98**

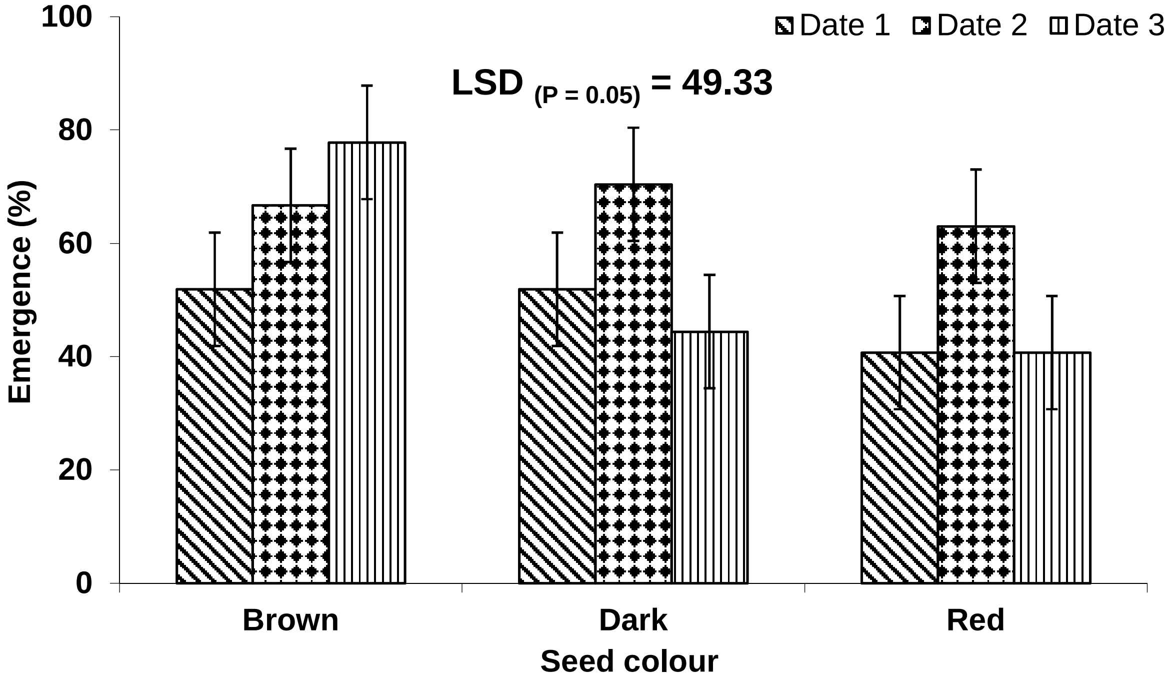

Figure 3.1: Percentage emergence of wild watermelon landrace selections (Brown, Dark and Red) planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

There were no significant differences ($P > 0.05$) between planting dates and seed colour with respect to number of vines (Figure 3.2). For the early planting (Date 1), the red seeds were observed to have the highest number of vines whilst brown had the least vine number. Optimum planting (Date 2) resulted in an almost similar number of vines for all seed colours. Red coloured seed had the lowest number of vine observed for the late planting (Date 3). However, optimum planting (Date 2) resulted in the most vine number for all seed colours; the dark coloured seeds also produced almost equal amounts of vine numbers across all planting dates.

There were significant differences ($P < 0.05$) in planting dates, seed colour, and their interactions with respect to vine length (Figure 3.3). Based on mean values for all seed colours, optimum planting (Date 2) resulted in the longest vine lengths compared with early and late planting dates (Figure 3.3). Similar to results of vine number, the dark coloured seeds showed the longest mean vine length across all seed colours (Figure 3.4).

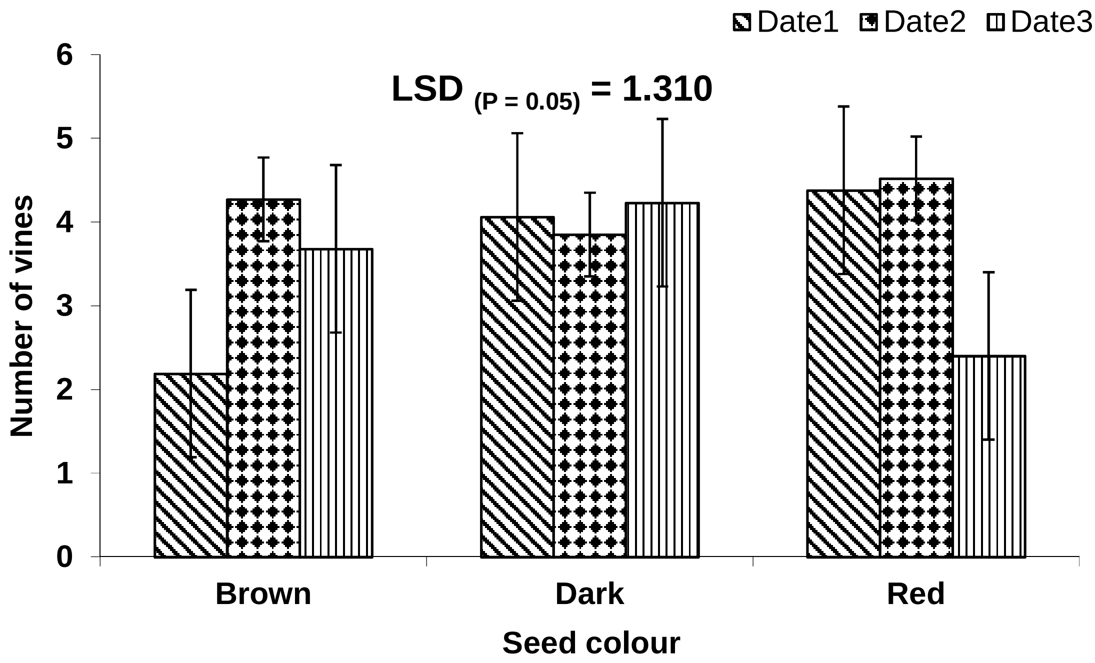

Figure 3.2: Number of vines of wild watermelon landrace selections (Brown, Dark and Red) planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

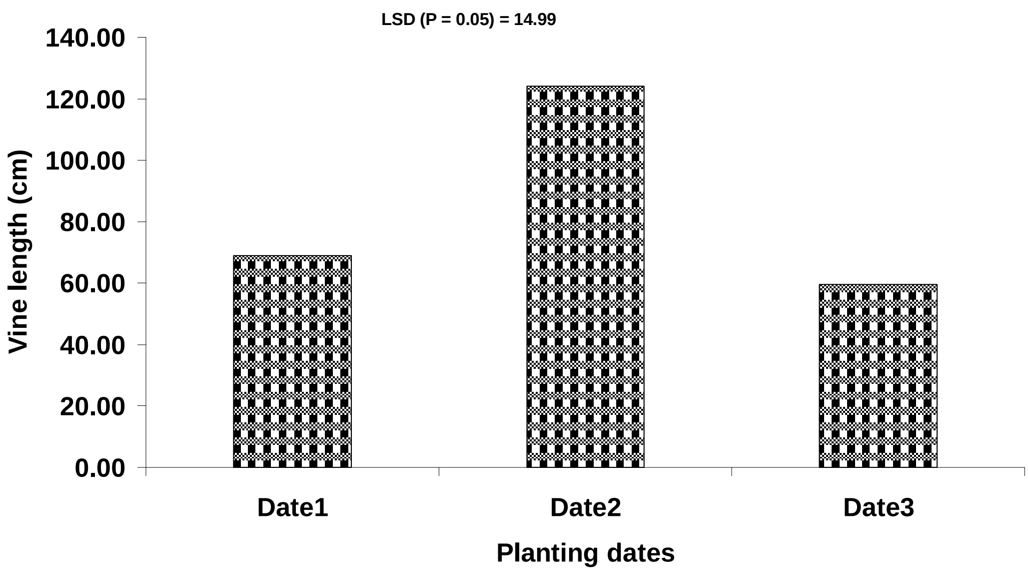

Figure 3.3: Vine length, based on mean values of wild watermelon landrace selections, planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

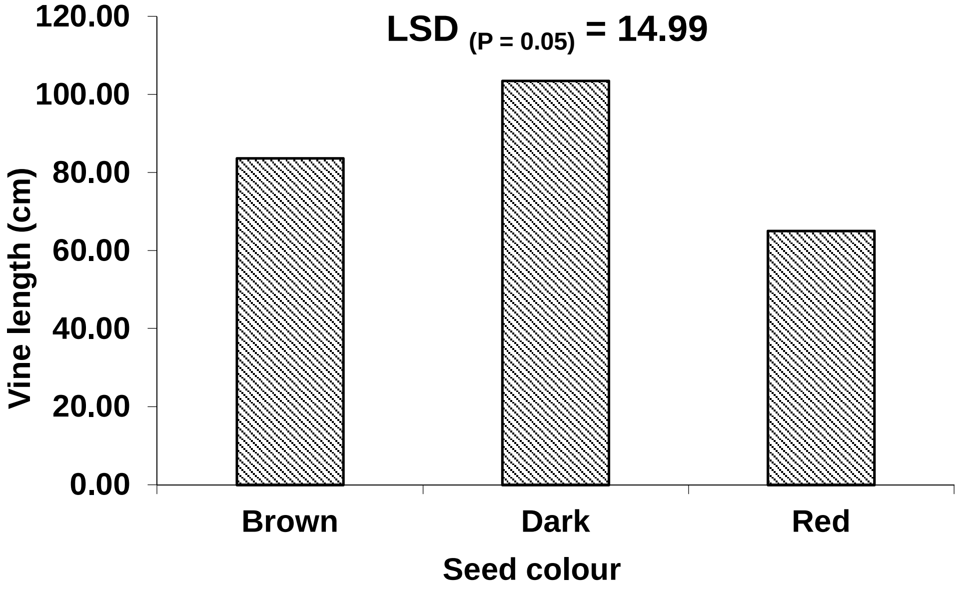

Figure 3.4: Vine length, number of Brown, Dark and Red wild watermelon landrace selections. Values are means of three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

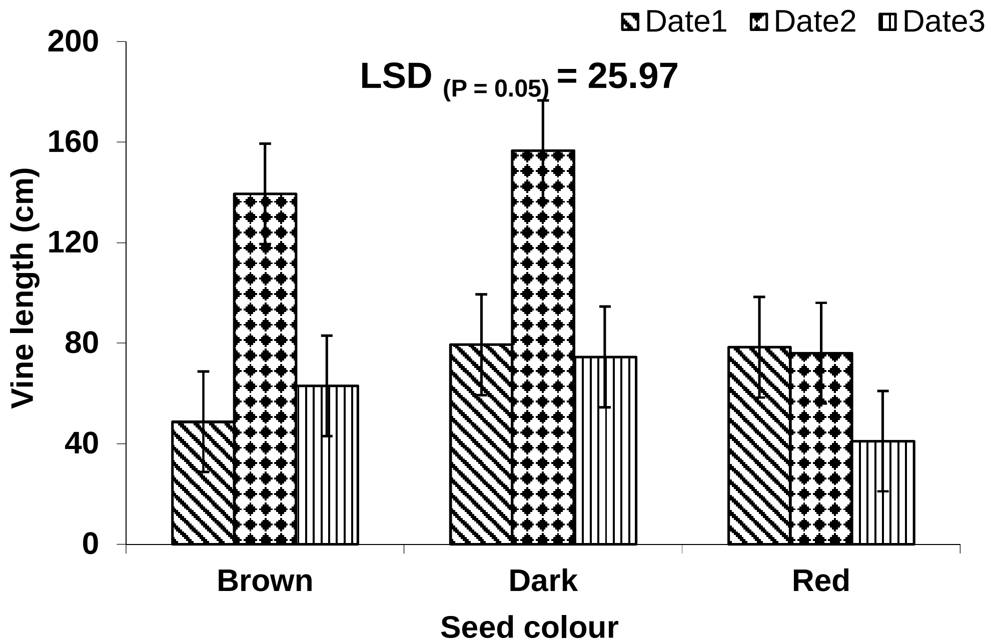

Figure 3.5: Vine length of wild watermelon landrace selections (Brown, Dark and Red) planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

There were significant differences ($P < 0.05$) between planting dates, seed colour selections, and their interactions with respect to number of leaves. The optimum planting (Date 2) showed the highest mean number of leaves across all planting dates (Figure 3.6). The red seed colour selection showed the fewest number of leaves across all seed colours (Figure 3.7). The red seed colour selection showed a trend of declining leaf number with successive planting date from the early to the late planting date 3 (Figure 3.8).

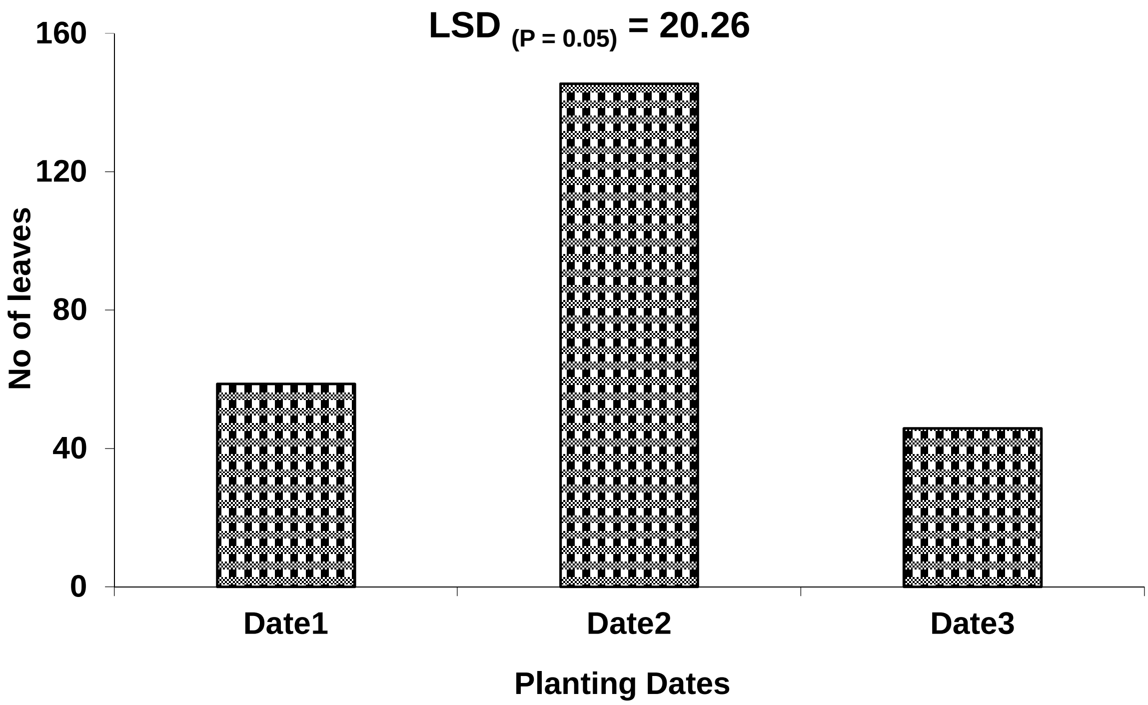

Figure 3.6: Plant leaf number, based on mean values of wild watermelon landrace selections, planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

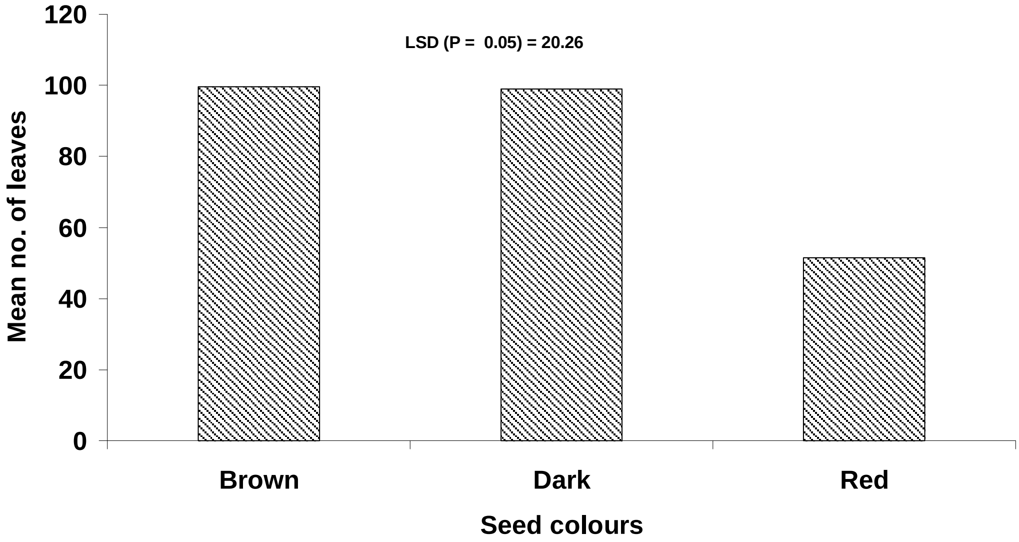

Figure 3.7: Plant leaf number of Brown, Dark and Red wild watermelon landrace selections. Values are means of three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

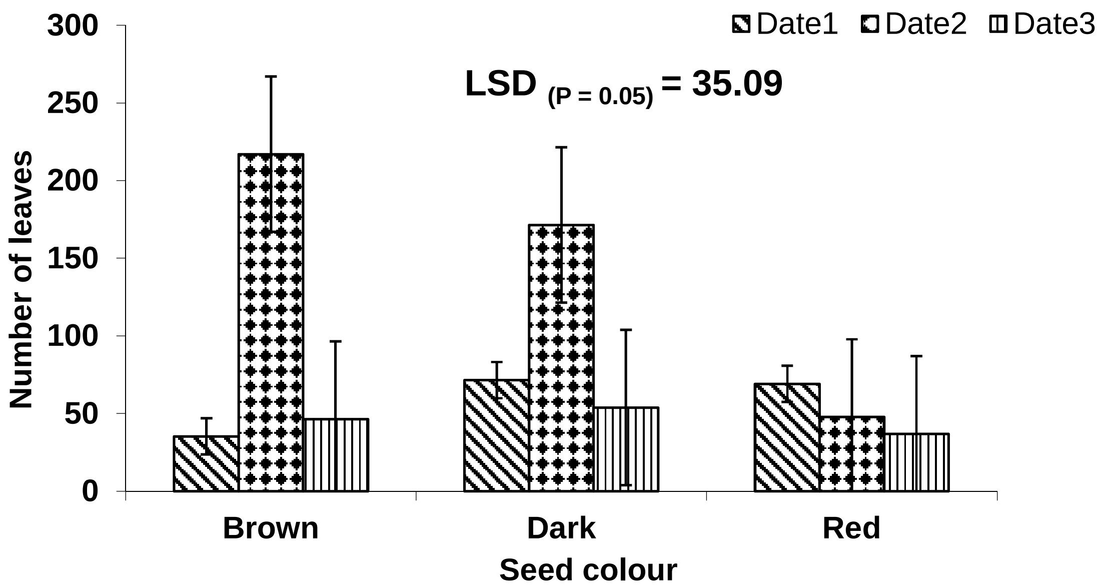

Figure 3.8: Plant leaf number of wild watermelon landrace selections (Brown, Dark and Red) planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

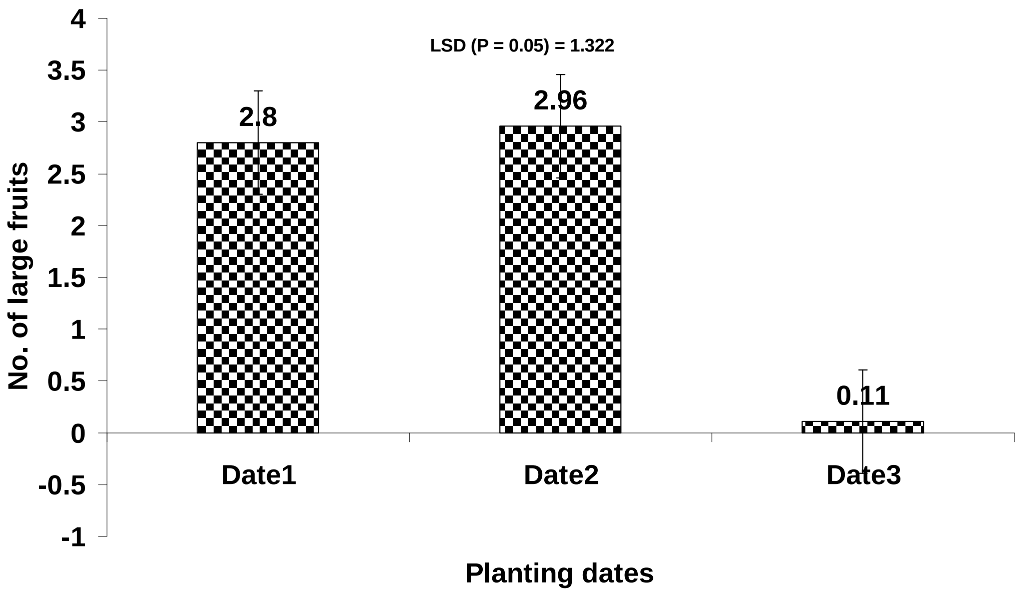

Figure 3.9: Fruit number, based on mean values of wild watermelon landrace selections, planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

Results of fruit number showed that there were only significant differences ($P < 0.05$) between planting dates (Figure 3.9). There were no significant differences ($P > 0.05$) between seed colour selections; the interaction between planting date and seed colour selection was also shown to be not significant. Early planting (Date 1) resulted in the highest fruit number; fruit number was lower for each successive planting date (Figure 3.10). However, interesting to note, although early planting (Date 1) had the highest number of fruit, it was the optimum planting (Date 2) that resulted in the highest number of large fruit (Figure 3.9).

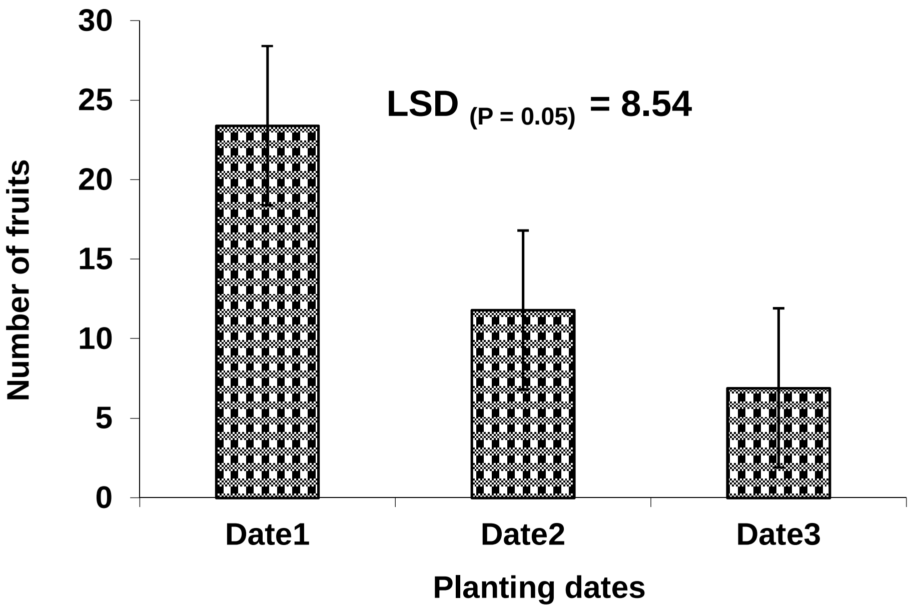

Figure 3.10: Fruit number per plant, based on mean values of wild watermelon landrace selections, planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

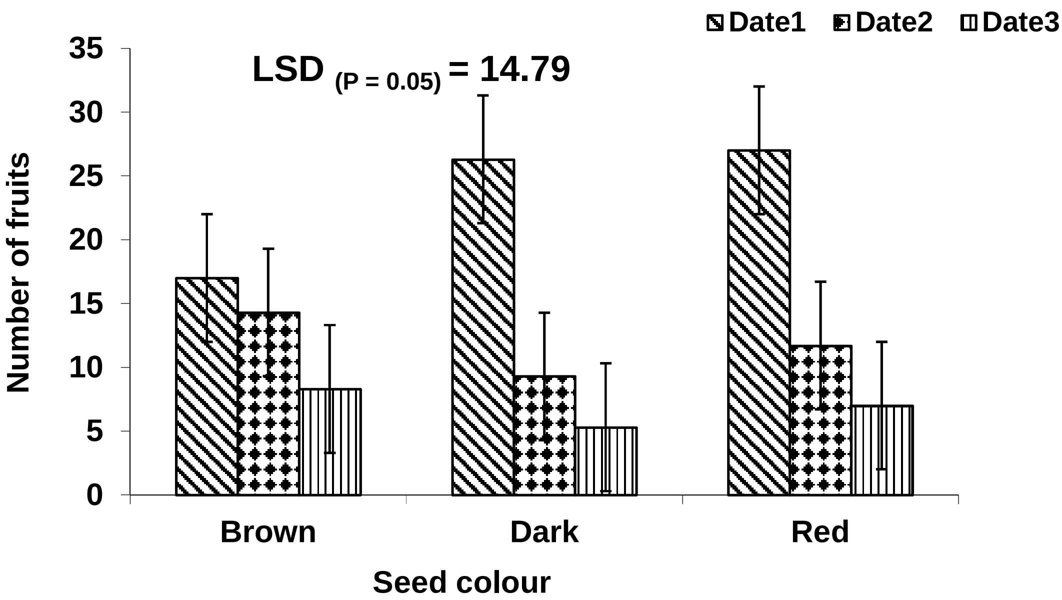

Figure 3.11: Fruit number per plant of wild watermelon landrace selections (Brown, Dark and Red) planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

There was a highly significant difference ($P < 0.05$) in planting date with respect to mean number of large fruits. Planting date 3 had the least mean number of fruits than other planting dates. However, red seed colour showed the highest mean number of large fruits even though there were not significant differences with respect to seed colours (Figure 3.12).

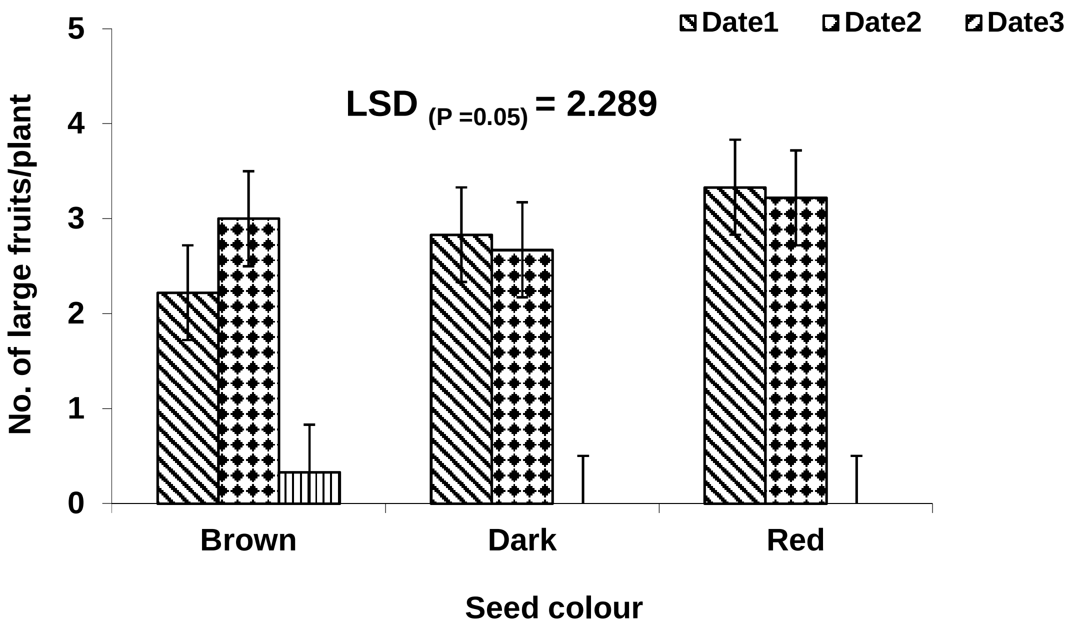

Figure 3.12: Number of large fruits per plant of wild watermelon landrace selections (Brown, Dark and Red) planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

There was a high significant difference ($P < 0.05$) in planting date with respect to mean number of medium fruits. Planting date 3 had no number of fruits produced (Figure 3.13) whilst planting date 1 had the highest mean medium fruits. However, red seed colour showed the highest mean number of medium fruits even though there were not significant differences with respect to seed colours (Figure 3.14).

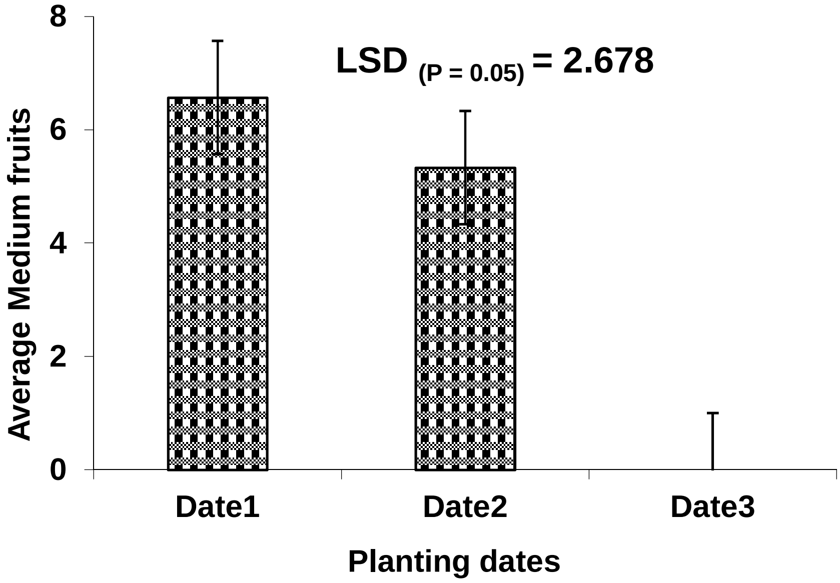

Figure 3.13: Number of medium fruit produced per plant, based on mean values of wild watermelon landrace selections, planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

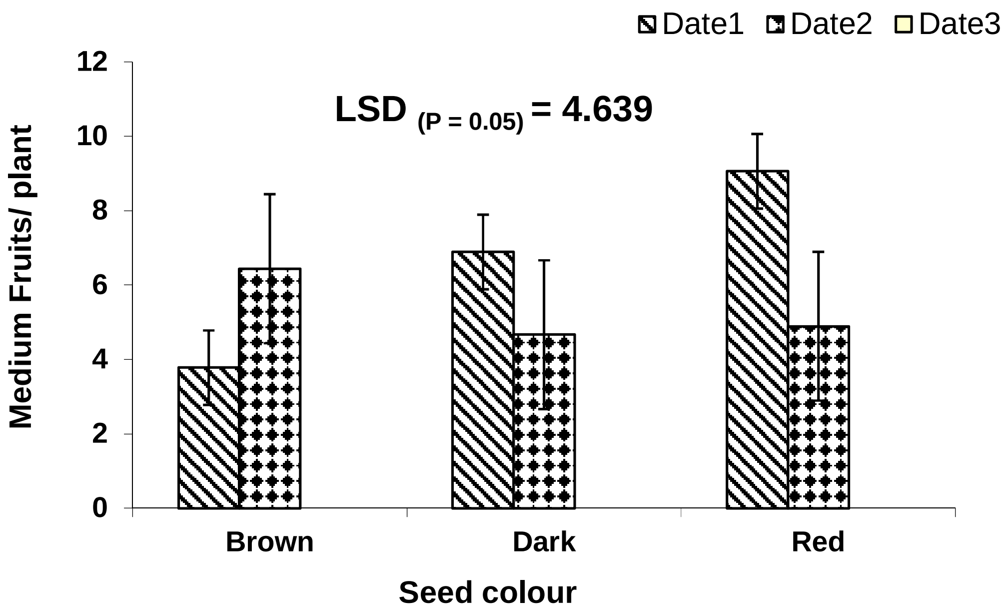

Figure 3.14: Number of medium fruits per plant of wild watermelon landrace selections (Brown, Dark and Red) planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

There were significant differences ($P < 0.05$) between planting dates with respect to mean number of small fruits. Early planting (Date 1) resulted in the highest number of small fruits produced across all planting dates (Figures 3.15 & 3.16). Early planting did not receive much rain, especially during the vegetative stage. However, rainfall coincided with the onset of flowering (data not shown) for the early planted crop. According to Whitmore (2000), moderate water stress can be tolerated during early vegetative growth. Crop sensitivity to drought increases in the late vegetative period; this is when the vines which will bear flowers and fruits develop. The most drought-sensitive stage is flowering. The optimum planting (Date 2) was planted after the onset of the rainy season. This resulted in vigorous vegetative growth in plants planted during the optimum planting. Late planting (Date 3) still managed to receive enough rainfall for emergence and during vegetative growth, hence the slightly better emergence and vegetative growth observed compared with the early planted crop. However, rainfall seemed to peter out as the late planted crop approached the flowering stage. As such, the late planted crop may have been exposed to water stress during flowering and yield formation stages. This possibly resulted in low fruit set owing to possible flower abortion while some fruits were observed to have senesced while still immature. All this translated to loss of yield. However, the red seed colour selection showed the highest number of medium fruits even though there were no significant differences ($P > 0.05$) between seed colours (Figure 3.16).

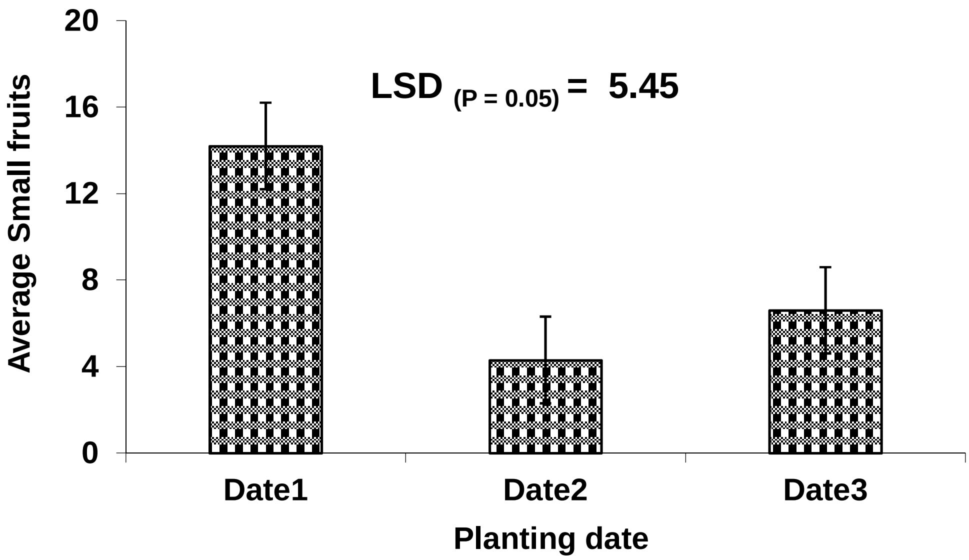

Figure 3.15: Number of small fruit produced per plant, based on mean values of wild watermelon landrace selections, planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

There were significant differences ($P < 0.05$) between planting dates with respect to average fruit mass. Based on mean values for all seed colour selections, early planting (Date 1) had the highest fruit mass (Figure 3.17 & 3.18). Overall, for all planting dates, the red seed colour selection had the highest fruit mass even though there were no significant differences ($P > 0.05$) between seed colour selections (Figure 3.18).

Following determination of yield and yield components, fruit were selected and used to obtain seed which was then used to evaluate seed quality. Results showed that the seed obtained from late planted crop (Date 3) failed to germinate; percentage germination was zero (Figure 3.19). Their failure to germinate was due to rotting during incubation. The reasons for the seed rotting were not fully understood. In general, germination percentage was very low for all seed lots, with a maximum of 52% observed in seed from the early planted crop. Furthermore, dark coloured seeds from the early planted crop showed the highest germination capacity compared with other seed lots (Figure 3.20 & 3.21).

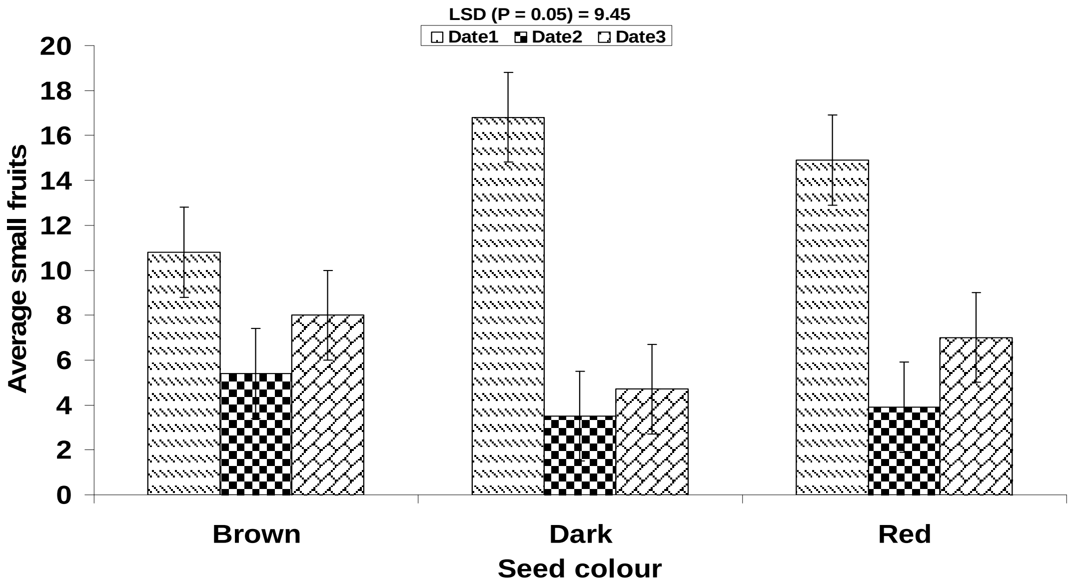

Figure 3.16: Number of small fruits per plant of wild watermelon landrace selections (Brown, Dark and Red) planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

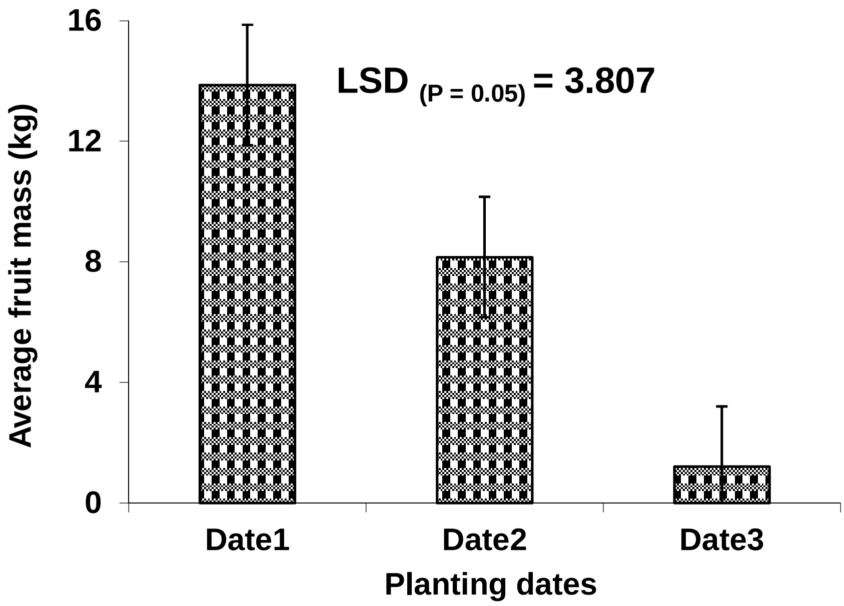

Figure 3.17: Average fruit mass (kg) produced per plant, based on mean values of wild watermelon landrace selections, planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

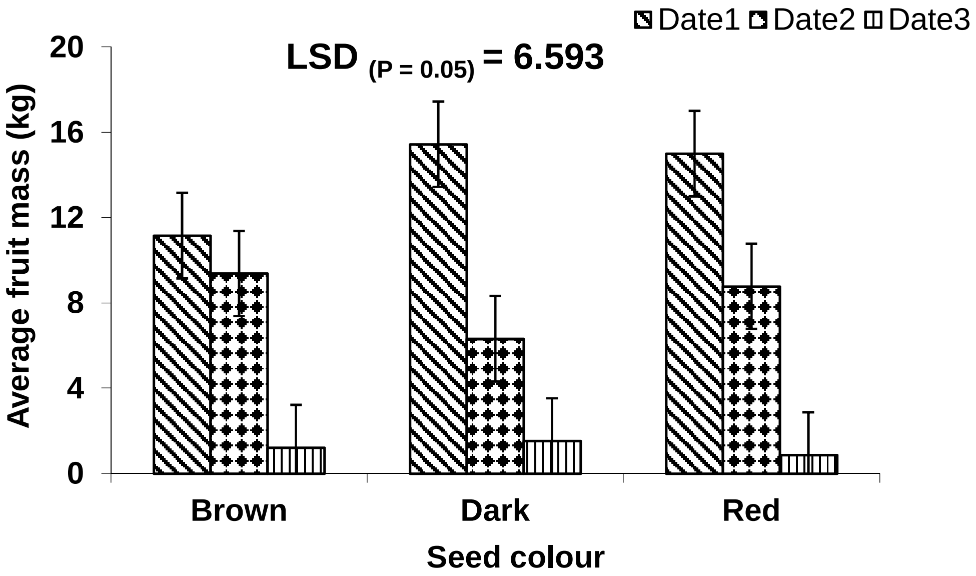

Figure 3.18: Average fruit mass (kg) per plant of wild watermelon landrace selections (Brown, Dark and Red) planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

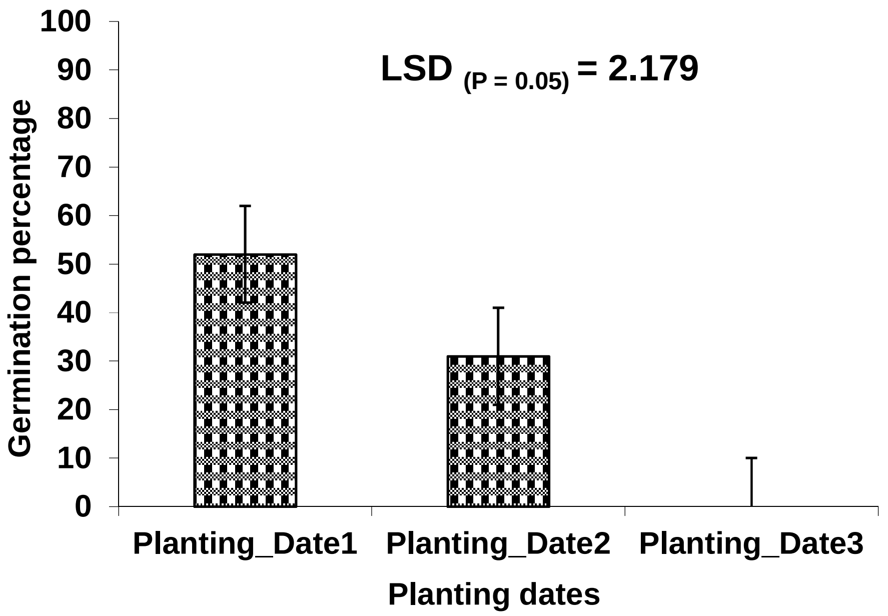

Figure 3.19: Germination percentage, based on mean values of wild watermelon landrace selections, planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

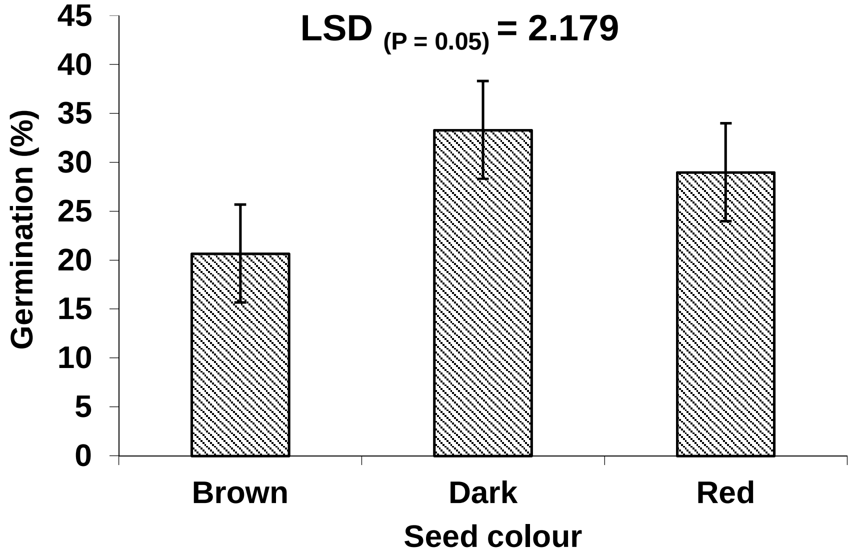

Figure 3.20: Germination percentage of Brown, Dark and Red wild watermelon landrace selections. Values are means of three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

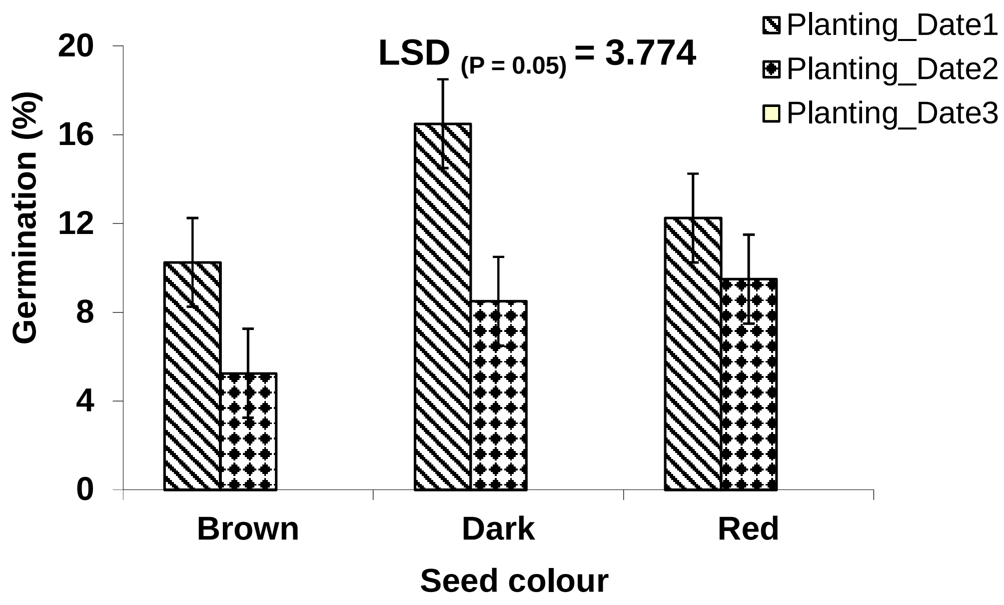

Figure 3.21: Germination percentage of wild watermelon landrace selections (Brown, Dark and Red) planted over three planting dates – Early (Date 1), Optimum (Date 2) and Late (Date 3) – at Ukulinga Research Farm during 2008/09 planting season.

3.4 Conclusion

Although wild watermelon is reported to be extremely drought tolerant, results of this study showed that water stress occurring during the late vegetative stages when vines that will bear flowers and fruits develop can be detrimental to yield attainment. For the early planted crop, there was no rainfall received after sowing for almost four weeks and minimal rainfall received during the early vegetative stages. The onset of the rainy season coincided with the late vegetative stages and flowering stages in the early planted crop. As such, the early planted crop was not subjected to water stress conditions during the flowering stages; this explained the high fruit and large fruit number observed in the early planted crop. The optimum and late planted trials were planted after the onset of the rainy season when there was sufficient rainfall and soil water content for crop growth and development. As such, the optimum and late planted crop exhibited better emergence and vegetative growth (vine length, the number of vines and leaf numbers) compared with the early planted crop due to improved soil water availability during establishment and early vegetative stages. However, the early planted crop still gave the highest yield with largest and highest number of fruits compared with the optimum and late planted trials. This suggests that the crop's tolerance to water stress during the early vegetative stages makes it suitable for early planting with possibility of obtaining high yields. This suggests that wild watermelon may be suitable for several semi-arid environments where farmers typically plant early before the onset of the rainy season. The fact that the late planted crop failed due to lack of sufficient soil water in the later growth stages (flowering) suggests that wild watermelon is sensitive to water stress at the flowering stage. As such, farmers should be discouraged from planting it late in the season.

The study showed that seed quality is a major challenge to the successful production of wild watermelon. The crop appeared to have inherent poor seed quality. The use of seed colour as a selection criterion for seed quality seemed to imply that darker coloured seeds may have better seed quality. This also translated to better performance under field conditions. There is need to further explore the issue of seed quality in wild watermelon if the crop's drought tolerance is going to be fully exploited. Strategies to improve seed quality and/or emergence at the farm level such as priming should be evaluated. At the same time, breeding efforts to come up with varieties that have high seed quality should also be taking place.

Chapter 4

Drought tolerance of selected wild mustard landraces: *Brassica juncea and Brassica nigra*

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4.1 Introduction

African leafy vegetables (ALVs) form part of a collective of leafy vegetable species that have historically formed part of the traditional foods of African communities (Oelofse & Van Averbeke, 2012). They are highly recommended due to their high nutritional quality (Modi, 2006). They are rich sources of vitamins, mineral trace elements and dietary fibre (Oelofse & Van Averbeke, 2012); they are also a source of proteins (Humphrey *et al.*, 1983; Fafunso & Bassir, 1976). This of major importance within the South African context since deficiencies in vitamin A, iodine and zinc are also important (Faber & Wenhold, 2007). Eliminating these deficiencies is estimated to result in IQ increase of 10-15 points, lower maternal deaths and infant mortality by one third African (Darton-Hill *et a*l., 2005). In addition, ALVs are reported to have medicinal properties which include anti-diabetic, anti-carcinogenic and anti-bacterial properties (Kesari *et al.*, 2005; Kubo *et al.*, 2004; Khana *et al.*, 2002). The use of leafy vegetables by many South Africans is highly dependent on factors such as poverty, urbanisation and accessibility of fresh produce markets as well as seasonality of production (Voorster *et al.*, 2002).

African leafy vegetables are important for food and nutrition security during periods of drought and poor harvests as well as for income generation. In a recent report by Oelofse and Van Averbeke (2012), they evaluated the drought and heat tolerance of six ALVs compared with Swiss chard. The six ALVs included in their report were amaranth (*Amarunthus cruentus* L.), cowpeas (*Vigna unguiculata* L.), wild jute (*Corchorus olitorius* L.), *Cleome gynandra* (spider flower, cat's whiskers, spider plant and bastard mustard), *Citrullus lanatus* (Tsamma melon, bitter melon and *egusi* melon), pumpkin (*Curcubita maxima*), nightshade (*Solanum retroflexum*) and non-heading Chinese cabbage (Brassica rapa L. subsp. Chinensis). Their results indicated that, on average, ALVs were more drought tolerant than Swiss chard (Oelofse & Van Averbeke, 2012). This is of particular significance to South Africa, already a water stressed country, and whose water sector is set to be considerably negatively affected by climate change (Schulze, 2011). African leafy vegetables could therefore play a key role in securing the dietary requirements of ordinary South Africans.

Wild mustard is an indigenous African leafy vegetable in South Africa. It is believed to have been originally consumed by the Khoisan people, the original inhabitants of southern Africa. Since they originated in the wild and have survived there with little or no help from man, wild mustard landraces are thought to have possibly evolved to become drought tolerant It is also due to this fact that they remain a neglected underutilised species (NUS). Not much is known about its agronomy and mechanisms of adapting to water stress. It is important to gain such knowledge (Geissler *et al*., 2002) in order to reinstate them within the rural communities in South Africa. Although wild mustard is an indigenous ALV in South Africa, literature on its growth response to water stress and its adaptation is lacking. In this study, it was hypothesised that wild mustard landraces are drought tolerant and that such drought tolerance could be associated with seed coat colour. Thus, the objective of this study was to evaluate the responses of wild mustard landraces separated into distinct seed colour selections to water stress under field conditions.

4.2 Material and methods

4.2.1 Plant materials

Seeds of three wild mustard landraces, Isaha, Masihlalisane (*Brassica juncea* L. Czern & Coss) and Kwayimba (*Brassica nigra* L. W.D.J. Koch), were originally sourced from subsistence farmers in Tugela Ferry and multiplied at the University of KwaZulu-Natal during 2007. The seeds from the multiplication trials were then used for a field experiment at the University of KwaZulu-Natal's Ukulinga Research Farm, Pietermaritzburg (29°16'S; 30°33'E). To create more variation within genotypes, seeds of each landrace were separated into black and brown seed colour types.

4.2.2 Experimental design and data collection

The experiment was conducted over two seasons: winter (May, 2009) and spring (September, 2009). A randomised complete block design with three replications was used for non-irrigated and irrigated (25 mm week^{-1}) trials. Water stress was imposed in the non-irrigated trial by withdrawing irrigation 14 days after planting (DAP). Soil samples were collected three times a week to determine soil water content at 5 cm, 15 cm and 30 cm depth. Tensiometers (up to 30 cm depth) were used to monitor soil water content in both trials. Emergence was measured up to 21 DAP. Determination of plant height and leaf number was done every 7 days. The experiment was terminated at the flowering stage. Thereafter, leaf area, fresh mass and dry mass were measured. The second trial was treated the same way as the first trial. Leaf samples were taken for proline determination at harvesting.

4.2.3 Proline determination

Proline accumulation in wild mustard leaves from both stressed and unstressed leaves was determined according to the method of Bates *et al*. (1973). Samples of freeze-dried leaf tissue (0.5 g) were homogenised in 10 ml of 3% sulfosalycic acid (w/v) and ultraturaxed for 60 seconds. The homogenate were then centrifuged at 11 000 rpm for 10 min at 4°C. Supernatant were added to 2 ml of acid ninhydrin and 2 ml of acetic acid. The mixture was incubated in a hot water bath (100°C) for one hour with constant shaking and the reaction terminated in ice. The reaction mixture was extracted with 4 ml toluene, and vortexed for 15-20 sec. The toluene phase was used to measure the absorbance at 520 nm (Beckman Coulter DU® 800). Toulene was used as a blank. A standard curve was used to determine the concentration of proline by using the formula:

[(µg proline/ml x ml toluene)/ (115µg/µmole)]/ [(g sample)/5] = µmoles proline/g of dry weight material.

4.2.4 Statistical analyses

Data were analysed using analysis of variance from GenStat® Version 11 (VSN International, UK). Thereafter, means were separated using least significant differences (LSD) at the 5% level of significance (P = 0.05).

4.3 Results and discussion

There were significant differences among cropping seasons with respect to soil water content. Seeds planted in winter were able to emerge under low soil water content (< 20%) under non-irrigated conditions characterised by low rainfall and low temperatures (Figure 4.1). However wild mustard selections emerged very well under moderate rainfall and high temperatures with high soil water content (see other results below).

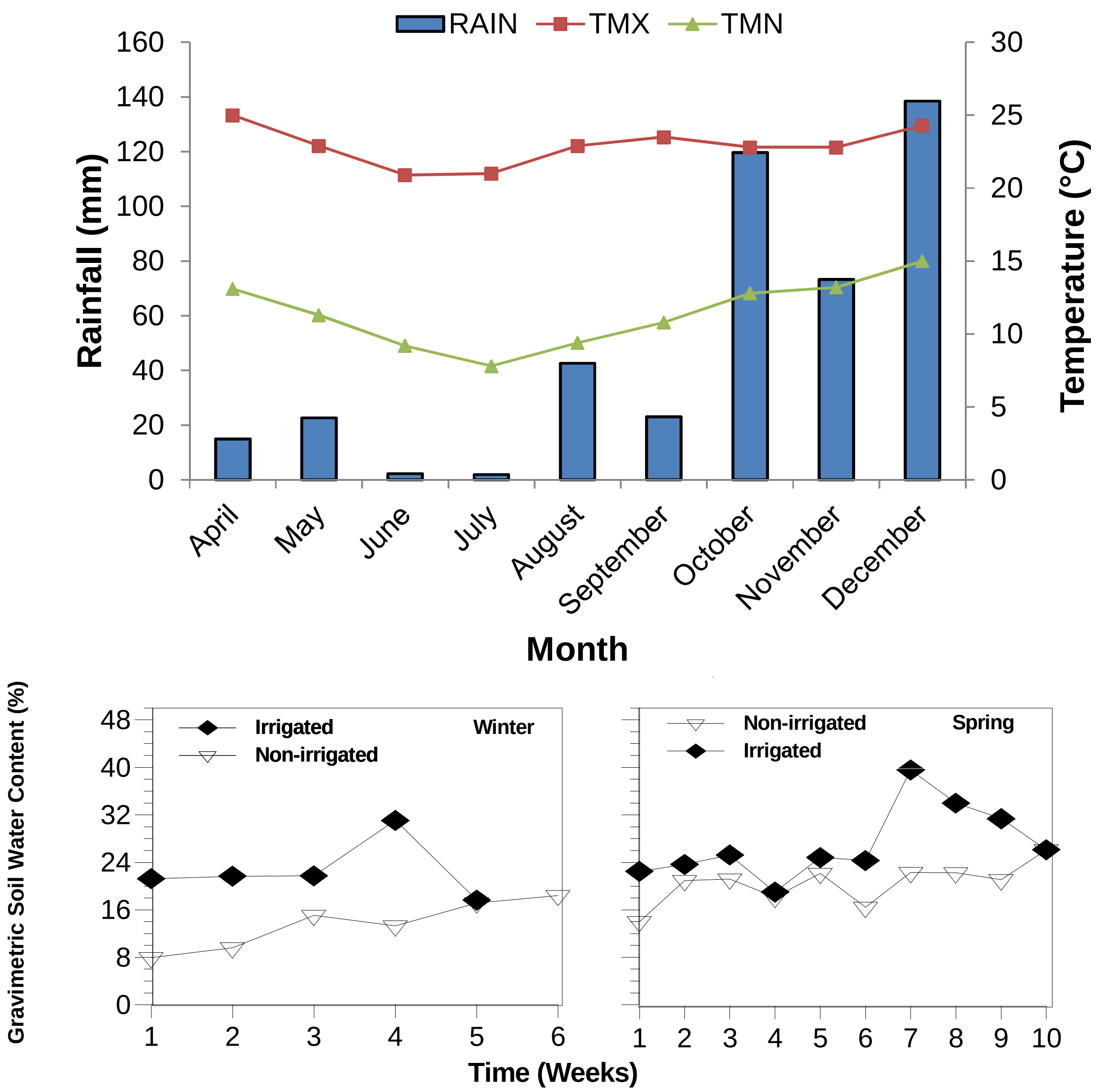

Figure 4.1: Total rainfall (mm) received, monthly average maximum and minimum temperatures (TMX & TMN) and gravimetric soil water content (%) observed during the planting season (April-December 2009).

The interaction between planting date (PD), irrigation treatment (IT) and landrace (LR) was not significant ($P > 0.05$) for plant height (mm), but there were significant differences ($P < 0.05$) between (PD x LR) and (PD x IT) (Figure 4.2) and for both the main effects planting date and landraces. In winter, plant height did not differ ($P > 0.05$) between irrigated and non-irrigated treatments for Isaha and Kwayimba landraces; however, for Masihlalisane, plant height was significantly ($P < 0.05$) lower for Masihlalisane grey seed colour when trials were not irrigated. No significant differences ($P > 0.05$) were observed for black seed colour of Masihlalisane (Table 4.1).

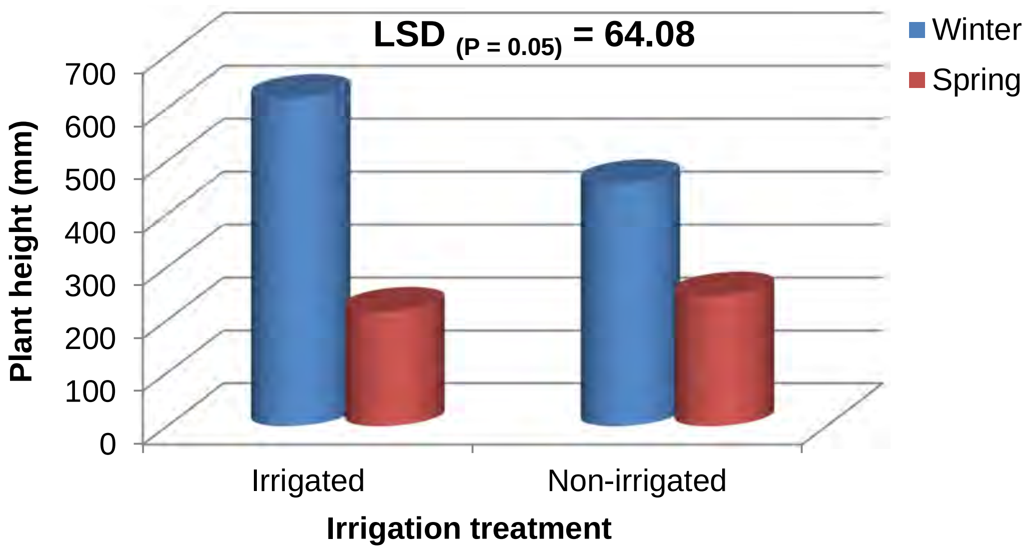

Figure 4.2: Response of wild mustard landraces in terms of plant height with respect to planting date and irrigation treatment. Values plotted are means of all wild mustard landraces.

Kwayimba black and reddish brown seeds responded positively in spring with an increase in leaf area, with brown seeds showing no significant difference. A similar response was observed for brown seeds of Masihlalisane which showed an increase in leaf area in spring while the grey and black seed colours showed an increase in leaf area of which there were highly significant differences ($P < 0.001$) (Table 4.2). The leaf area of all the seed colours of Kwayimba was low in winter; however, leaf area was relatively higher in spring. Leaf area and leaf number are plant mechanisms associated with drought avoidance. In addition, they are important for estimation of photosynthetic rate, light interception as well as water and nutrient use by the plant during growth. Plants will reduce their leaf area under water stress in order to minimise transpirational losses. The study showed that leaf area and leaf number were sensitive to water stress in some wild mustard landraces. Masihlalisane brown and Kwayimba black landraces did not show their sensitivity to water stress through leaf area and number reductions.

Table 4.1: Plant height (mm) for wild mustard landraces planted in winter and spring during 2009. Values are means of wild mustard landraces across water regimes.

Landrace and seed colours	**Planting date**		
	Spring	**Winter**	**Mean**
Isaha			
Brown	567ab	264c	**414.5**
Greyish-black	601a	215c	**408.0**
Reddish-brown	619a	248c	**433.5**
Kwayimba			
Black	455b	210c	**332.5**
Brown	500ab	191c	**345.5**
Reddish-brown	511ab	224c	**367.5**
Masihlalisane			
Black	431b	229c	**330.0**
Brown	439b	287c	**363.0**
Grey	722a	217c	**469.5**
Mean	**538.3**	**231.4**	**384.8**

LSD (Planting date) = 45.8

LSD (Landraces) = 97.2

LSD (Planting Date x Landrace)= 137.5

CV% = 30.8

Means followed by the same letter are not significantly different at P = 0.05.

Table 4.2: Leaf area (cm^2) interaction for wild mustard landraces at different planting dates (winter and spring). Values are means of wild mustard landraces across water regimes.

Landraces and seed colours	**Planting date**		
	Winter	**Spring**	**Mean**
Isaha			
Brown	125c	557b	**341.0**
Greyish-black	83c	645b	**364.0**
Reddish-brown	83c	645b	**364.0**
Kwayimba			
Black	52c	1145a	**598.5**
Brown	57c	545b	**301.0**
Reddish-brown	54c	1325a	**689.5**
Masihlalisane			
Black	129c	498bc	**313.5**
Brown	131c	1237a	**684.0**
Grey	122c	616b	**369.0**
Mean	**92.8**	**801.4**	**447.1**

LSD (Planting Date)=120.4

LSD (Landraces) = 255.3

LSD (WR x LR) = 361.1

CV% = 69.3

Means followed by the same letter are not significantly different at P = 0.05.

The interaction between landrace, irrigation treatment and planting date (LR x IT x PD) was not significant (P > 0.05) for fresh mass, but significant differences were found for (PD x IT) and (PD x LR) interaction (Table 4.3). Masihlalisane brown seed colour had significantly high biomass accumulation in spring whereas in winter all Masihlalisane seed colours landraces brown seed colour was the lowest but there were no significant difference within the seed colours landrace. Black seeds of Kwayimba showed a significant increase in fresh mass on different planting dates. Reddish-brown seed of Kwayimba had significantly high biomass accumulation in spring. Brown seeds of Isaha showed a similar pattern in terms of fresh mass which showed a significant increase in biomass during spring. Means in biomass over all landraces seed colour increased significantly from 24.0 g to 106.2 g when planting date was changed from winter to spring.

Table 4.3: Fresh mass interaction for different wild mustard landrace seed colours at two different planting dates winter and spring. Values are means of wild mustard landraces across water regimes.

Landraces and seed colours	**Planting date**		
	Winter	**Spring**	**Mean**
Isaha			
Brown	26.8cd	91.4bc	**59.1**
Greyish-black	13.5d	80.1cd	**46.8**
Reddish-brown	30.4cd	73.8cd	**52.1**
Kwayimba			
Black	12.8d	141.1a	**77.0**
Brown	18.4d	88.8bc	**53.6**
Reddish-brown	20.5d	184.2a	**102.4**
Masihlalisane			
Black	35.2cd	54.2cd	**44.7**
Brown	26.6cd	155.5a	**91.1**
Grey	32.1cd	86.3bcd	**59.2**
Mean	**24.0**	**106.2**	**65.0**

LSD (Planting date)=19.86

LSD (Landraces) = 42.14

LSD (WR x LR) = 59.59

CV% = 79.0

Means followed by the same letter are not significantly different at P = 0.05.

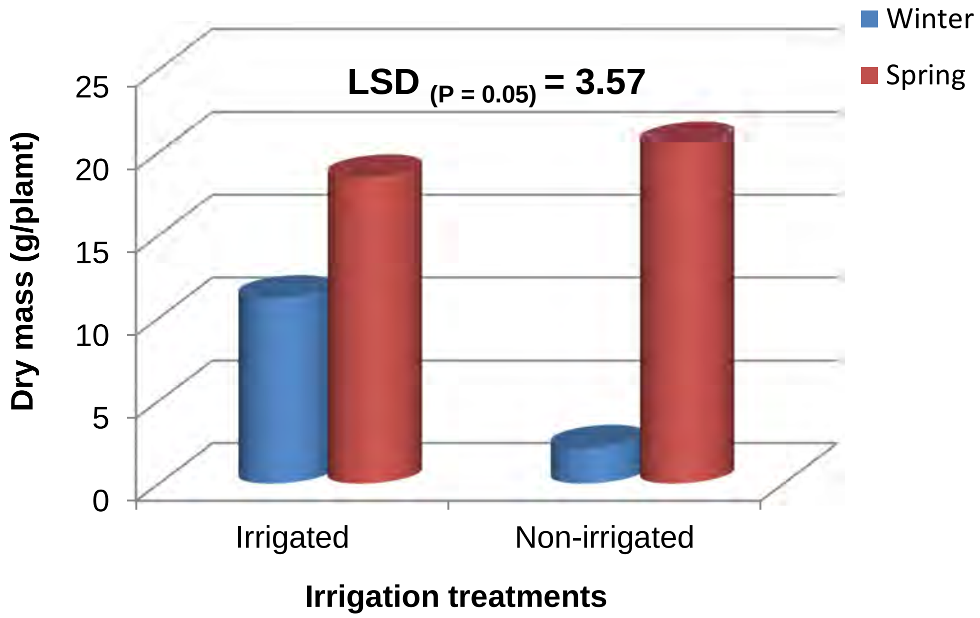

Figure 4.3: Main effects for dry mass for different planting dates and irrigation treatments of irrigated and non-irrigated. Values shown are means of all wild mustard landraces across water regimes and planting dates.

There was a significant interaction ($P < 0.05$) between planting date, irrigation treatment and landraces with respect to dry mass (Table 4.4). Wild mustard landraces showed significantly higher dry mass in the irrigated for both winter and spring planting date. However, dry mass was significantly reduced in the non-irrigated plots in winter. Wild mustard plants showed a significant difference in the non-irrigated treatment (Figure 4.3). In the non-irrigated treatment dry mass increased significantly from 2.15 g in winter to 20.48 g spring. Kwayimba reddish-brown of all the landraces had the higher (48.33 g) dry mass in the irrigated treatment in winter than all the landraces. Means in dry mass over all landraces was reduced from 11.19 g to 2.15 g in winter in both the irrigated and non-irrigated treatment. However, over all wild mustard landraces dry mass was slightly reduced from 14.84 g to 11.32 g for both planting date and irrigation treatment. Dry mass was not significantly reduced.

Table 4.4: Dry mass of wild mustard landraces planted over two planting dates (winter and spring) under irrigated and non-irrigated field conditions.

		Irrigation Treatment		
Planting date	**Landraces**	**Irrigated (IR)**	**Non-irrigated (NIR)**	**Mean**
Winter	IB	4.6d	1.49c	**3.79**
	IGB	2.93d	0.87c	**1.90**
	IRB	16.27cd	1.54c	**8.91**
	KBL	0.99d	3.69c	**2.34**
	KBR	3.98d	3.83c	**3.91**
	KRB	48.33a	2.85c	**25.59**
	MBL	6.63d	1.11c	**3.87**
	MBR	11.79d	1.5c	**6.65**
	MG	5.16d	2.45c	**3.81**
Spring	IB	13.29cd	19.68ab	**16.49**
	IGB	18.8bcd	15.3b	**17.05**
	IRB	13.12cd	17.33b	**15.23**
	KBL	22.63bcd	25.67ab	**26.15**
	KBR	16.65cd	17.37b	**17.01**
	KRB	22.33bcd	24.99ab	**23.66**
	MBL	14.41cd	15.96b	**15.19**
	MBR	29.42b	29.42a	**29.42**
	MG	15.74cd	18.63b	**17.19**
Mean		**14.84**	**11.32**	**13.23**

LSD (Planting Date) =2.526

LSD (Landraces) = 5.358

LSD (Irrigation Treatment) = 2.526

LSD (PD x LR x IT) = 10.716

CV% = 50

Means followed by the same letter are not significant at p=0.05

There was a highly significant interaction ($P < 0.001$) between landrace and treatment (LR x T) with respect to proline accumulation (Figure 4.2a, b). In winter Kwayimba black seeds accumulated more proline than all landraces seed colour. However, in spring under non-irrigated conditions Masihlalisane black and grey seed colour showed higher proline content than Kwayimba and Isaha. Plants in the non-irrigated trial accumulated more proline than plants in the irrigated trial.

High yield obtained in Kwayimba black during winter was correlated to proline accumulation. Kwayimba avoided stress through accumulation of proline. However, plant growth in Isaha and Masihlalisane under low soil water content during winter was negatively correlated to proline accumulation. Proline accumulation in Masihlalisane (black and grey) and Isaha was high under low soil water content. The results agreed with Lutts *et al*. (1996) that proline was involved in osmotic adjustments under water stress. Proline involvement in osmotic adjustment (under stress) is still debated; however, it is believed that it varies according to the species which agrees with the results obtained in this study (Lutts *et al*., 1996; Rhodes & Hanson,1993) that proline accumulation in wild mustard varies with cultivars.

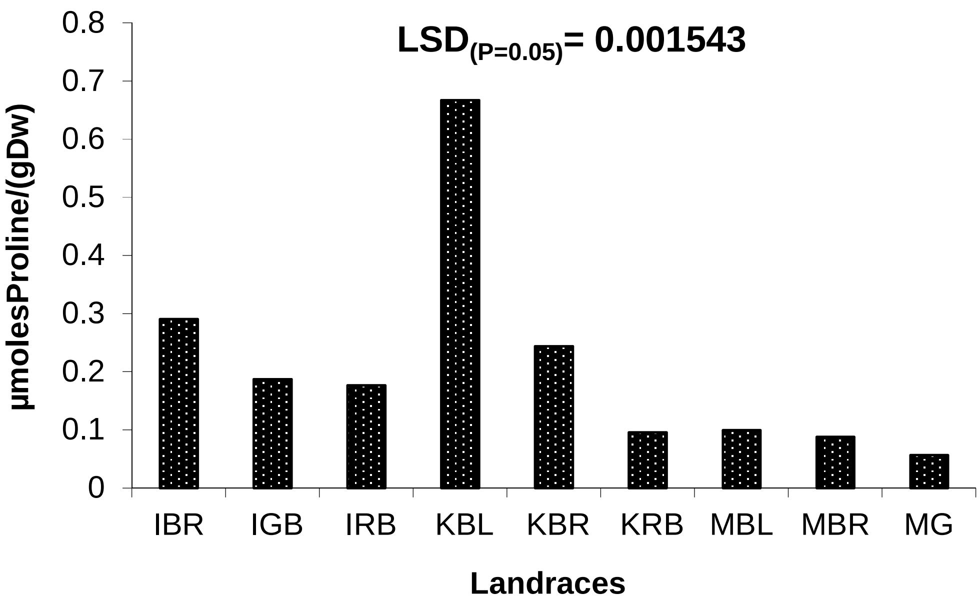

Figure 4.4: Changes in proline content of plants harvested from a winter planted trial (non-irrigated only).

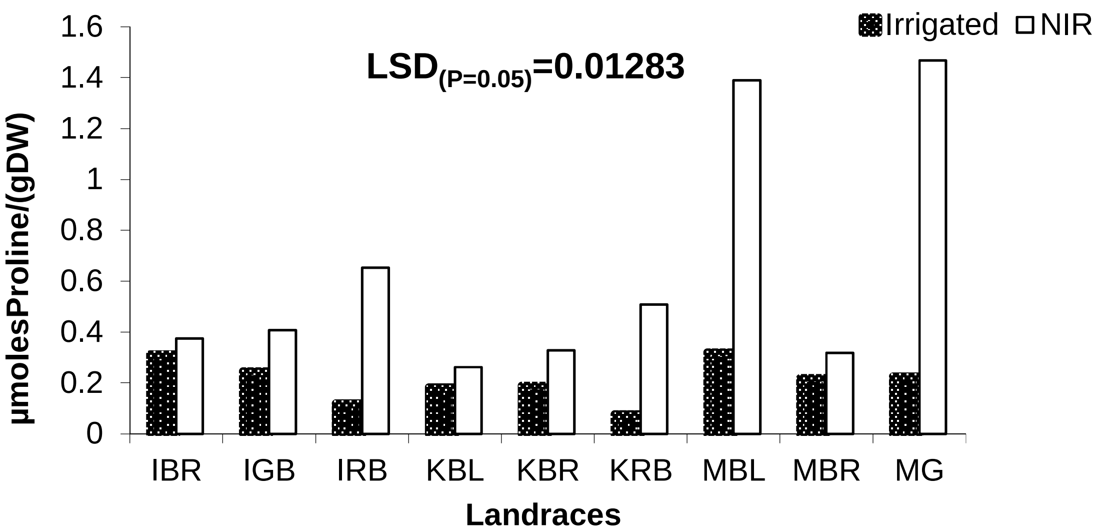

Figure 4.5: Changes in proline content of plants harvested from a spring planted trial (both irrigated and non-irrigated (NIR). Note: I = Isaha, M = Masihlalisane, K = Kwayimba; BL= black seed, BR = brown seed, G = grey seed, GB = greyish-black, RB = reddish-brown.

4.4 Conclusions

The study showed that the wild mustard landraces used were drought tolerant. Drought tolerance in wild mustard was achieved through reduced plant height, leaf number and leaf area under non-irrigated compared with irrigated conditions. The study showed that wild mustard grows better in spring than in winter hence farmers would be advised to plant it during spring. The use of proline, a metabolite associated with drought tolerance, to evaluate drought tolerance was explored in this study. Our results showed that drought tolerance in wild mustard is physiologically negatively correlated to proline accumulation. However, these results of proline are inconclusive. Measurement of proline accumulation in response should not be a once of measurement, but rather a continuous measurement, as is with other growth parameters. This would facilitate to observe when it starts to accumulate (onset of stress), when it peaks and when it declines. Such information would be more meaningful and beneficial to its role in plant stress acclimation. Therefore, it is recommended that a future study be done whereby proline accumulation is measured periodically, possibly on a daily time scale – a time scale similar to the one that plants experience under field conditions. The use of seed colour as a possible drought tolerance criterion proved useful in that Masihlalisane brown was shown to be drought tolerant. Overall, this study would be useful as an initial step towards genetic selection for drought tolerance in wild mustard in an attempt to identify, select and develop wild mustard as a horticultural crop for production in water limited areas.

Chapter 5

Drought tolerance of cowpeas

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5.1 Introduction

Cowpea [*Vigna unguiculata* (L.) Walp] is an important legume known for its uses as a grain and fodder crop (Singh *et al*., 2003). It is cultivated worldwide in tropical and subtropical regions (Ogunkamni *et al.,* 2006) and has potential to contribute significantly towards food security. Since both cowpea leaves and grain are rich sources of vitamins and minerals (Bressani, 1985), it could provide dietary support for rural households as a relatively cheap protein source (Sebetha *et al*., 2010). Cowpea is reported to be a drought tolerant, and hot weather crop due to its adaptation to semi-arid regions where other legume crops do not perform well (Singh *et al*., 2003). However, despite such potential, the crop still remains neglected in terms of research and crop improvement (Barrett, 1990; Schippers, 2002).

In many parts of Africa, it is a common practice to consume young cowpea leaves as a vegetable (Barret *et al.,* 1997). In South Africa, Oelofse and Van Averbeke (2012) reported that that cultivation of cowpeas, as a leafy vegetable, is being done fairly widely. They went on to rank it as the 6th most popular ALV cultivated and consumed by smallholder farmers in South Africa. Previous research has shown that cowpea leaves contain carbohydrates and protein content comparable to that in cowpea grain (Bubenheim *et al.,* 1990). As such, the consumption of cowpea leaves as a vegetable may provide nutritional and harvest versatility (Bubenheim *et al.,* 1990). However, leaf harvesting may have a negative impact on grain yield if the crop is grown for both purposes (Bittenbender, 1992). Several studies have been conducted on cowpea to improve the methods of sequential leaf harvesting without imposing a significant damage on grain yield. These include suitable plant growth stage for leaf harvesting (Matikiti *et al*., 2009; Ibrahim *et al*., 2010) and intensity of harvesting (Nielsen *et al*., 1997; Ibrahim *et al.,* 2010).

While the effect of leaf harvesting on grain yield of cowpea has been studied, few studies have evaluated the combined effect of water stress and leaf harvesting on grain yield of cowpea.

Although cowpea is reported to be drought tolerant, these two factors: sequential harvesting and drought stress need to be well understood. Such information would prove useful in advising farmers who grow cowpea in marginal areas of production; such that they understand the potential of the crop to produce both green leafy vegetables and grain yield. In addition, recent reports by Spreeth et al. (2004) suggested that cowpeas could be developed as a cash crop for smallholder farmers as an alternative bean. As such, such information on the effect of leaf harvesting on grain yield under water limited conditions could be useful in formulating recommendations for farmers. Therefore, the objective of this study was to evaluate the effect of water stress and sequential leaf harvesting on plant growth and grain yield of two cowpea varieties.

5.2 Materials and Methods

5.2.1 Plant material

Two determinant cowpea varieties differing in seed colour (Brown and White birch) were purchased from a local seed supplier, Capstone Seeds, in 2011 and used for the experiment.

5.2.2 Field description and experimental design

A field trial was conducted at the University of KwaZulu-Natal’s Ukulinga Research Farm in Pietermaritzburg (29°37’S; 30°16’E; 775 masl). Ukulinga soils were characterised as clay loam (SA Taxonomic system). Ukulinga has a semi-arid climate with an average annual rainfall of about 694 mm received mainly during the summer months (mid-October to mid-February).

The experimental design was a factorial experiment (three factors) laid out in a split-plot design, replicated three times. Water application [full irrigation (IRR) vs. rainfed (RF)] was the main factor, with cultivar (white and brown birch variety) as sub-factors. The third factor, sequential harvesting, had three levels: no harvest (HO), harvested once (H1) and harvested twice (H2), during plant growth. All treatments were arranged in a randomised complete block design. The total size of the field trial was 868 m^2. Main plots (IRR and RF) measured 356.5 m^2 each, with 10 m spacing between them to prevent water sprays from IRR plots from reaching RF plots. Sprinklers were designed to have a maximum range of 6 m radius. Sub-plot size was 13.5 m^2 with an inter-plot spacing of 1 m, and plant spacing of 0.45 m x 0.35 m, translating to 122 plants per plot.

Irrigation for the full irrigation treatment was applied twice weekly and scheduled to meet 100% of crop water requirement (ET_c) calculated using reference evapotranspiration (ET_o) and a crop factor (K_c) (Allen *et al*., 1998). The ET_o was obtained from an automatic weather station (AWS) and calculated according to the FAO Penman-Monteith method. Crop factors for cowpea were obtained from the FAO Irrigation and Drainage Paper No.56 (Allen *et al*., 1998). During the growing season (December to March) 373.3 mm of rainfall were received. Supplementary irrigation in the full irrigation treatment amounted to 260 mm**.** Both trials were established under full irrigation until the seedlings were fully established, and then irrigation was withdrawn in the rainfed treatment.

5.2.3 Data collection

Emergence counts were taken weekly starting from seven (7) days after planting (DAP) until full emergence. Full emergence was defined as when crops had achieved at least 90% emergence. Thereafter, measurements of plant height and leaf number were taken weekly until 50% of the plants had flowered. Leaf area index (LAI), stomatal conductance (SC) and chlorophyll content index (CCI) were measured weekly. Leaf area index was measured using the LAI2200 canopy analyser (Li-Cor, USA & Canada). Stomatal conductance and chlorophyll content index were measured using a steady state leaf porometer (Model SC-1, Decagon Devices, USA) and the CCM-200 *Plus* (Optisciences, USA), respectively. Sequential harvesting of leaves for the H1 treatment was performed at 55 DAP and the second harvest (H2) was done at 69 DAP. Sequential harvesting was done by carefully removing all the leaves from the plants whilst leaving the nodes intact to allow for new leaves to form. Yield components (total biomass, pod number/plant, pod mass/plant, see number/pod, seed mass/plant and harvest index) were measured at harvest.

Weather data for the duration of the experiment were obtained from an AWS located within a 50 m radius from the experimental site. Soil water content (SWC) was measured using a PR2/6 profile probe connected to an HH-2 moisture meter (Delta-T Devices, UK) at depths of 10, 20, 30, 40, 60 and 100 cm.

5.2.4 Crop management

Prior to planting, soil samples were taken and submitted for soil textural and fertility analyses. Results of soil fertility analysis revealed that there was no need for fertiliser application to meet cowpea requirements for macro and micro-nutrients. Therefore, no fertiliser was applied. Plants were sprayed with Kemprin (Cyphermethrin at 20 ml/10L) against cutworm and routine weeding was performed manually.

5.2.5 Data analysis

Data were subjected to analysis of variance (ANOVA) using GenStat® (Version 14, VSN International, UK). Means of significantly different variables were separated using least significant differences (LSD) at a probability level of 0.05.

5.3 Results

The minimum temperature for cowpea germination is 9°C and the optimum temperature for vegetative growth is 21-33°C. When the crop was planted minimum temperatures were above the base temperature (10°C), thus providing favourable conditions for successful germination and emergence (Figure 5.1). Maximum temperatures were within the range of optimum temperatures for cowpea growth. The total rainfall received during the growing season was 373.3 mm.

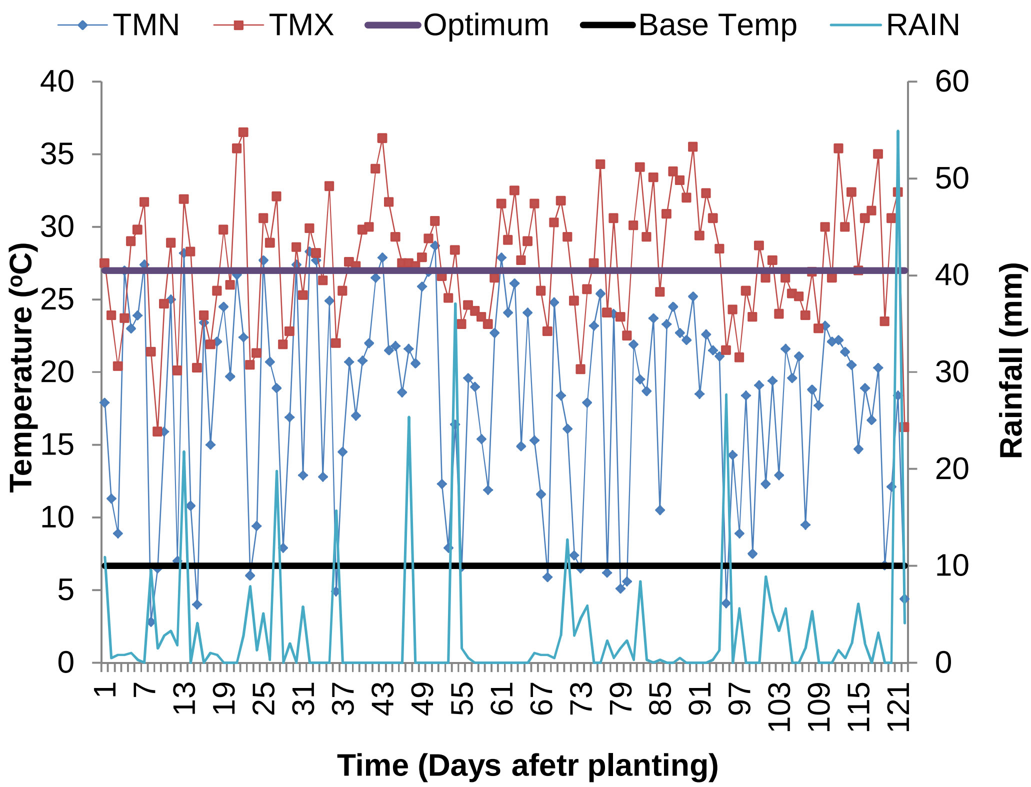

Figure 5.1: Weather parameters (Tmax, Tmin and rainfall) observed during the cowpea growing period plotted against the cowpea's base and optimum temperatures.

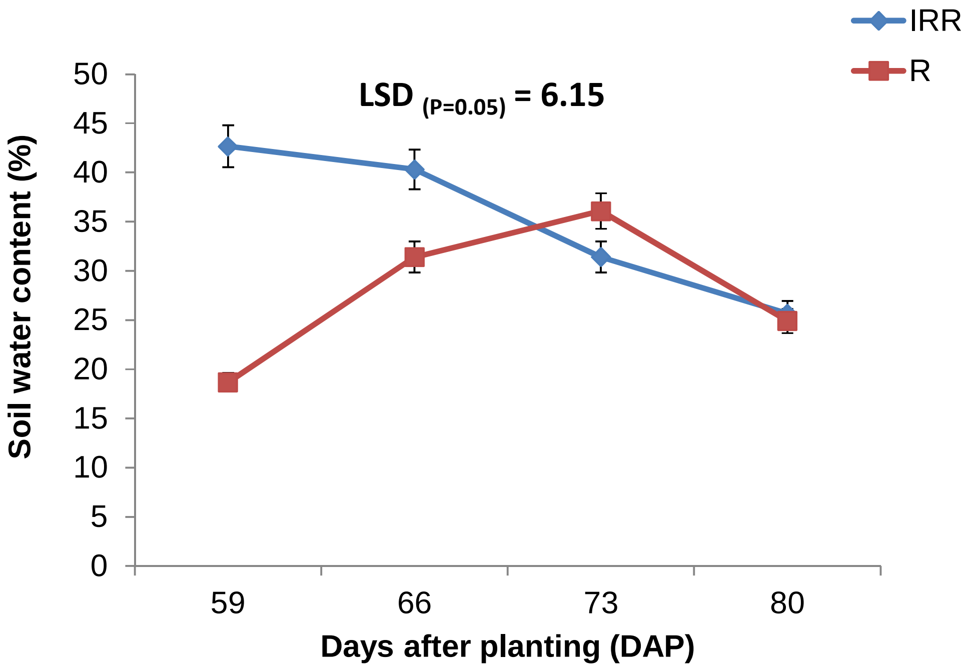

Figure 5.2: Changes in soil water content measured over time in the fully irrigated (IRR) and ranfed (R) treatments.

Water regimes had a highly significant ($P < 0.001$) effect on soil water content (SWC). Measurement of SWC commenced 59 DAP. The irrigated plots had higher SWC than rainfed plots (Figure 5.2). Soil water content in the rainfed plots was observed to have increased from 59 DAP and reaching a peak at 73 DAP; thereafter, SWC decreased in both irrigated and rainfed plots.

Plants in both water regimes (Irrigated and Rainfed) were established with full irrigation until 90% emergence was attained. Therefore, results of emergence reported here only show differences between varieties and not between water treatments (Figure 5.3). Results showed that there were no significant differences ($P > 0.05$) in emergence of two cowpea varieties (Figure 5.3). The crop established very fast, by 7 DAP about 80% of plants had emerged; by 21 DAP 100% emergence was reached (Figure 5.3).

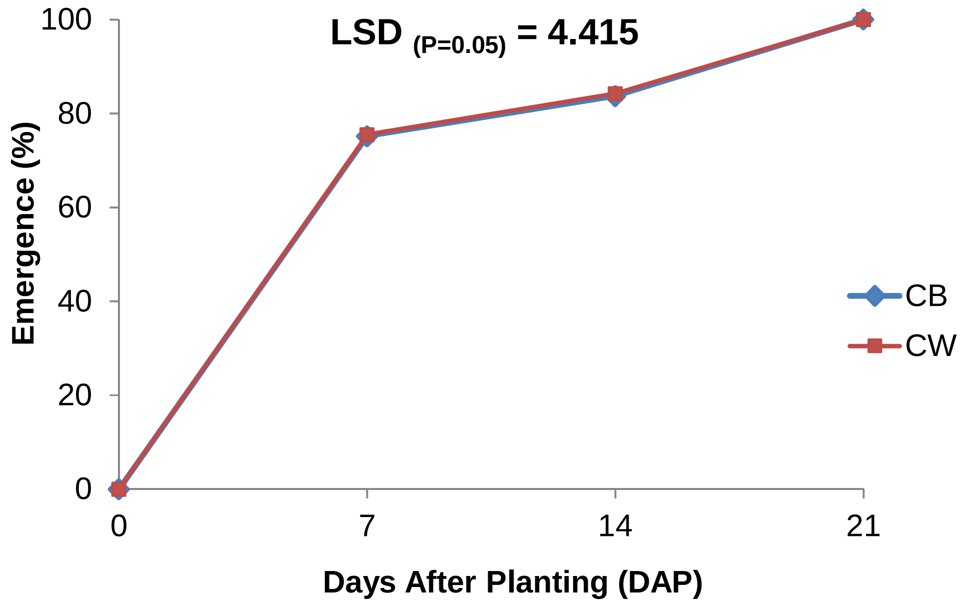

Figure 5.3: Percentage emergence of cowpea varieties (Brown & White birch) over time.

Response of plant height to water regimes showed highly significant ($P < 0.001$) differences (Figure 5.4). Plants grown under irrigated conditions performed better than those under rainfed conditions (Figure 5.4). On average, cowpea plants were shorter under rainfed compared to irrigated conditions. Cowpea varieties also differed significantly ($P < 0.001$) in response to plant growth. The brown birch variety performed better than the white birch variety. The interaction between water regimes and varieties was also significant ($P < 0.05$) (Figure 5.4). Plant height of brown and white birch variety was respectively 23% and 20% lower under rainfed relative to irrigated conditions.

There were no significant differences ($P > 0.05$) between water regimes with respect to leaf number (Figure 5.5). However, highly significant ($P < 0.001$) differences in terms of leaf number were observed between cowpea varieties (Figure 5.5). Although the interaction between water regimes and variety was not significant ($P > 0.05$), brown birch variety had fewer leaves than white birch variety under both irrigated and rainfed conditions (Figure 5.5). Over-all, leaf number of brown birch was 22% lower whereas that of white birch was 21% higher under rainfed compared to irrigated conditions.

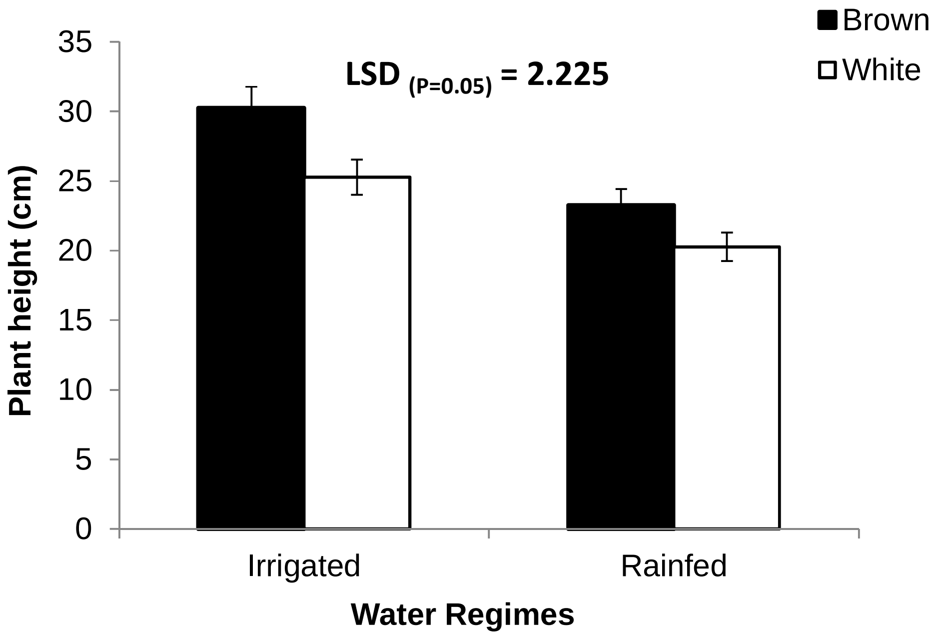

Figure 5.4: Effect of water regimes (Irrigation & Rainfed) on plant height of cowpea varieties (Brown & White).

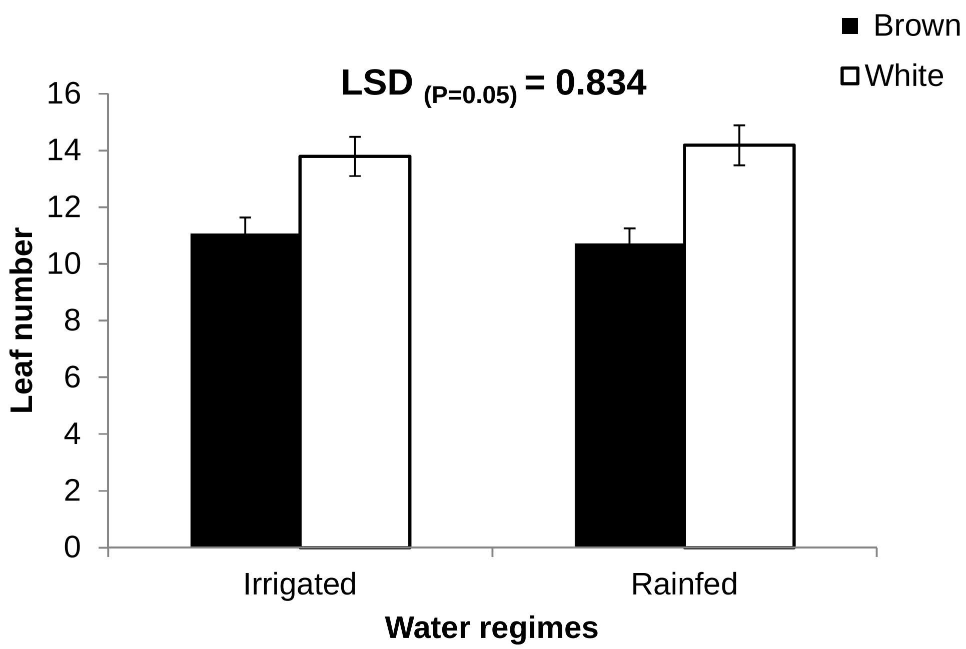

Figure 5.5: Effect of water regimes (Irrigated & Rainfed) on leaf number of two cowpea varieties (Brown & White).

Results of leaf area index (LAI) showed that water regimes had a significant ($P < 0.05$) effect on LAI. Plants grown under irrigated conditions had higher LAI compared with those grown under rainfed conditions (Figure 5.6). There were no significant differences ($P > 0.05$) between varieties with respect to LAI. Under irrigated conditions, white birch had higher LAI (6.6) than brown birch (5.61); whereas under rainfed conditions brown birch had slightly higher (2.77) LAI than white birch (2.51). The LAI of brown and white birch varieties was respectively 50% and 62% lower under rainfed relative to irrigated conditions. Leaf area index also varied significantly ($P < 0.05$) over time (Figure 5.6). The lower LAI at 66 DAP observed under both water regimes corresponded with the time when leaf number decreased due to sequential leaf harvesting.

Chlorophyll content index (CCI) showed no significant differences ($P > 0.05$) between water regimes (Figure 5.7). However, based on mean values, CCI was higher under irrigated compared to rainfed conditions (Figure 5.6). Chlorophyll content index (CCI) of the two cowpea varieties was highly significant ($P < 0.001$) with brown birch having higher CCI than white birch (Figure 5.6). Chlorophyll content index increased up to 77 DAP and decreased thereafter (Figure 5.7). This decrease in CCI coincided with the reproductive phase.

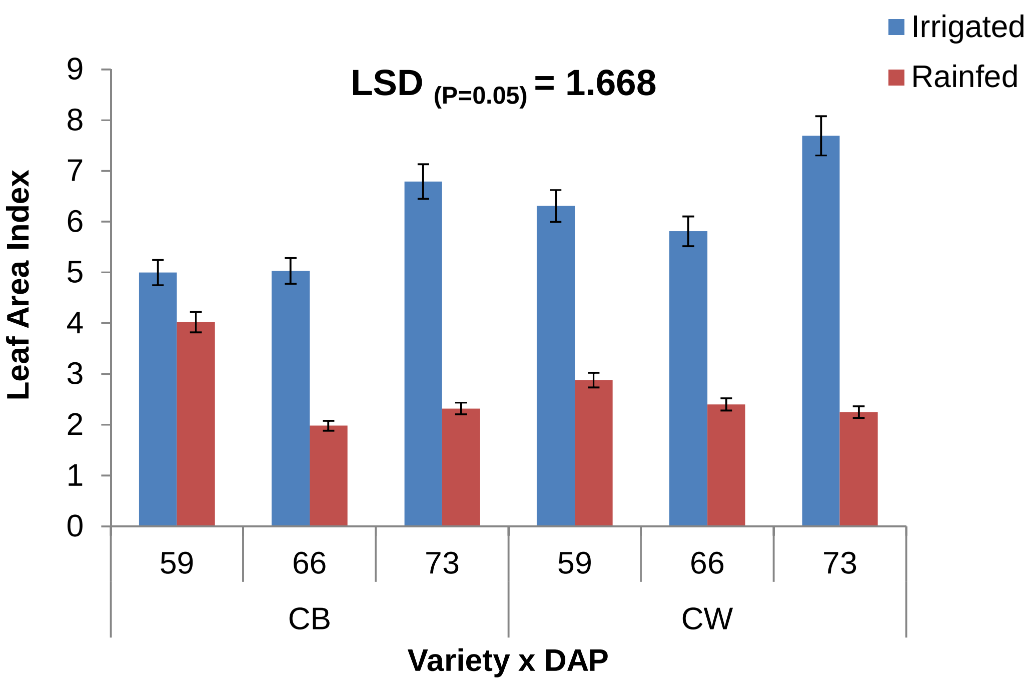

Figure 5.6: Effect of water regimes on leaf area index (LAI) of cowpea varieties over time (DAP: 59, 66 and 73).

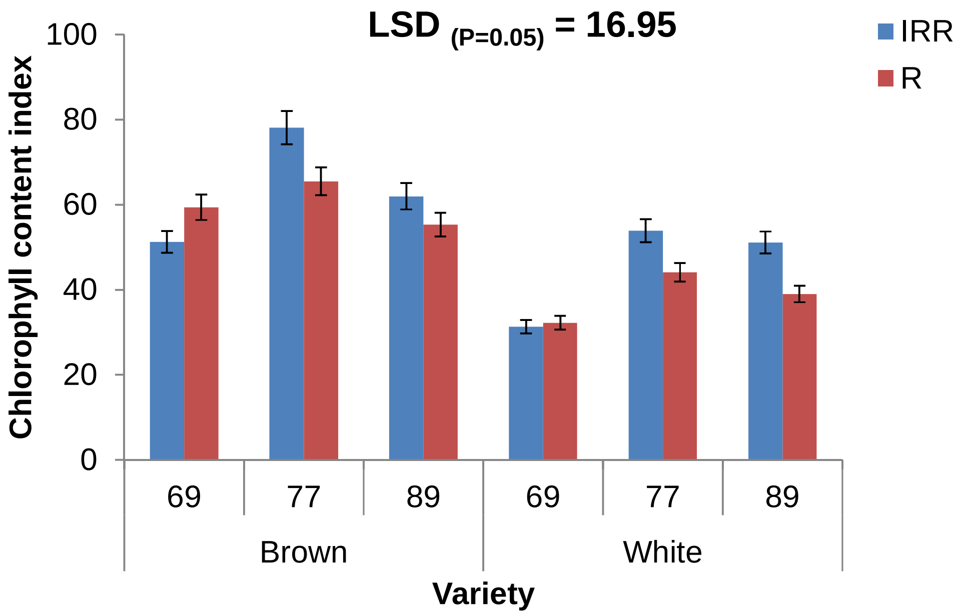

Figure 5.7: Effect of water regimes, irrigated (IRR) and rain fed (R), on chlorophyll content index (CCI) of cowpea varieties over time (DAP).

Water regimes had a highly significant ($P < 0.001$) effect on stomatal conductance (SC). Stomatal conductance was higher under irrigated compared to rainfed conditions (Figure 5.7). Both varieties showed highly significant differences ($P < 0.001$) in SC; however, there was no clear trend with respect to their SC response to water regimes. Highly significant differences ($P < 0.001$) were also observed for SC over time. These observations can be related to weather conditions at which SC measurements were made. The first record was done at 69 DAP and it coincided with a dry spell. Irrigated plots had higher SC (Figure 5.7) due to the supplementary water received from irrigation

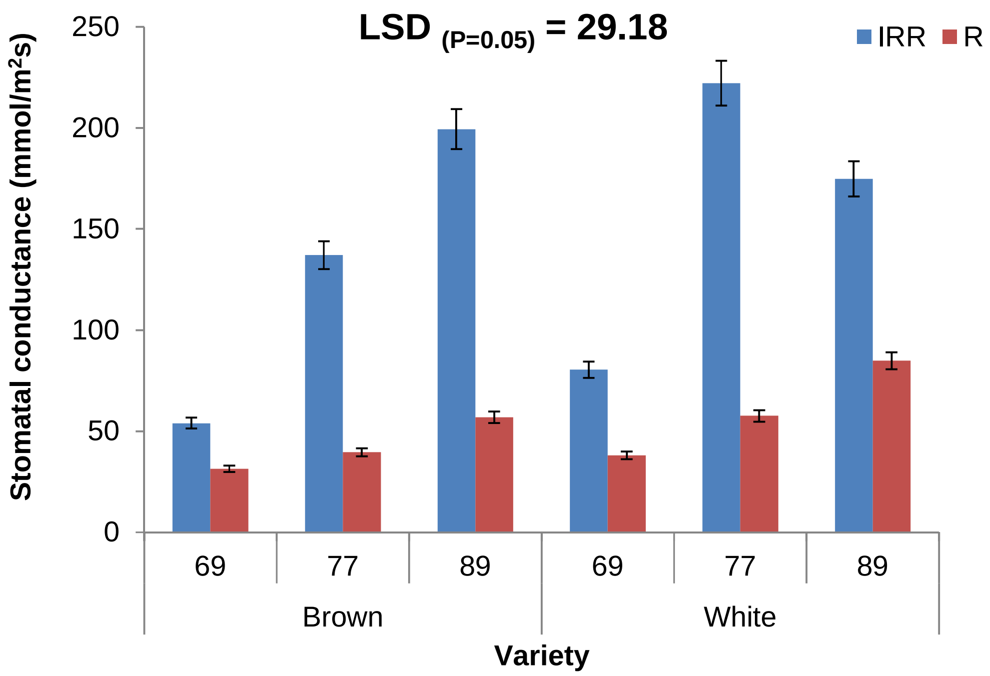

Figure 5.8: Effect of water regimes, irrigated (IRR) and rain fed (R), on stomatal conductance different days after planting (69, 77 and 89 DAP).

The interaction between water regimes, variety and sequential harvesting showed no significant ($P > 0.05$) differences. With the exception of total biomass and pod mass, sequential harvesting had no significant effect on yield components of cowpea (Table 5.1). The no harvest treatment (HO) had the highest total biomass followed by treatments that were harvested once (H1) and twice (H2) (Table 4.2). There were no significant differences ($P > 0.05$) between water regimes with respect to total biomass (Table 5.1). The differences between total biomass of cowpea varieties were highly significant ($P < 0.001$). Brown birch had more biomass than white birch (Table 5.1).

Water regimes had a highly significant ($P < 0.001$) effect on harvest index (HI) which was higher under rainfed compared to irrigated conditions (Table 5.1). The differences between varieties with respect to HI were also highly significant ($P < 0.001$). The interaction between water regimes and variety was shown to be significant ($P < 0.05$) for HI (Table 5.1). Under irrigated conditions, brown birch had zero HI. Although white birch did not produce satisfactory yield, it had a HI of 19.1% (Table 5.1). Interestingly, both varieties performed better under rainfed compared to irrigated conditions. Although there was no supplementary irrigation, brown birch had a HI of 7% (compared with 0% under irrigated conditions) whilst white birch had a HI of about 30% under rainfed conditions compared to 19.1% under irrigated conditions (Table 5.1).

Table 5.1: Yield components of cowpea varieties (Brown & White birch) grown under irrigated and rainfed conditions at Ukulinga Research Farm and subjected to different levels of sequential harvesting (HO, H1 & H2).

Water regime	Variety	Harvest	Total biomass (g)	HI (%)	Pod mass plant^{-1} (g)	Pod no. plant^{-1}	Grain no. pod^{-1}	Total grain mass plant^{-1} (g)
Irrigated	**Brown**	**HO**	61.5	0.04	2.17	0.33	3.67	0.56
		H1	38.2	0.0	0.0	0.00	0.00	0.00
		H2	33.8	0.0	0.0	0.00	0.00	0.00
		Mean	44.5	0.013	0.72	0.11	1.22	0.19
	White	**HO**	28.0	23.6	6.88	5.42	3.67	3.35
		H1	25.4	27.8	6.39	5.35	5.00	2.07
		H2	19.2	5.9	1.09	1.33	6.50	0.43
		Mean	24.2	19.1	4.79	4.03	5.06	1.95
Rainfed	**Brown**	**HO**	50.9	5.7	6.65	3.17	3.00	2.94
		H1	36.1	12.4	2.27	3.67	6.33	4.30
		H2	37.5	5.0	2.70	1.89	1.67	1.88
		Mean	41.5	7.70	3.87	2.91	3.67	3.04
	White	**HO**	30.6	53.3	17.04	8.75	9.54	12.41
		H1	28.4	23.8	8.25	4.30	8.02	6.15
		H2	23.5	43.8	10.07	5.90	8.48	7.33
		Mean	27.50	30.30	11.79	6.32	8.68	8.63
LSD (Water*Var)$_{(P=0.05)}$			8.26	10.35	4.494	2.252	0.853	2.909
LSD (Water*Var*Harvest)$_{(P=0.05)}$			14.93	17.92	2.654	3.900	4.331	5.039

Results of pod mass showed significant ($P < 0.05$) differences in response to water regimes (Table 5.1). Pod mass was lower in irrigated than rainfed plots (Table 5.1). Cowpea varieties also showed significant differences ($P < 0.05$) in terms of pod mass, with white birch having higher pod mass than brown birch. Although the interaction between water regimes and variety was not significant ($P > 0.05$), the varieties had higher pod mass under rainfed than irrigated conditions. Pod number per plant was significantly ($P < 0.05$) affected by water regimes; the rainfed plots continued to perform better than irrigated plots (Table 5.1). The trend of the effect of water regimes and varieties was similar for all yield components (Table 5.1), whereby rainfed plots gave higher yield than irrigated plots and white birch had higher yield than brown birch.

5.4 Discussion

Cowpea requires 550-775 mm and 550-850 mm of rainfall for seed and fodder production, respectively (Smith, 2006). Rainfall received during the study (373.3 mm) was 32% less than the minimum requirement; as such the rainfed treatment was representative of drought. However, since the crop was established under irrigation, results of emergence only showed varietal differences. This study showed that there were no differences in emergence of the two varieties. Previous research (Odindo, 2007; Mabhaudhi & Modi, 2010; Mbatha & Modi, 2010; Zulu & Modi, 2010; Sinefu, 2011) suggested that seed colour may be associated with seed quality.

Plant height and leaf area index were lower under rainfed compared to irrigated conditions. This is a drought avoidance mechanism (Blum, 2005) which serves to minimise surface area available for transpiration. The results of plant height concurred with previous reports by Specht *et al.* (2001) and Zhang *et al*. (2004) on soybean (*Glycine max*). Leaf area index (LAI) was lower under rainfed compared to irrigated conditions. This suggested that leaf expansion was also inhibited by under rainfed conditions. Water stress has been reported to negatively affect cell division and expansion (Nonami, 1998). Similar observations on LAI have also been reported by Hossain *et al.* (2010) on sunflower plants subjected to drought stress.

Although the effect of water regimes on chlorophyll content index was not statistically significant, chlorophyll content index was lower under rainfed compared with irrigated conditions. This trend was in line with reports of lower chlorophyll content in response to water stress in crops such as cotton (Massacci *et al*., 2008), sunflower (Kiani *et al*., 2008) and *Vaccinium myrtillus* (Tahkokorpi *et al.,* 2007). Chlorophyll content index increased with time, reaching a maximum of 78 and 65 at 77 DAP for brown and white birch under irrigated and rainfed conditions. However, at 89 DAP chlorophyll content index decreased for both varieties; this decrease may be associated with plant growth stage. Chlorophyll content increased, reaching a peak, during vegetative growth before decreasing as the crop started to mature. Therefore, chlorophyll content index may be a useful indicator for crop maturity in cowpea.

Results of stomatal conductance (SC) were consistent with reports in literature. Irrigated conditions had higher SC than rainfed conditions; these observations suggest stomatal regulation as a drought tolerance mechanism in cowpeas. Lower SC under rainfed conditions implies that plants were able to close their stomata in order to minimise water losses. Hamidou *et al.* (2007) reported that five cowpea varieties possessed a drought avoidance mechanism which involved lowering stomatal conductance in response to water deficit. Genotypic differences with respect to SC were observed in this study and since the varieties differ in seed colour, these differences can be associated with seed colour. However, despite varietal differences, the overall pattern showed that stomata closed in response to water stress. Cowpea is known to have good stomatal regulation (Hall *et al.*, 1997; Scotti *et al.*, 1999; Cruz De Carvalho, 2000; Sarr *et al.*; 2001; Ogbonnaya *et al.*, 2003).

A secondary objective of this study was to determine the interactive effect of water regimes and sequential leaf harvesting on growth and yield of cowpea varieties. Results of the study showed that there was no interaction between these factors with respect to leaf number and yield. The capacity of the crop to recover from leaf harvesting suggested that the two varieties used in this study may be suited for cultivation as leafy vegetables although sequential leaf harvesting was found to decrease pod yield. These observations were expected since leaf harvesting is a form of plant manipulation which alters the source-sink relationship (Shibles *et al*., 1981). Within the context of this study, sequential harvesting of leaves slowed down and reduced vegetative growth which accounts for biomass accumulation and assimilate reserves. As a result, photosynthates were used to replenish the lost vegetation as opposed to pod formation and filling; thus, the canopy was a stronger sink than the pods. It was also reported that leaf removal alters hormone balance, starch, sugar, protein and chlorophyll content of the source leaves as well as stomatal resistance and senescence rate (Mondel *et al.,* 1978; Selter *et al.,* 1980).

5.5 Conclusion

The varieties used in this study are mainly used for pastures and fodder; however, we explored the possibility of using them as dual purpose crops. The results obtained from the study showed that brown birch cannot be used as a dual purpose crop, especially under irrigated conditions. This variety favoured vegetative growth more than pod formation. Therefore, the brown birch variety may be recommended for production exclusively as a leafy vegetable. White birch, on the other hand, can be used as a dual purpose crop since the crop was able to form pods despite sequential leaf harvesting. White birch also performed well under rainfed conditions. These observations were interesting since it was expected that plants would perform and yield better under irrigated compared to rainfed conditions. Contrary to this, brown birch produced satisfactory yield under rainfed while white birch produced higher yield under rainfed compared to irrigated conditions. It can be concluded therefore, that cowpea is a drought tolerant crop.

Chapter 6

Drought tolerance and water use of Amaranth (*Amaranthus cruentus*) and Pearl Millet

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6.1 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 ET_o of 2 198 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 a 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 has 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 to be 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 amaranth and pearl millet, as C4 crops, their water use can be used to address the effect of environment and their genetic conditions. Therefore, the purpose of this study was to assess and compare both the water use efficiency and productivity of vegetable amaranthu and pearl millet under irrigated and rainfed conditions in a semi-arid area.

6.2 Materials and Methods

6.2.1 Facilities and site descriptions

Lysimeter trials for pearl millet were conducted at the University of Free State, Department of Soil, Crop and Climate Sciences' lysimeter facility over two seasons (2008/09 and 2009/10). Field trials for both crops were carried out at the Department of Soil, Crop and Climate Sciences' Kenilworth Experimental Farm (29.02°S; 26.15°E; 1354 masl). The average minimum and maximum temperatures for Kenilworth are 15℃ and 30℃, respectively. The mean annual rainfall is ± 559 mm and the maximum precipitation is in February with ± 111 mm. The soil in the experimental field was a loamy aridic ustorthents (*Amalia family*) and has characteristics associated with high evaporative demand. The morphological properties of the soil are reddish brown in colour with fine sandy loam texture having low clay content (8-14% clay & 2-4% silt) in the first one meter profile.

6.2.2 Treatments and plots layouts

The study was carried out over two summer growing seasons in 2008/09 and 2009/10. The plot size for the two crops in total was 90 x 60 m^2. The plot was ploughed and rotovated before planting. Irrigation was supplied by a line source sprinkler system and the plots were laid out in a split-plot design with four replications. The treatments include five levels of water application from fully irrigated (W5, plots closest to the line source) to rainfed plots (W1: plots furthest from line source):

- W5 – Full irrigation
- W4 – Closer to line source
- W3 – Moderately irrigation
- W2 – Least irrigation
- W1 – Rainfed

Rainfed plots were twice the size of the irrigated plots to avoid border and lateral movement of water effects. Rain gauges were used to measure the amount of irrigation water per distance from the sprinkler source of the line source sprinkler system. This enabled quantification of water availability per treatment in reference to the fully irrigated plots. Irrigations were 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.

6.2.3 Weather components

Weather variables such as maximum and minimum air temperature (°C), solar radiation (MJ m^{-2}), wind speed (m s^{-1}), rainfall (mm) and relative humidity (%) were monitored by automatic weather stations (AWS) on the experimental sites. The components of the AWS are tipping bucket rain gauge, cup anemometer and wind vane, a pyrometer and combined temperature and humidity sensor. Details of some of the observed climatic data at the experimental site for the two seasons are presented in Table 6.1. The reference evapotranspiration (ET_o) for the two cropping seasons calculated from the observed weather data by the AWS are presented in Figure 6.1.

6.2.4 Crop water use

6.2.4.1 Pot experiment

The pots (28.5 L) were filled with Bainsvlei top soil from the experimental site where field trials were conducted. The soil was oven dried at 105°C for 24 hours to determine the initial water content of the soil. Pots were filled with soil and then saturated with water and left to drain and weighed daily until constant mass was observed. Differences between the dried and drained soil mass were taken as the water content at full water holding capacity. The mass difference over a period of time (2 days interval) was taken as water uptake of the plant. The amount of water uptake was then converted to volumes and assumed to be representative of transpired water. The pots were covered with quartz hence evaporation was assumed to be negligible. Transpired water in the pots was calculated as follows:

$$\text{Transpired water (T)} = PW_n - PW_f \qquad \text{Equation 6.1}$$

where PW_n is the initial mass of the pot on a given date, and

PW_f is the mass of the pot at the end of the interval.

Table 6.1: Monthly means of climatic data measured at Kenilworth experimental site for the two seasons.

	Weather parameters	**Temperature max (˚C)**	**Temperature min (˚C)**	**Monthly precipitation (mm)**	**Wind speed (ms^{-1})**	**Relative Humidity (%)**
2008/09	*November*	28.67	14.28	7.3	0.45	81.25
	December	26.35	17.98	48.25	1.71	59.79
	January	26.37	15.4	92.9	2.56	88.18
	February	27.4	16.22	59	1.94	86.46
	March	28.31	13.36	22.5	1.44	80.35
2009/10	*November*	28.72	13.63	8.5	2.49	76.11
	December	32.79	15.03	57.6	3.59	77.52
	January	28.36	16.79	133.3	2.56	86.97
	February	29.93	16.78	34.9	2.04	83.11
	March	29.73	12.4	14.4	1.71	82.56

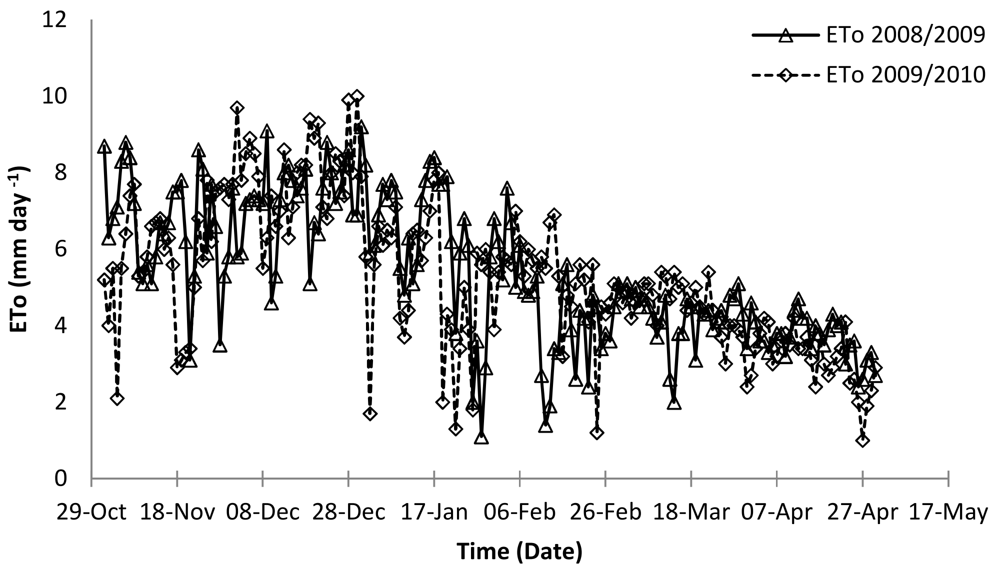

Figure 6.1: Daily reference evapotranspiration (ET_o) observed at Kenilworth experimental site, Bloemfontein, for the two cropping seasons (2008/09 and 2009/10).

6.2.4.2 Lysimeter experiment

Crop water use of the two lines of pearl millet on lysimeter is considered to be amount of transpired water. Evapotranspiration (ET) is widely considered to be water use by the field crops. However, partitioning of the ET into E and T provides the opportunity to quantify the actual amount of water intake and loss by the crop (T) which is the only productive loss of water within the soil-plant-atmosphere-continuum (SPAC). Therefore, transpiration was observed as water use by the crop because soil evaporation (E) was negligible due to the quartz gravel that was used to cover each lysimeter. The rainfall (P) was zero as rainfall was excluded with the aid of a rain shelter throughout the study period while drainage (D) and runoff (R) were zero.

6.2.4.3 Field trials

The soil water balance was estimated at weekly intervals, for each plot, and for the two crops and seasons. The soil water balance was carried out to estimate evapotranspiration (ET) which was the crop water use during the two seasons. Changes in soil water content (ΔSW), at six levels up to 1.8 m depth at 30 cm interval, which is one of the soil water balance components, were monitored with the Waterman Neutron moisture meter (Campbell Pacific Neutron Water Meter, Model 503DR). Other soil water balance components are precipitation (P), irrigation (I) and deep percolation (D) and runoff (R), both D and R were assumed to be negligible.

6.2.5 Biomass sampling

Four plants per treatment were harvested for biomass at every sampling period in pots trials. All the plants per stand per lysimeter tank for each treatment were harvested at maturity as the total aboveground biomass for lysimeter experiment. However, for field trials, a single plant per replicate for each treatment was sampled in amaranth plots. For pearl millets plots, five plants per stand per replicate for each treatment per each line of pearl millet were sampled every week. Plant samples were oven dried at 65°C for 36-48 hours to determine dry mass.

6.2.6 Yield and yield components

Economic yield in amaranth was fresh mass because it is a vegetable crop. Therefore, weekly total aboveground fresh mass data were regarded as yield for that specific period of time. Amaranth yield was reported in dry mass for the purpose of agronomic and productivity quantification. Amaranth was harvested continuously at 30 cm above ground. This was repeated on the same plants at the same height at 14 day intervals and this yield was regarded as edible portion of the plant. Edible portion was reported in fresh and dry mass for both seasons. Grain yield per lysimeter per treatment was converted to tonnes per hectare while harvest from 1 m^2 of each treatment plots was used for yield measurement.

6.2.7 Water physiology

Plant water status was monitored by measurement of leaf water potential and stomatal conductance as parameters measured with the aid of a pressure chamber (PMS-600) and leaf porometer (Decagon Devices, Inc.), respectively. Leaf water potential was monitored only in 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 condition. Transparent plastics were used to cover the leaf before cutting to minimise loss of water through transpiration. Mounting of detached leaves was done within 30 seconds. This was to avoid water loss from the point of incision of the leaves. Pressure was applied slowly until a 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 of time when water appeared at the point of incision and the reading taken immediately. Stomatal conductance measurements also took place at midday between 12:00 and 14:00 hours. Five fully expanded and exposed leaves per treatment were sampled for the measurements. All leaves were sampled randomly and at the same upper level on the stem of the plant.

6.2.8 Crop water productivity parameters

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

6.2.8.1 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. Water use efficiency is calculated using the equation 4.2 (Tanner & Sinclair, 1983).

$$\mathrm{WUE} = \frac{\mathrm{Y}}{\mathrm{ET}} \qquad \text{Equation 6.2}$$

$$WUE_{bm} = \frac{\mathrm{BM}}{\mathrm{ET}} \qquad \text{Equation 6.3}$$

$$WUE_{gy} = \frac{\mathrm{GY}}{\mathrm{ET}} \qquad \text{Equation 6.4}$$

where Y = yield and it is total aboveground biomass (BM) for $\mathrm{WUE_{bm}}$ and grain yield (GY) for $\mathrm{WUE_{gy}}$ ET = seasonal evapotranspiration, $\mathrm{WUE_{bm}}$ = Water use efficiency for biomass production and $\mathrm{WUE_{gy}}$= Water use efficiency for grain yield.

Water productivity (WP)

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

$$WP = \frac{\mathrm{Y}}{\sum \mathrm{T}} \qquad \text{Equation 6.5}$$

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

6.2.8.2 Precipitation use efficiency (PUE)

This parameter evaluates the efficiency at which rainwater is converted to yield in rainfed crop production for growing and previous fallowing period together (Hensly *et al*., 1990). Equation 6.6 is used to calculate PUE:

$$PUE = \frac{Y}{P_g + P_f + (SWC_{(n-1)} - SWC_n)} \qquad \text{Equation 6.6}$$

where Y = yield,

P_g = Precipitation during the growing season,

P_f = Precipitation during the fallow period,

$SWC_{(n-1)}$ = water content of the root zone at harvest in year n-1, and

SWC_n = water content of the root zone at harvest in year n.

6.2.9 Statistical analyses

Data 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 Test.

6.3 Results and Discussion

6.3.1 Amaranth

6.3.1.1 Pot experiment

At the end of the study, stressed (stressed) plants produced less biomass (fresh and dry mass) than the well-watered (WW) plants (Figure 6.2). For the stressed plants, the highest fresh mass was produced around 30 days after transplanting with a slight decline at 40 days after transplanting. Well-watered plants continued to increase in biomass throughout the experiment. Figure 6.3 represents water uptake (transpiration) by plants of in the two treatments. The water use of stressed plants started to decline 25 days after transplanting till the end of the study. The difference in water use of the plants from the two treatments at 40 days after transplanting was up to 30 mm. Figure 6.3 reveals a good linear relationship between transpiration and biomass production of amaranth. Irrespective of the treatment, fresh and dry mass increased with increasing transpiration. With transpiration of 100 mm, over 100 g m^{-2} of fresh mass and 20 g m^{-2} were produced.

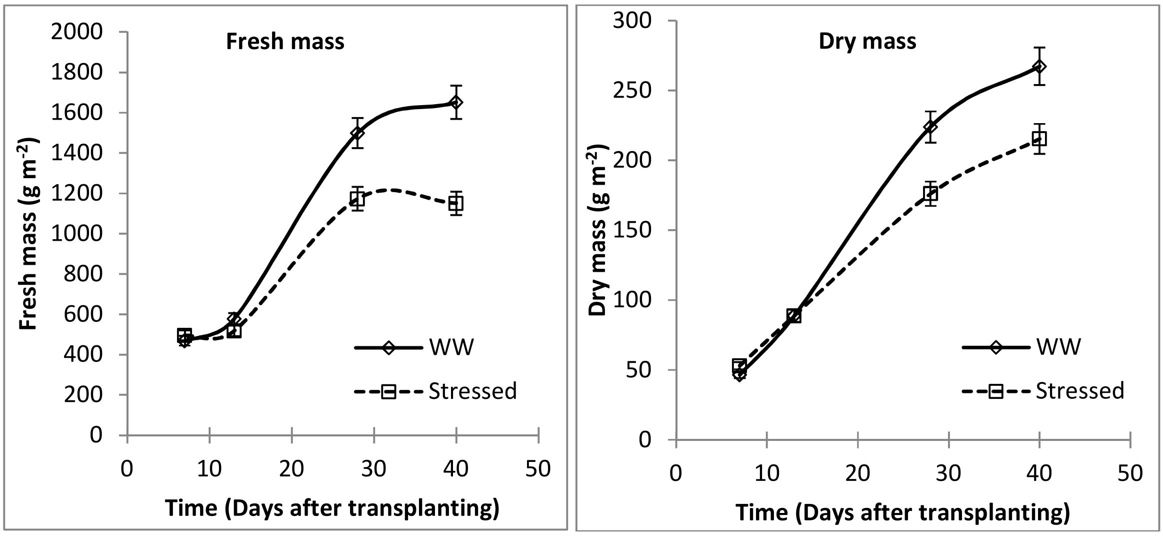

Figure 6.2: Fresh and dry mass produced by amaranth as affected by the two water treatment.

There was a decline in stomatal conductance of the plants for both treatments between days 25 and 30 after transplanting (Figure 6.4). However, stressed plants had lower stomatal conductance than well-watered plants. Well-watered plants had higher relative water content than stressed plants throughout the study period (Figure 6.4). Leaves of the two treatments were similar at the 15 days after transplant as little, if any, stress had occurred at this stage. By day 40, the RWC of the well-watered was above 80% while that of water stressed leaves was as low as 70%, giving an indication of the stress level.

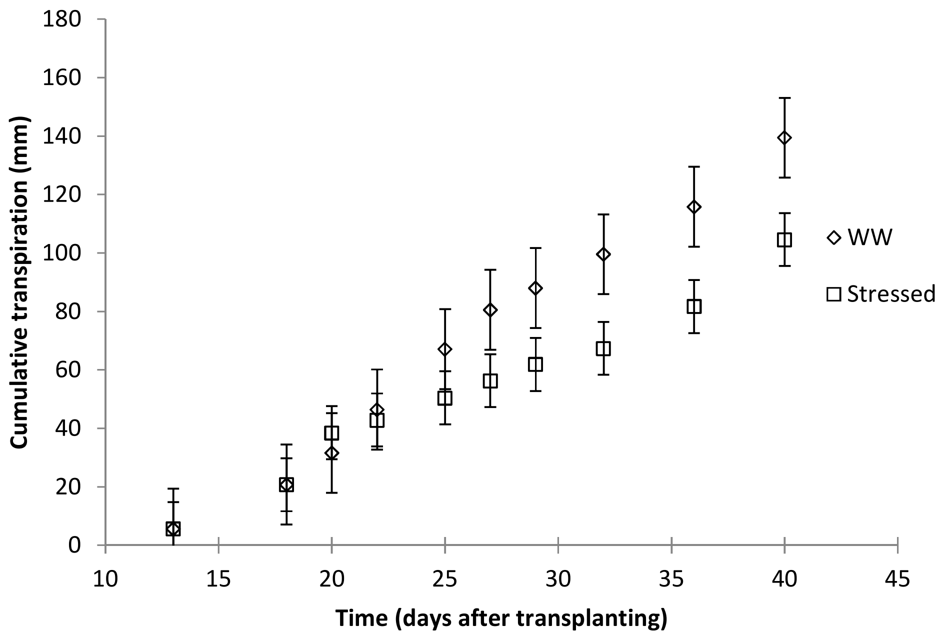

Figure 6.3: Amount of water use (Transpired water) by amaranth for the two water treatment.

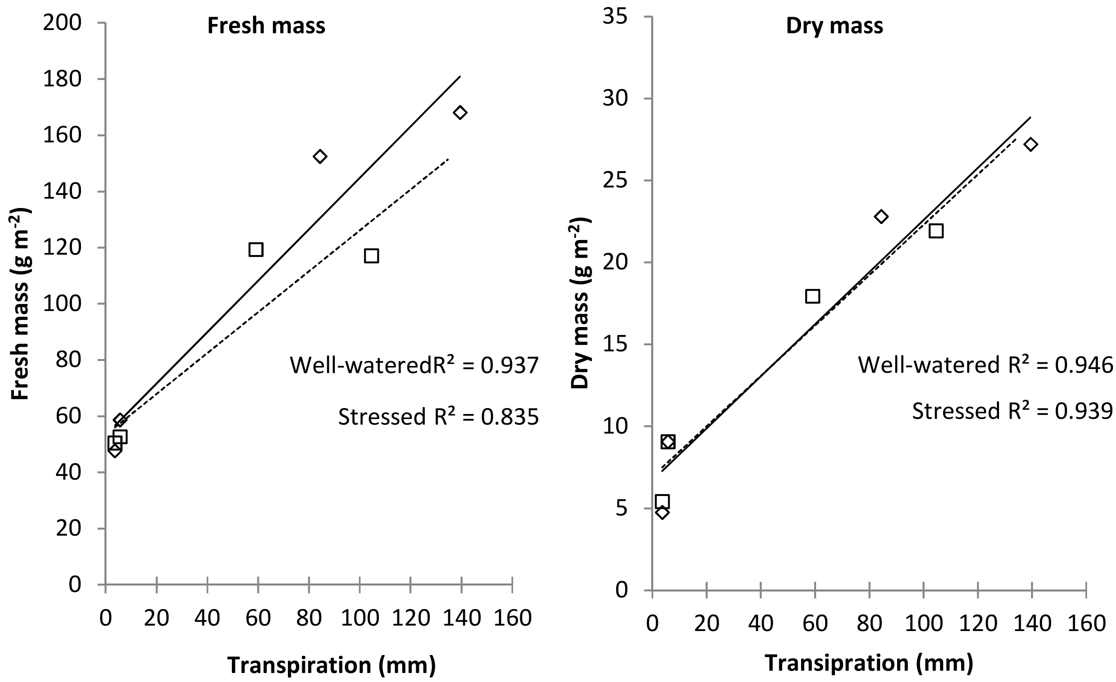

Figure 6.4: Relationship between water use (transpired water) and biomass production of amaranth for the two water treatments.

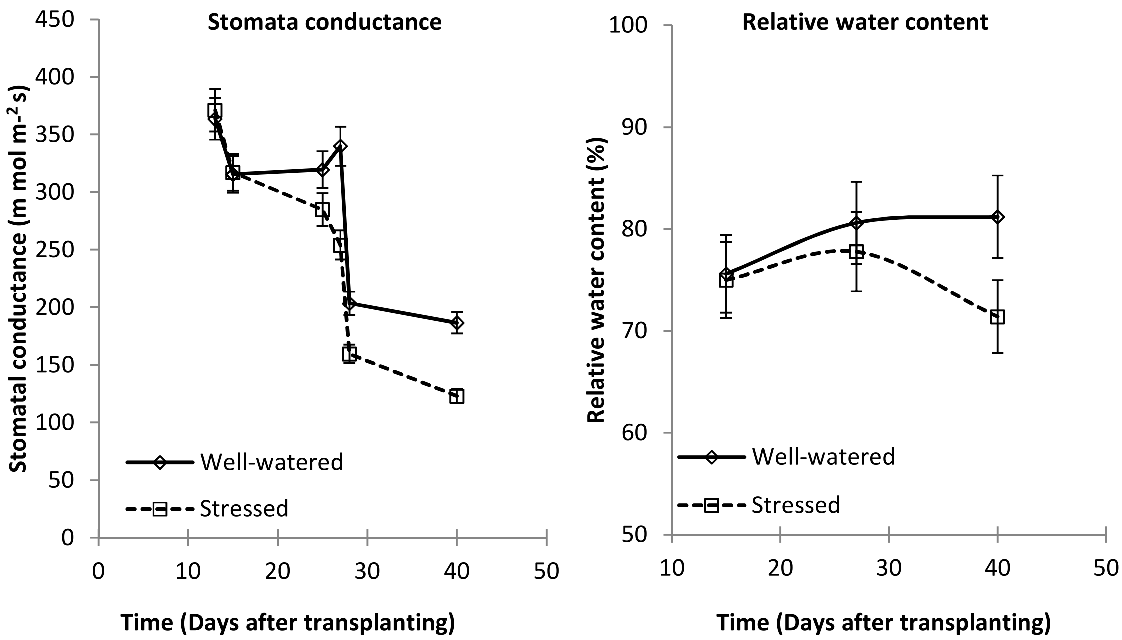

Figure 6.5: Stomatal conductance and relative water content of amaranth subjected to two water treatments.

The objective of pot studies on effects of water stress on crops is often to simulate arid soils and soil drying. Their effects on the crop may be observed in terms of biomass production, water uptake and physiological processes. Liu and Stutzel (2002) observed differences in the rate of soil water extraction among four genotypes of amaranth. They found a relationship between rate of soil water extraction of these genotypes and the rate of leaf area expansion and stomatal conductance. In the present study, well-watered plants used more water and had higher stomatal conductance than stressed plants. The higher stomatal conductance contributes to the higher rate of water use while the low rate of water use in stressed plants signifies low stomatal conductance of amaranth (Liu & Stutzel, 2002; Omami & Hammes, 2006). Plants exposed to water or salinity stress in an amaranth pot trial produced lower biomass (Omami & Hammes, 2006) which is consistent with the result of this study. Liu and Stutzel (2002) found similar response of amaranth to 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 close to 60%.

6.3.1.2 Field trials

The total amount of water supplied for the 2009/10 season was higher than the previous season (Table 6.2). During 2008/09, irrigation was low, which may be due to higher rainfall received during the growing period. The pattern of soil water content for the two seasons was similar (Figure 6.5). The lowest soil water content was observed in rainfed plots (W1) while the soil water content of other treatment plots were not significantly different. The transpiration rate of all the treatments for the two seasons was between 8 and 10 mm day^{-1} (Figure 6.6). However, the seasonal water use (ET) for the 2009/10 season was higher than for the 2008/2009 season, irrespective of the treatment. During the two seasons, the plants from the W1 plots had the least water use and were also significantly different from the other treatments in the 2009/10 season (Figure 6.6). In the 2009/10 season, there was no significant difference between the ET of the plants from the W5 and W4 plots. This could be due to the fact that the initial soil water content of the two plots at the beginning of the season was relatively the same.

Water applied significantly affected biomass production for the two seasons (Figure 6.7). Irrespective of the season, W2 produced the highest fresh mass followed by W3 plants. During the 2008/09 season, the W1 plots produced the least biomass followed by W5 plots while it was reversed in 2009/10 (Figure 6.7). This suggests that irrigation can increase the productivity of the crop but there is still need to explain the reason for the fully irrigated plots producing plants with lesser biomass than the other water treatment plots.

Table 6.2: Amount of rain and irrigation water (mm) supplied in both seasons (2008/09 & 2009/10)

	2008/2009			**2009/2010**		
Treatments	*Irrigation*	*Rainfall*	*Total*	*Irrigation*	*Rainfall*	*Total*
W5 (Full irrigation)	122.0	174.0	296.0	199.7	115.0	314.7
W4	89.1	174.0	263.1	167.0	115.0	282.0
W3	69.5	174.0	243.5	131.0	115.0	246.0
W2	47.6	174.0	221.6	93.0	115.0	208.0
W1 (Rainfed)	0.0	174.0	174.0	0.0	115.0	115.0

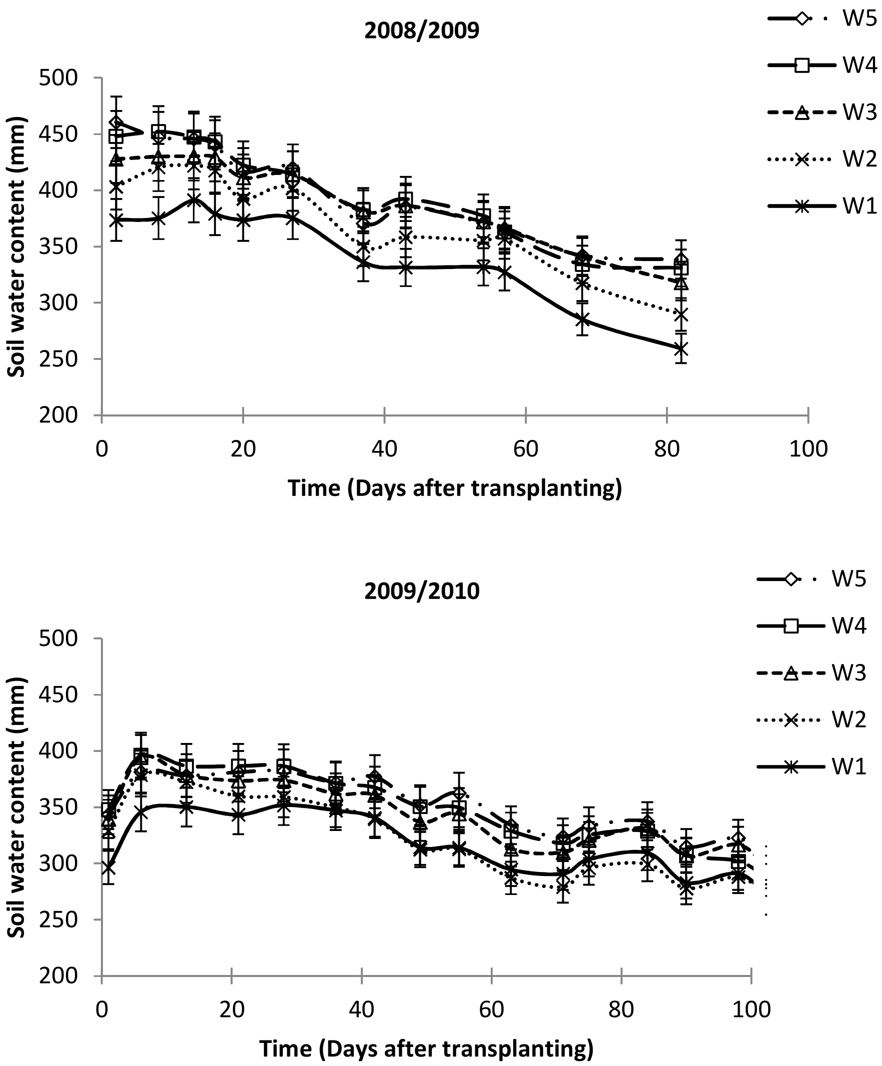

Figure 6.6: Soil water content pattern of amaranth plots as affected by water treatments over the two cropping seasons (2008/09 and 2009/10).

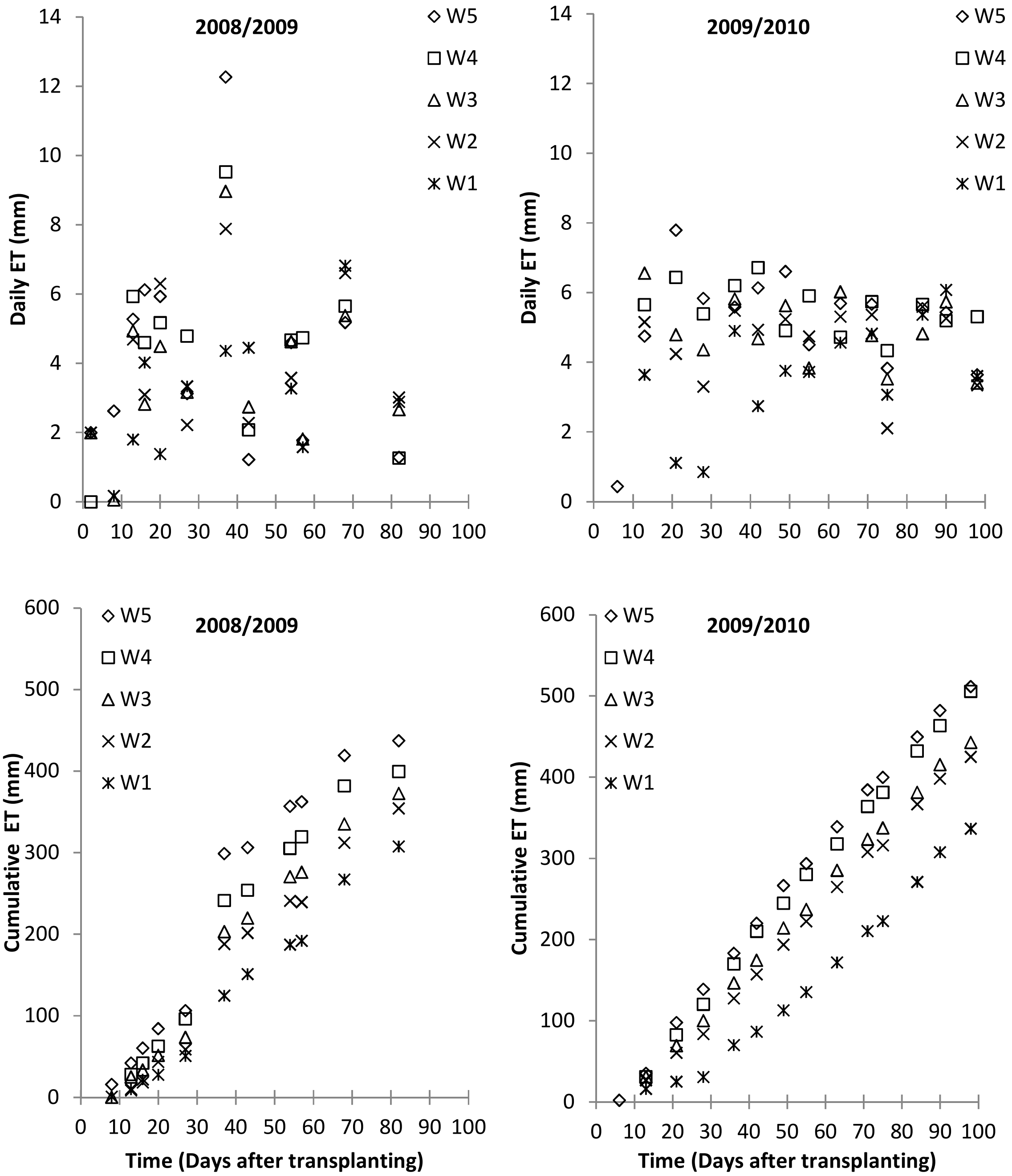

Figure 6.7: Daily and cumulative evapotranspiration (ET) during the 2008/09 and 2009/2010 seasons.

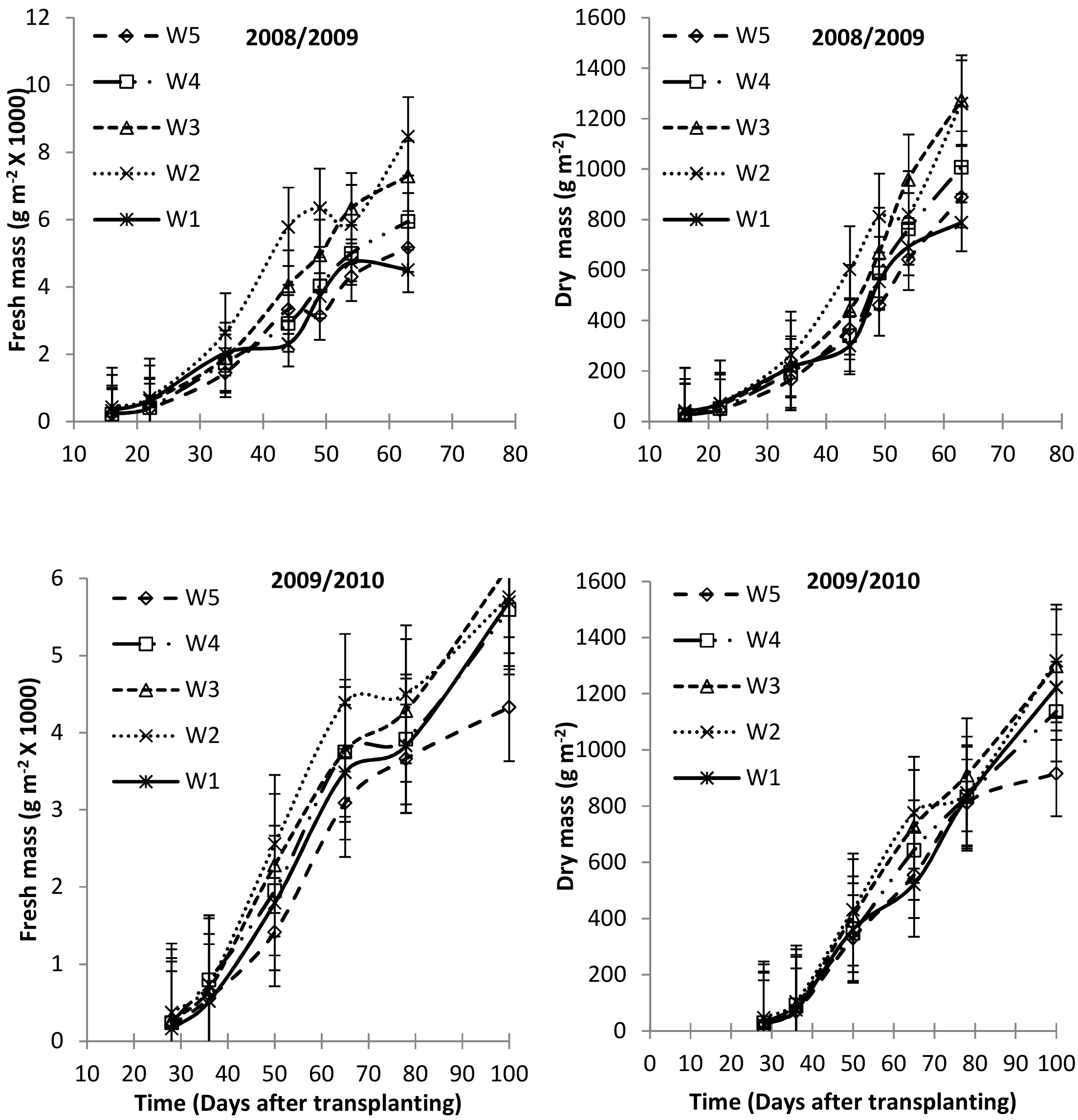

Figure 6.8: Above ground fresh and dry mass of amaranth as affected by different water treatments during 2008/09 and 2009/10.

The importance of serial or continuous harvesting in leafy vegetables is to increase the average yield and quality of the crop. During the two seasons, W2 produced the highest biomass for the first two consecutive cuttings, while W5 produced the least yield for these periods (Figure 6.8). Comparing treatments during the first cutting in 2008/09 season, fresh mass was similar across water treatments except for W2, which produced the highest amount. The same trend of fresh mass production in 2008/09 was followed in 2009/10 except that W2 and W3 were not significantly different while W1 produced the least fresh mass at the second cutting. At the third cutting, the response of amaranth to different amounts of water applied was less apparent between the treatments (Figure 6.8). The W2 treatment produced more edible leaf portions at both the first and second harvests, showing that the crop can be grown with little amount of water.

The final fresh mass harvest of the whole plants during the 2009/10 season was used to justify the importance of the continuous harvest method. Cumulatively, biomass produced from the cuttings was higher than total above ground biomass of whole uncut plants at the end of 2009/10 season (Table 6.3). This illustrates the fact that this crop will be able to produce more leaves for food if it is harvested on a regular basis. For the season, cumulative biomass of cuttings followed the same trend of biomass production but was higher than the total above ground biomass throughout the treatments (Table 6.3).

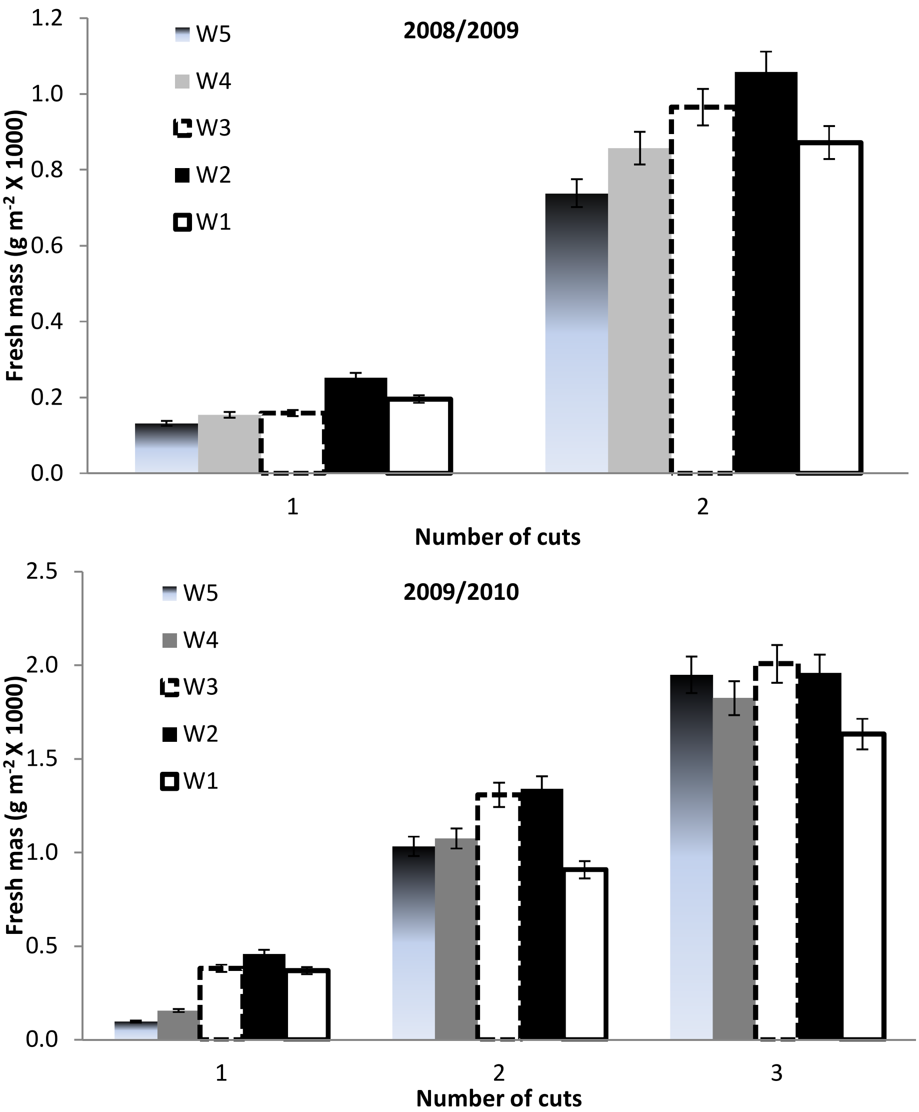

Figure 6.9: Fresh mass of edible portion of amaranth during the 2008/09 and 2009/10 seasons (30 cm above ground harvest).

The harvest index (HI) was calculated as the summation of stem and leaf dry mass divided by the total above ground biomass. This was carried out at the end of the 2009/10 season. The W5 plants had the highest HI irrespective of their low biomass production (Figure 6.9). The W4 and W2 treatments did not differ significantly with HI.

Table 6.3: Total Amaranth leaf cuttings versus final fresh mass of whole plants (2009/10).

Treatments	Total cuttings ($g\ m^{-2}$ X 1000)	Final biomass whole plant ($g\ m^{-2}$ 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

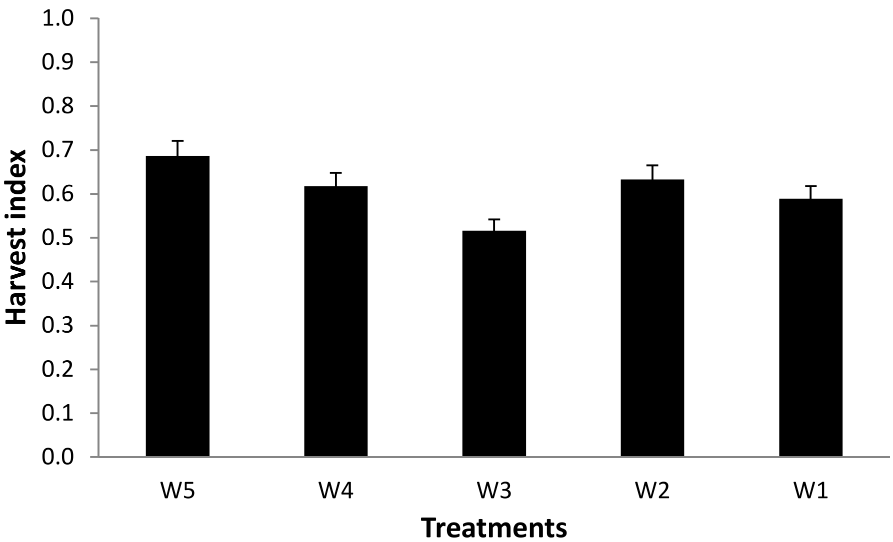

Figure 6.10: Harvest indices as affected by different water treatments during 2009/10.

The water use efficiency (WUE) observed among the treatments was as expected. For both fresh and dry mass, WUE was higher in the first season than the second season (Figure 6.10). In 2008/09 season, the WUE follows the same trend of the biomass production among the treatments. However, the rainfed plots had the highest WUE in the 2009/10 season with 192 kg $ha^{-1}\ mm^{-1}$ for fresh mass and 28.7 kg $ha^{-1}\ mm^{-1}$ for dry mass production.

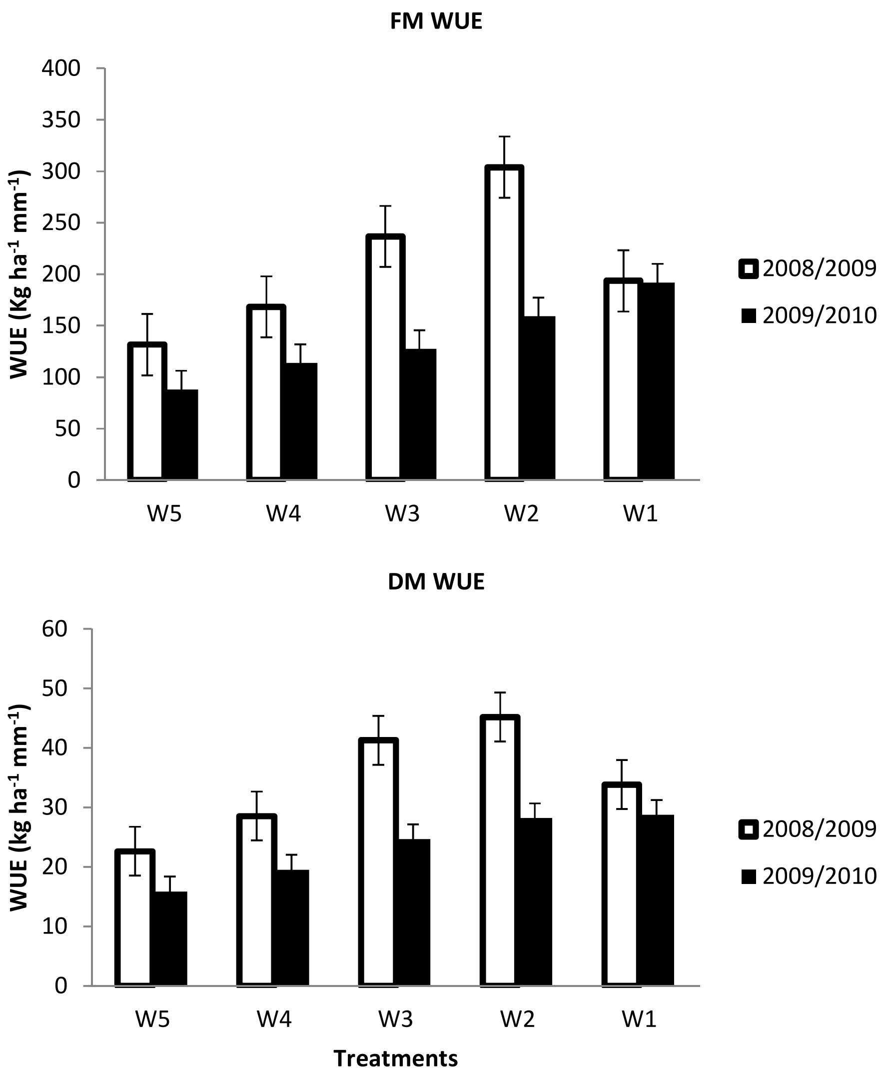

Figure 6.11: Calculated water use efficiency (WUE) of amaranth for fresh and dry mass production during the two cropping seasons (2008/09 and 2009/10).

Stomatal conductance will be reported for only 2009/10 season. Amaranth responds to water as any other crop in terms of physiology. Figure 6.11 illustrates that stomatal conductance of amaranth reduces with age. The treatments were not significantly different in stomatal conductance except for that of the W1 treatment which was totally different from the others. Relationship between the soil water content and stomatal conductance is shown in Figure 6.12. High stomatal conductance interprets to high soil water content. At soil water content between 300 and 320 mm, the stomatal conductance of the plants of rainfed plots (W1) was below

100 mmol m^{-2} s^{-1} while at soil water below 300 mm, stomatal conductance of the plants from the W2 plots were as high as 155 mmol m^{-2} s^{-1}.

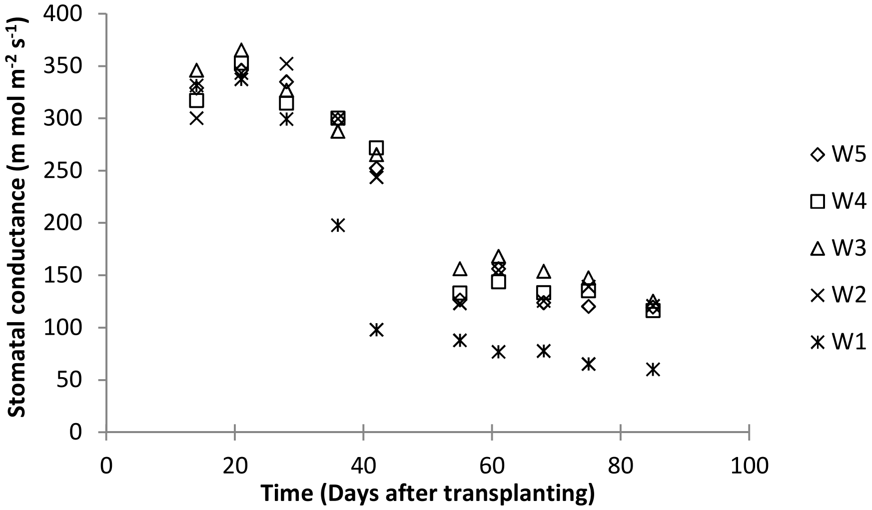

Figure 6.12: Stomatal conductance of amaranth as affected by water treatments during the 2009/10 cropping season.

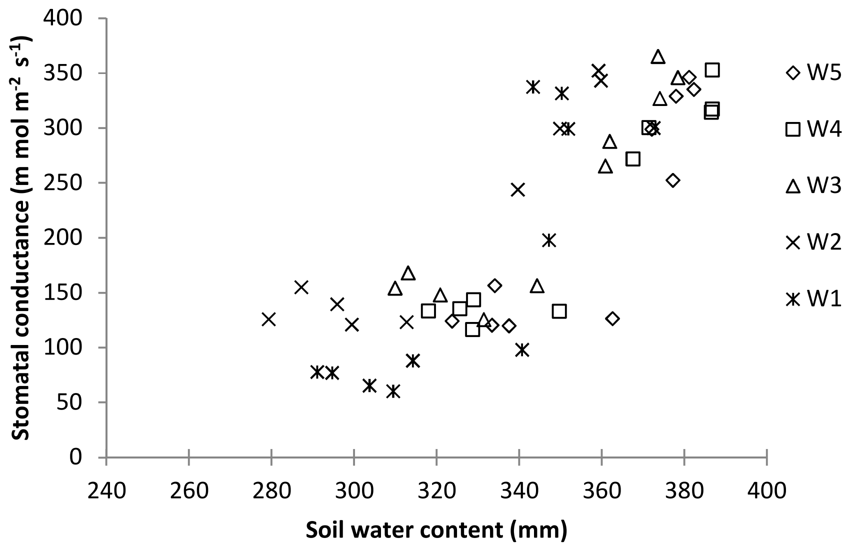

Figure 6.13: Relationship between stomatal conductance and soil water content during the 2009/10 season.

The results of this trial show that performance of amaranth 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 amaranth. Ayodele (2002) found that an increase in nitrogen fertilisation increases amaranth yield irrespective of the species. Increase in the rate of farmyard manure application also increases the growth parameters, such as plant height, leaf area, fresh and dry mass of amaranth (Akparobi, 2009). The fertility aspects need further investigation in combination with the amount of water applied and irrigation system. Continuous 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. However, this observation contradicts the findings of Allemann *et al.* (1996) that yield decreased with subsequent harvest after the first cutting. There is a need to find the optimum threshold for water application amounts that will increase the yield of amaranth leaves. The fully irrigated plots could be regarded to be a waste of scarce water in semi-arid regions.

6.3.2 Pearl millet

6.3.2.1 Lysimeter trial

The total irrigation amount supplied during the trial shows that Bainsvlei soil requires less amount of water than Clovelly soil at no stress condition (WW) for the two lines of pearl millet (Table 6.4). This may be due to the higher clay content property of the Bainsvlei soil than the Clovelly soil which might increase its water holding capacity (see Ehler *et al*., 2003). The least amount of water supplied was recorded in reproductive growth stage stress (RGS) in the two forms of soils.

Table 6.4: Average amount of irrigation water (mm) supplied to different treatments on both soils of lysimeters.

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

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 Bainsvlei soil while there was no significant difference between the water use of the plants from the well-watered (WW) and vegetative stress (VS) tanks of Clovelly soil form (Figure 4.13). Throughout all the treatments, low water use was found in the grain stress (GS) and reproductive-grain stage stress (RGS) treatments tanks irrespective of the two lines of pearl millet and 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 water availability for these two treatments.

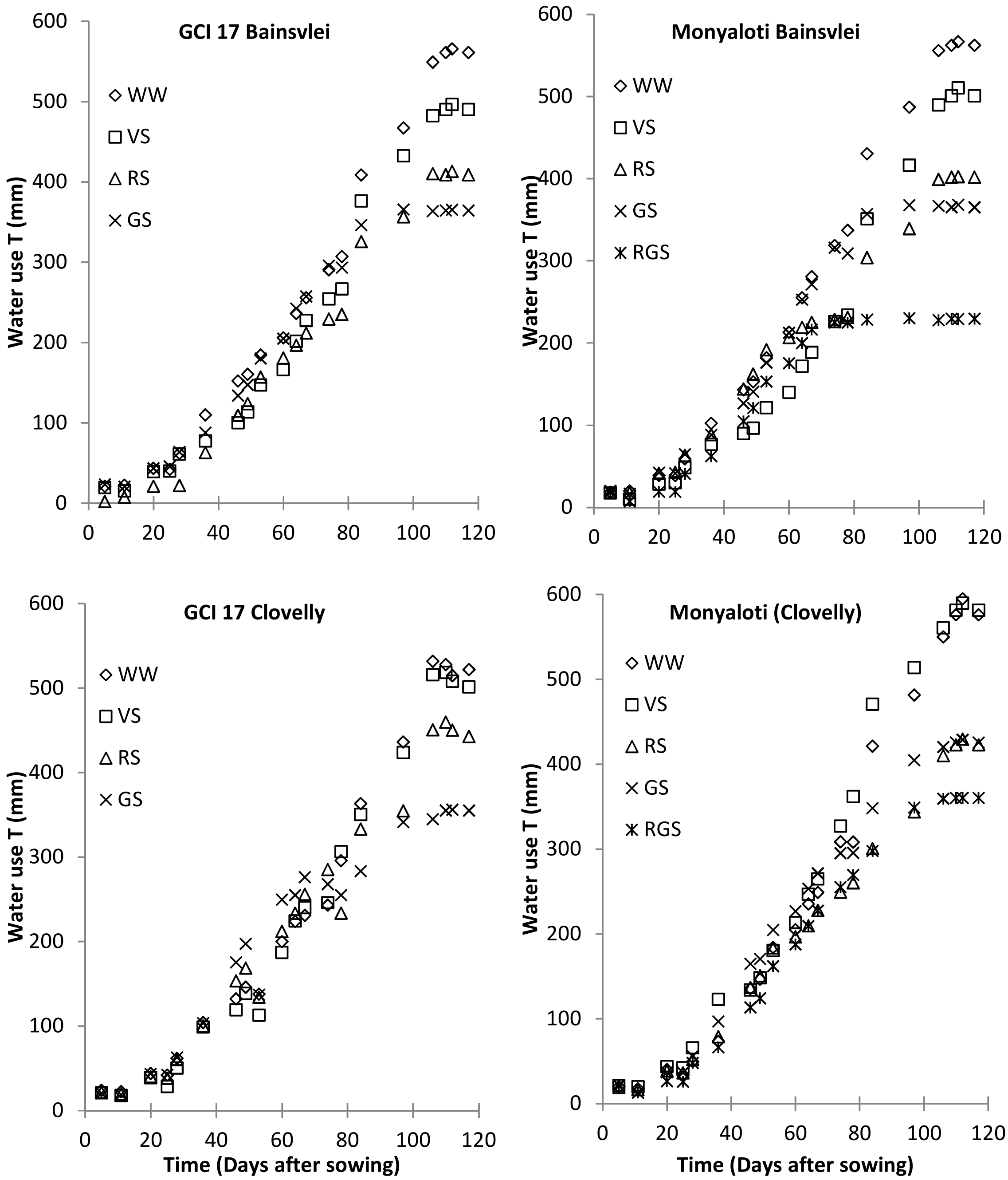

Figure 6.14: Cumulative transpiration (mm) as affected by water stress at different growth stages on two types of soil.

The mean water use (T) by the two lines of pearl millet ranges from 411 to 473 mm (Table 6.5). These are the highest and lowest T for the two soils and found on the Clovelly soil form. The well watered treatment lysimeter tanks produced the highest total aboveground biomass and grain yield irrespective of lines of pearl millet and soil forms. The number of heads per hectare as a yield component seems not to have any influence on the grain yield of the two lines of pearl millet. The highest grain yields for GCI 17 and Monyaloti respectively are 8.31and 10.74 ton ha^{-1} found on Clovelly soil type. The mean grain yields for GCI 17 are 6.86 ton ha^{-1} on Bainsvlei and 6.49 ton ha^{-1} on Clovelly soils. However, the GCI 17 plants from the RS and GS treatments exhibited high water productivity (WP) of biomass and grain yield on Bainsvlei soil. The mean WP_{bm} of GCI 17 is 0.035 tons ha^{-1} mm^{-1} on Bainsvlei and 0.033 tons ha^{-1} mm^{-1}on Clovelly soils while Monyaloti have 0.037 and 0.035 tons ha^{-1} mm^{-1} on Bainsvlei and Clovelly respectively. Reproductive stress (RS) caused high WP_{gy} of 0.017 tons ha^{-1} mm^{-1} in GCI 17 but very low WP_{gy} of 0.006 tons ha^{-1} mm^{-1} in Monyaloti on Bainsvlei soil.

Relationship between the transpiration (T) and the yield (total aboveground biomass and grain yield) is linear (Figure 6.14). Irrespective of the two types of soils and the two lines of pearl millet, the biomass and grain yield increases with water use. With the T of 561 mm, GCI 17 produced 18.36 tons ha^{-1} of total above ground biomass while with T of 422 mm, Monyaloti produced 13 tons ha^{-1} of total above ground biomass. In terms of grain yield, GCI 17 was more efficient in production. GCI 17 will use 561 mm of T to produce 8.18 tons ha^{-1} grain while Monyaloti will use 562mm of T to produce 6.6 tons ha^{-1} of grain. However, there is better agreement of relationship between T and total above ground biomass (0.723) than with grain yield (0.652) when all the water use, biomass, grain yield within treatments, soil forms and lines of pearl millet were pooled together.

Fraction of radiation intercepted is a measurement of canopy cover and development. Figure 6.15 illustrates that WW and VS plants of monyaloti intercepted more radiation on the two types of soil than the rest of the treatments plants. The maximum radiation intercepted was around 80 days after sowing for the two lines of pearl millet and the two soil forms. However, GCI 17 declined earlier in radiation interception than monyaloti irrespective of the two soil types and treatments. This shows that the line reaches senescence earlier than the local variety, monyaloti. On Bainsvlei lysimeter tanks, the VS treatment had the highest fraction of radiation interception of 0.77 for GCI 17 and 0.87 for monyaloti at 107 days after sowing. However, the plants from WW treated lysimeter tank intercepted the highest amount of radiation at the end of the measurement on Clovelly soil.

Table 6.5: 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.

	Transpiration (mm)		TBM (tons ha^{-1})		Number of heads (X 1000 ha^{-1})		Grain yield (tons ha^{-1})		Harvest index (HI)		WP_{bm} (tons ha^{-1} mm^{-1})		WP_{gy} (tons ha^{-1} mm^{-1})	
GCI 17	*B*	*C*	*B*	*C*	*B*	*C*	*B*	*C*	*B*	*C*	*B*	*C*	*B*	*C*
WW	561.08	522.01	18.36	16.75	243.61	172.89	8.18	8.31	0.446	0.496	0.033	0.032	0.015	0.016
VS	490.13	501.49	17.77	16.00	220.04	172.89	6.79	7.88	0.382	0.493	0.036	0.032	0.014	0.016
RS	409.17	442.73	14.82	16.33	204.32	172.89	6.76	5.22	0.456	0.320	0.036	0.037	0.017	0.012
GS	364.23	355.04	13.16	15.32	204.32	192.53	5.70	4.54	0.433	0.296	0.036	0.043	0.016	0.013
Mean	456.15	455.32	16.03	16.10	218.07	177.80	6.86	6.49	0.429	0.401	0.035	0.036	0.015	0.014
Monyaloti														
WW	562.31	576.01	22.71	26.34	180.75	286.83	6.60	10.74	0.290	0.408	0.040	0.046	0.012	0.019
VS	500.89	581.71	21.37	19.29	208.25	220.04	6.20	6.93	0.290	0.359	0.043	0.033	0.012	0.012
RS	401.77	422.91	10.84	13.96	86.44	168.96	2.57	5.97	0.237	0.428	0.027	0.033	0.006	0.014
GS	365.26	425.45	12.46	14.19	137.52	176.82	3.93	6.78	0.315	0.478	0.034	0.033	0.011	0.016
RGS	229.56	360.19	9.39	10.85	86.44	208.25	2.39	4.61	0.254	0.425	0.041	0.030	0.010	0.013
Mean	411.96	473.25	15.35	16.93	139.88	212.18	4.34	7.01	0.28	0.42	0.037	0.035	0.010	0.015

*WP_{bm} Water productivity for biomass

*WP_{gy} Water productivity for grain yield

*B – Bainsvlei

*C – Clovelly

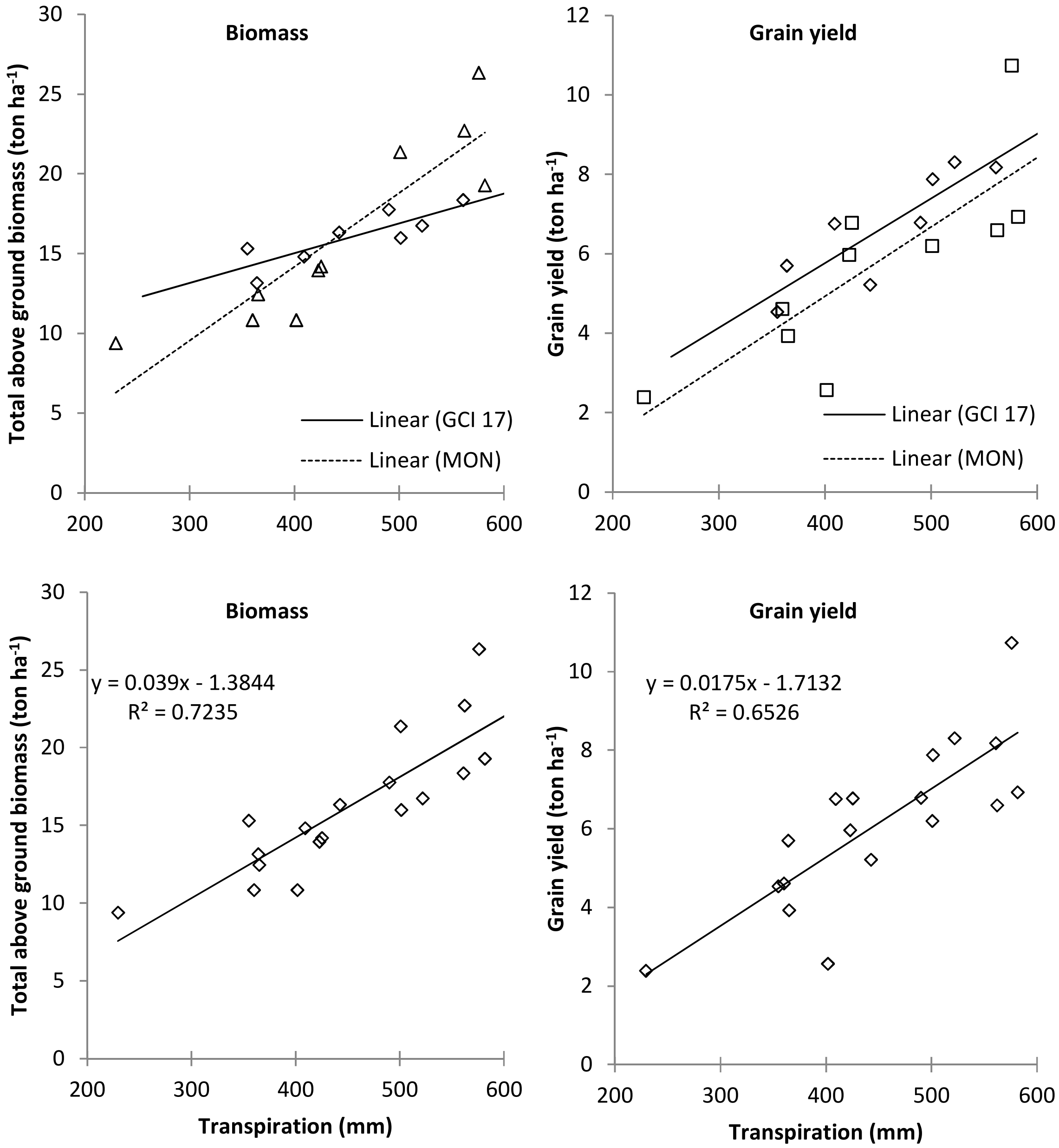

Figure 6.15: Relationship between biomass, grain yield of the two lines of pearl millet and seasonal transpiration (mm) as affected by water stress at different growth stages.

Leaf water potential of the two lines of pearl millet was affected differently by water stress at different growth stages (Figure 6.16). 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 least leaf water potential was found in RGS in Monyaloti plants but was not significantly different from GS of the same line of pearl millet irrespective of the soil type.

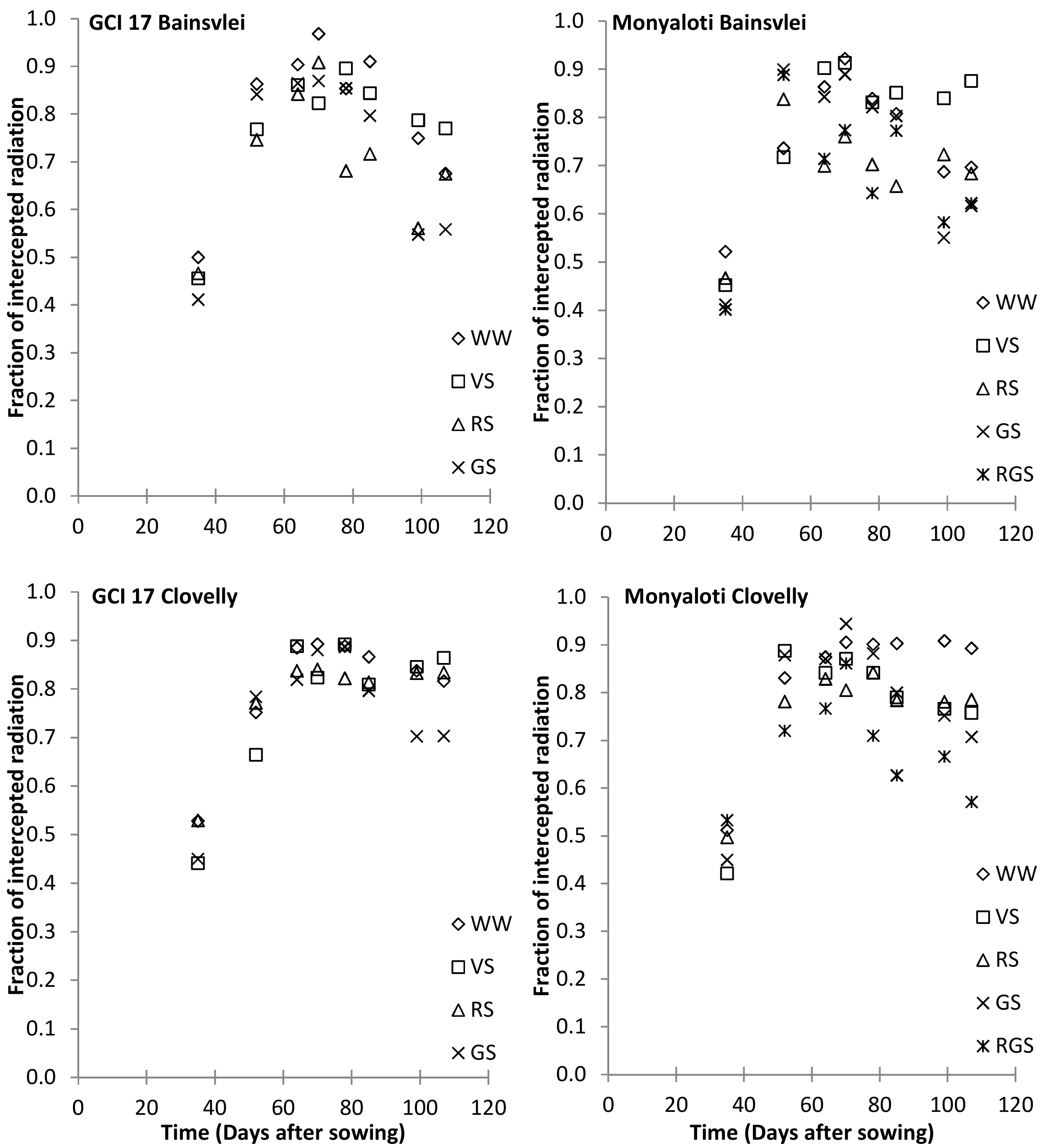

Figure 6.16: Intercepted radiation of canopies of the two lines of pearl millet during stress at different growth stages on two types of soil.

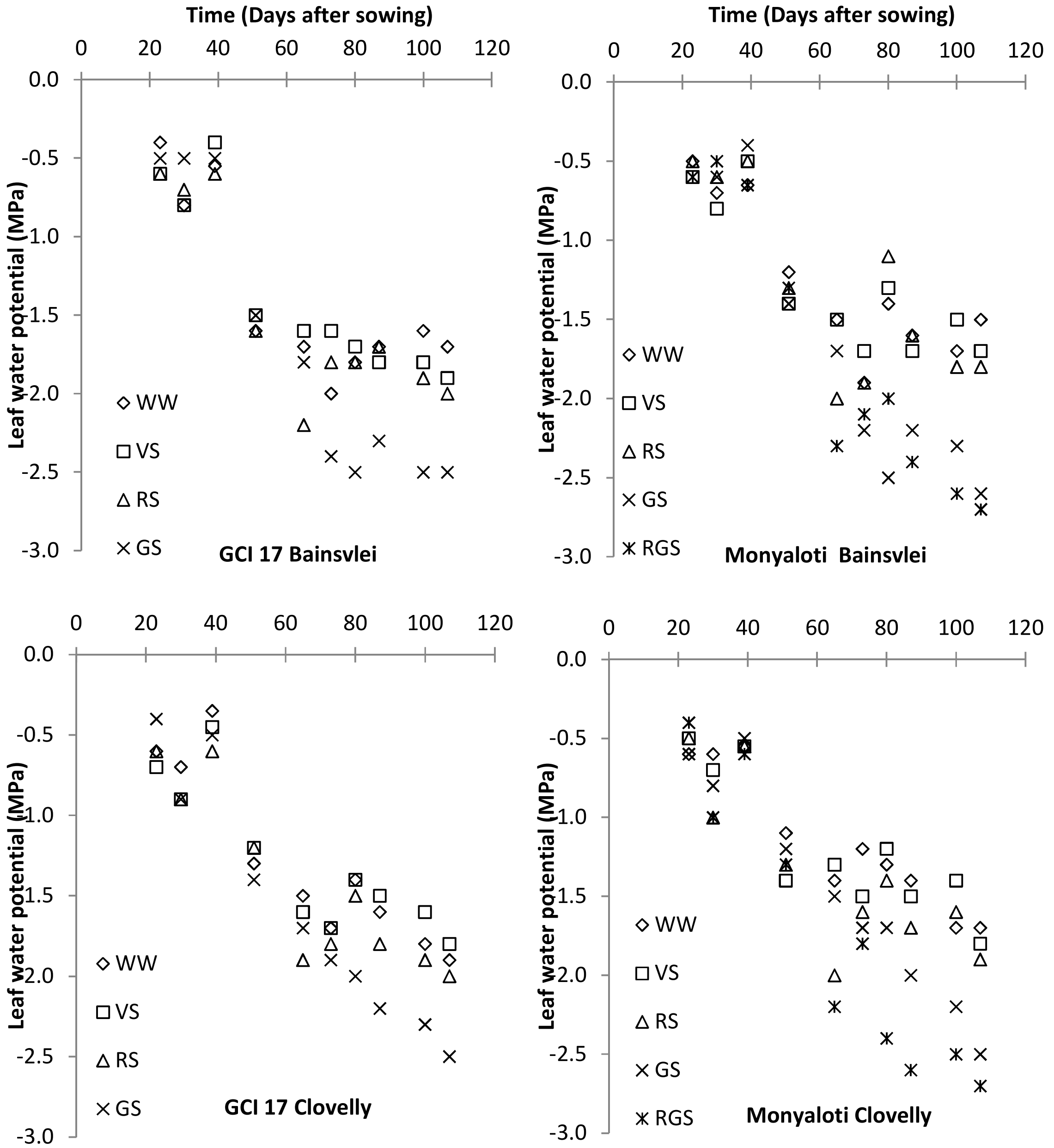

Figure 6.17: Change in leaf water potential with time of the two lines of pearl millet during stress at different growth stages on two types of soil.

Stomatal conductance of the two lines of pearl millet were different for the two type of soil for all the treatments (Figure 6.17). 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 mmol m^{-2} s^{-1} while it was around 300 mmol m^{-2} 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 tanks was zero indicating that they were already at senescence at this particular time.

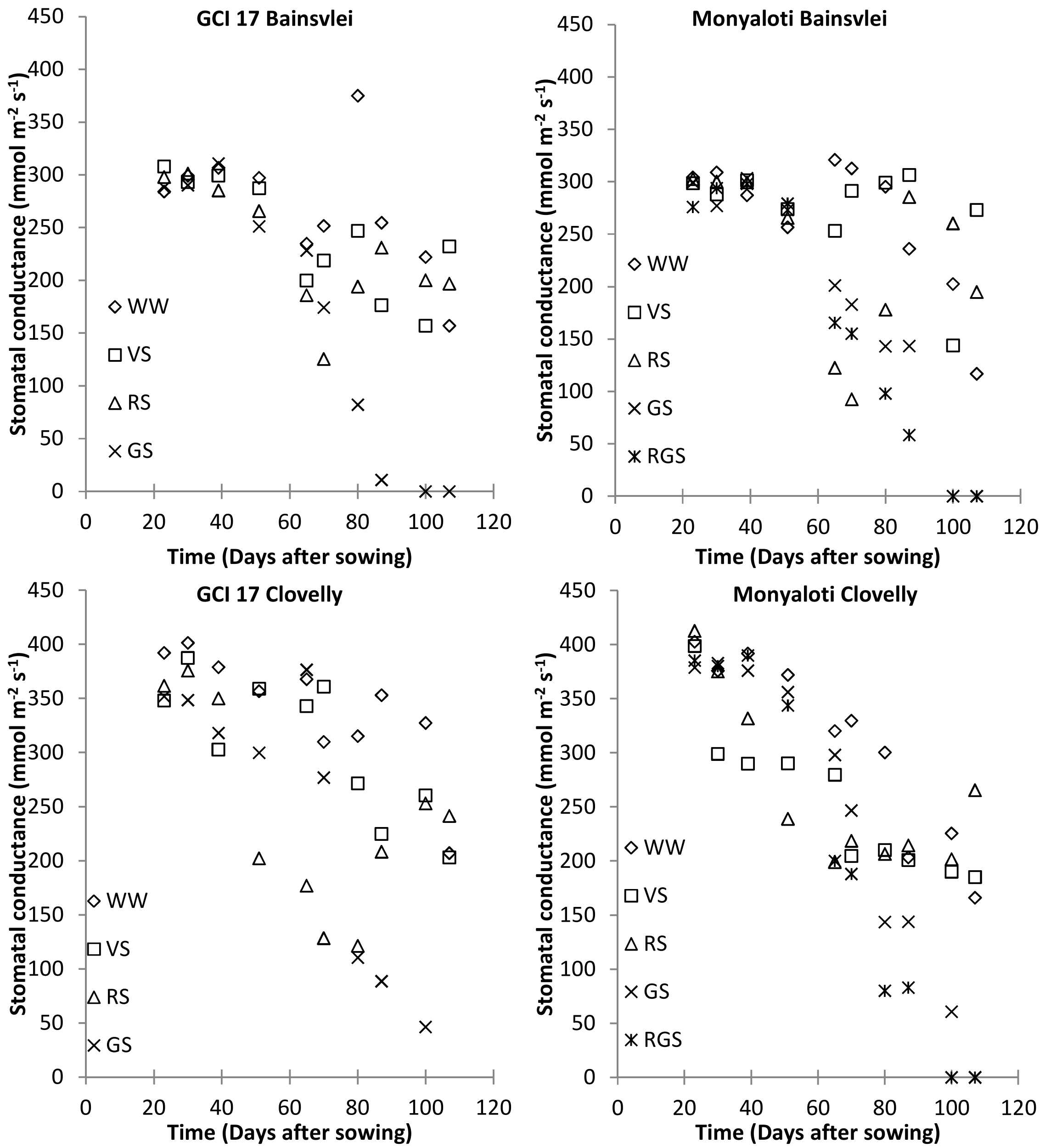

Figure 6.18: Stomatal conductance of the two lines of pearl millet during stress at different growth stages on two types of soil.

The linear relationship between the stomatal conductance shows that the lower the stomatal conductance the more pressure needed to get water out of these leaves (Figure 6.18). Comparing the coefficient of agreements of the relationship between the two lines of pearl millet and soil form, Monyaloti had the best fit on Clovelly soil type (Table 6.6).

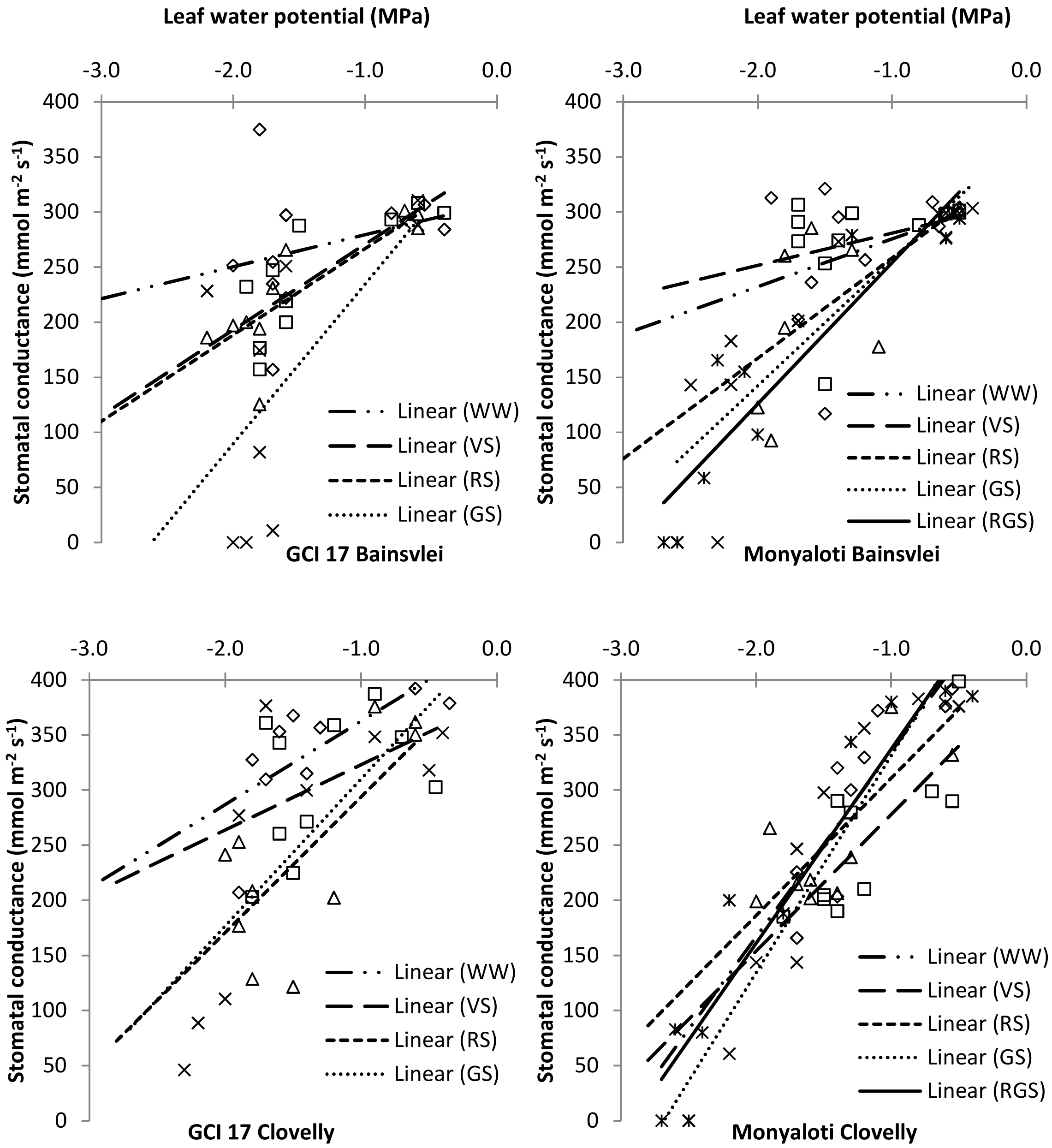

Figure 6.19: Relationship between leaf water potential and stomatal conductance of the two lines of pearl millet during stress at different growth stages on two types of soil.

Table 6.6: The coefficient of determination (R^2) for the 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.

	Bainsvlei		**Clovelly**	
Treatments	*GCI 17*	*Monyaloti*	*GCI 17*	*Monyaloti*
WW	0.079	0.107	0.533	0.769
VS	0.629	0.080	0.184	0.652
RS	0.691	0.492	0.533	0.689
GS	0.478	0.734	0.566	0.889
RGS	-	0.861	-	0.904

6.3.2.2 Field trials

The difference in irrigation water supplied during the two seasons was more than double (Table 6.7). The 2008/09 season received more irrigation water than the 2009/10 season. This may be due to the high rainfall recorded during the 2009/10 growing season, which resulted to lower total water supplied for the season in all the treatments. The only exception was found in the rainfed plots where the plots in 2009/10 received more water than the previous season due to high rainfall recorded. Soil water contents of the plots of the two lines of pearl millet were similar for each cropping season (Figure 6.19). However, more depletion was recorded in the 2008/09 season compared to the 2009/10 season. In 2009/10, the rainfed plots soil water content was significantly different from the other treatments plots throughout the season.

Table 6.7: Amount of rain and irrigation water (mm) supplied to the plots of the two lines of pearl millet over the two cropping seasons (2008/09 and 2009/10).

	2008/09			**2009/10**		
	Irrigation	*Rain*	*Total*	*Irrigation*	*Rain*	*Total*
W5 (Full irrigation)	134.2	263.4	397.6	58	295.3	353.3
W4	97.8	263.4	361.2	41.5	295.3	336.8
W3	76.4	263.4	339.8	20.65	295.3	315.95
W2	52.2	263.4	315.6	11.1	295.3	306.4
W1 (Rainfed)	0	263.4	263.4	0	295.3	295.3

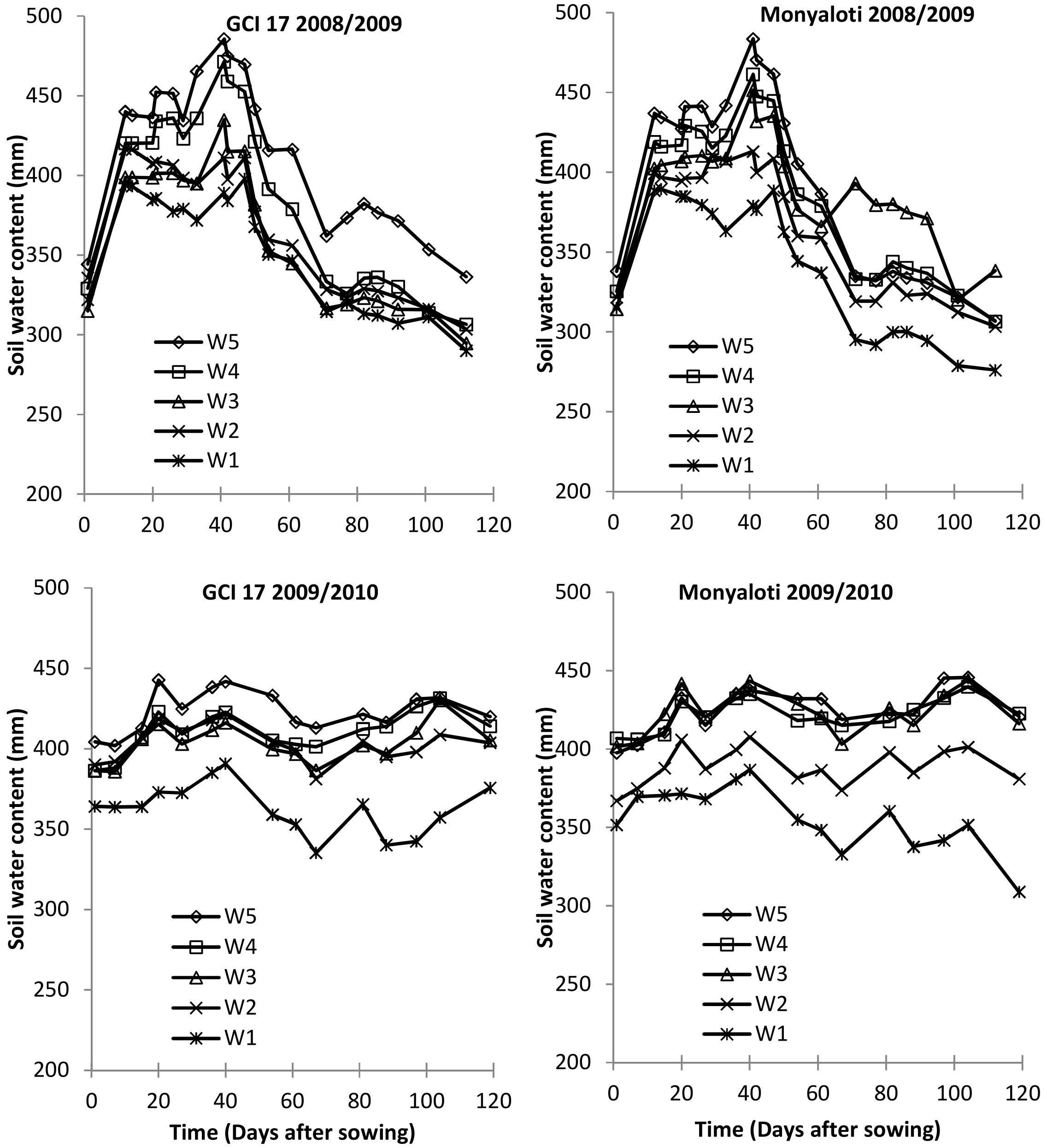

Figure 6.20: Change in soil water content of the plots of the two lines of pearl millet as affected by water treatments over the two cropping seasons (2008/09 and 2009/10).

Transpiration rate for the two seasons and the two lines of pearl millet did not exhibit a regular pattern (Figure 6.20). The range was around 10 mm day^{-1} in the 2008/09 season while it was around 7 mm day^{-1} in the 2009/10 season. There were significant differences between the treatments for cumulative water use (ET) in the 2008/10 season but no significant difference was found in the 2009/10 season (Figure 6.21). The weather condition might have reduced the atmospheric demand during the 2009/10 season resulting in low evaporation and transpiration. The rain incidence could be another reason for the insignificant differences in ET during the 2009/10 season.

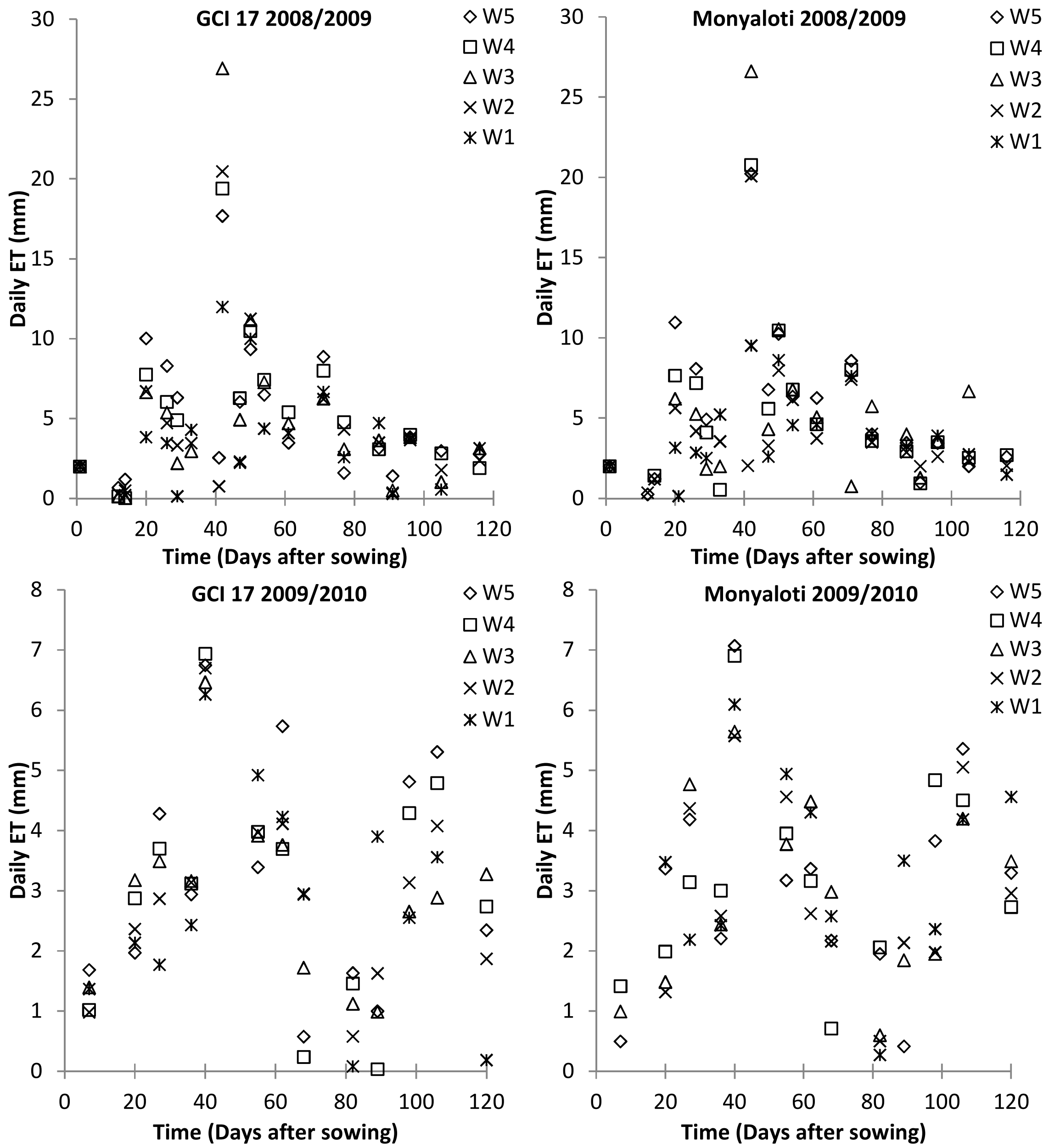

Figure 6.21: Daily evapotranspiration (ET) during the 2008/09 and 2009/10 seasons for the two lines of pearl millet.

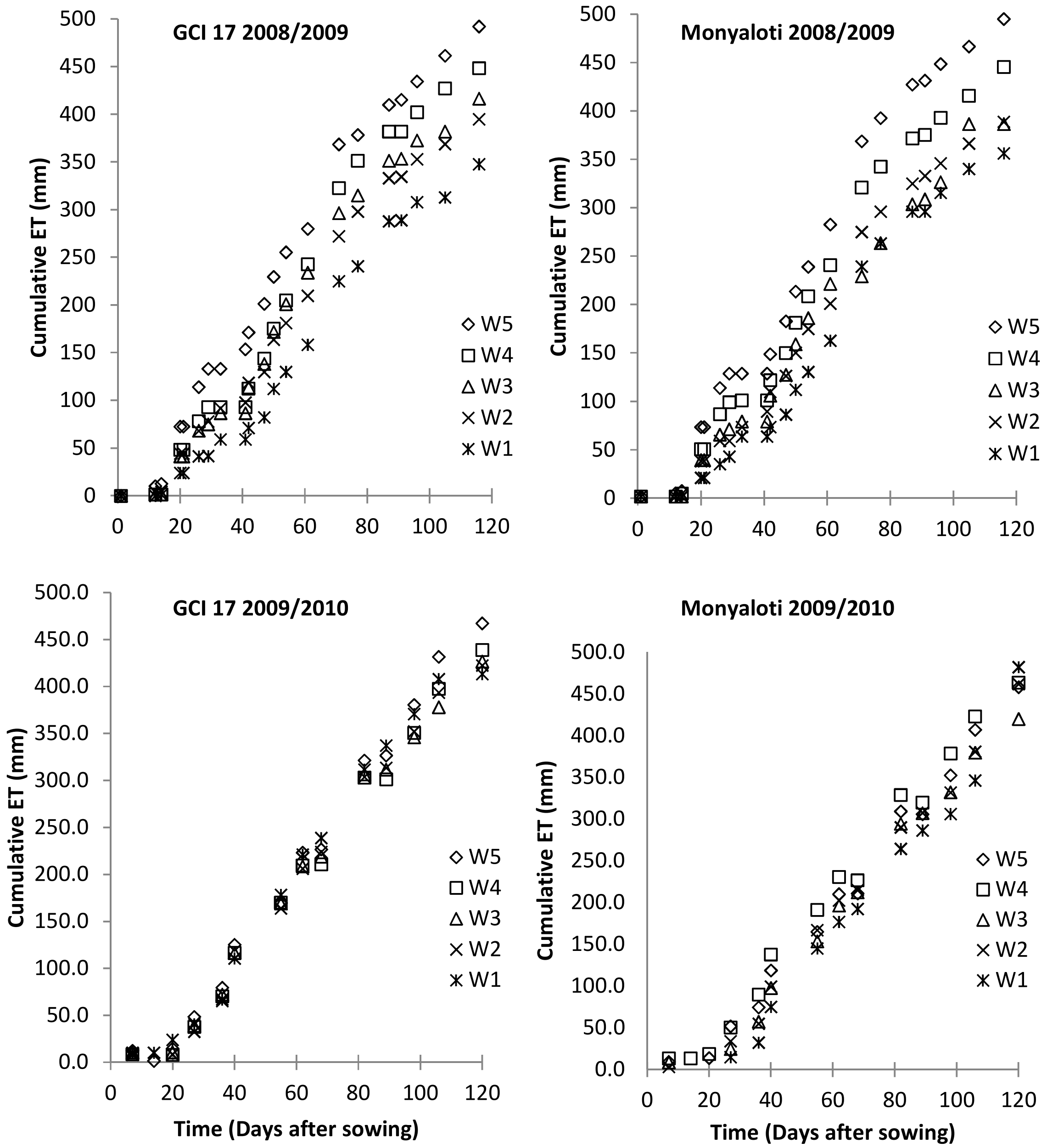

Figure 6.22: Cumulative evapotranspiration (ET) during the 2008/09 and 2009/10 seasons for the two lines of pearl millet.

The grain yield was reported only for the 2009/10 season due to the bird damage in the 2008/09 season. Therefore, final aboveground was the only yield parameter reported for 2008/09 season. The mean final above ground biomass for the two lines of pearl millet was higher during the 2008/09 season than the 2009/10 season (Table 6.8). Although, the mean ET was lower during the 2008/09 but the WUE_{bm} was greater than the 2009/10 season. However, the local variety, Monyaloti produced more biomass than the improved line, GCI 17 for both seasons. It is safe to say the plants from the W4 treatment plots had the highest biomass irrespective of the lines of pearl millet and the season. Number of heads per ha^{-1} as a yield component was not significant between the seasons and lines of pearl millet. In the GCI 17 plots, the W4 plots consistently produced the highest grain yield of 9.05 ton ha^{-1} while the lowest, 4.67 ton ha^{-1}, was from the rainfed (W1) plots. Grain yield and harvest index (HI) of Monyaloti was not significantly different within the treatments. However, the HI, WUE_{bm}, WUE_{gy} are 0.40, 0.040 ton ha^{-1} mm^{-1} and 0.016 ton ha^{-1} mm^{-1} respectively in the GCI 17 plots during the 2009/10 season.

Radiation interception for the 2009/10 shows that the highest canopy cover attained at around 70 days after sowing for the two lines of pearl millet (Figure 6. 22). In the GCI plots, W4 had the highest radiation interception while it was W3 in the monyaloti plots.

Table 6.8: Total above ground biomass (BM), seasonal evapotranspiration (ET), water use efficiency (WUE), number of heads per unit area (NH) , grain yield, harvest index (HI) of the two lines of pearl millet over the two cropping seasons (2008/09 and 2009/10).

	2008/09			2009/10						
GCI 17	*BM*	*ET*	*WUE_{bm}*	*ET*	*BM*	*NH*	*GY*	*HI*	*WUE_{bm}*	*WUE_{gy}*)
W5	18.53	492.21	0.04	467.24	23.39	305.56	7.07	0.43	0.035	0.015
W4	18.16	448.15	0.04	438.81	23.65	347.23	9.05	0.46	0.045	0.021
W3	21.54	416.49	0.05	426.67	20.85	305.56	7.10	0.41	0.040	0.017
W2	17.10	394.95	0.04	422.52	18.57	236.11	6.46	0.34	0.045	0.015
W1	19.15	347.63	0.06	413.40	16.63	222.22	4.67	0.36	0.031	0.011
Mean	18.90	419.89	0.05	433.73	17.14	283.34	6.87	0.40	0.040	0.016
Monyaloti										
W5	24.34	494.95	0.05	458.13	29.53	388.89	10.32	0.58	0.039	0.023
W4	29.94	445.49	0.07	463.52	25.68	347.23	5.70	0.23	0.053	0.012
W3	23.78	386.56	0.06	420.16	25.31	185.19	6.01	0.28	0.052	0.014
W2	21.64	388.94	0.06	461.94	28.51	425.93	10.38	0.58	0.039	0.022
W1	21.12	356.43	0.06	482.17	23.01	347.23	9.69	0.82	0.025	0.020
Mean	24.16	414.47	0.06	457.18	**18.76**	338.89	8.42	0.50	0.041	0.018

*WUE_{bm} Water use efficiency for biomass *WUE_{gy} Water use efficiency for grain yield *Units: BM = (ton ha^{-1}), GY= (ton ha^{-1}), ET = (mm), NH, (ton ha^{-1}), WUE_{bm} = (ton ha^{-1} mm^{-1}), WUE_{gy}= (ton ha^{-1} mm^{-1})

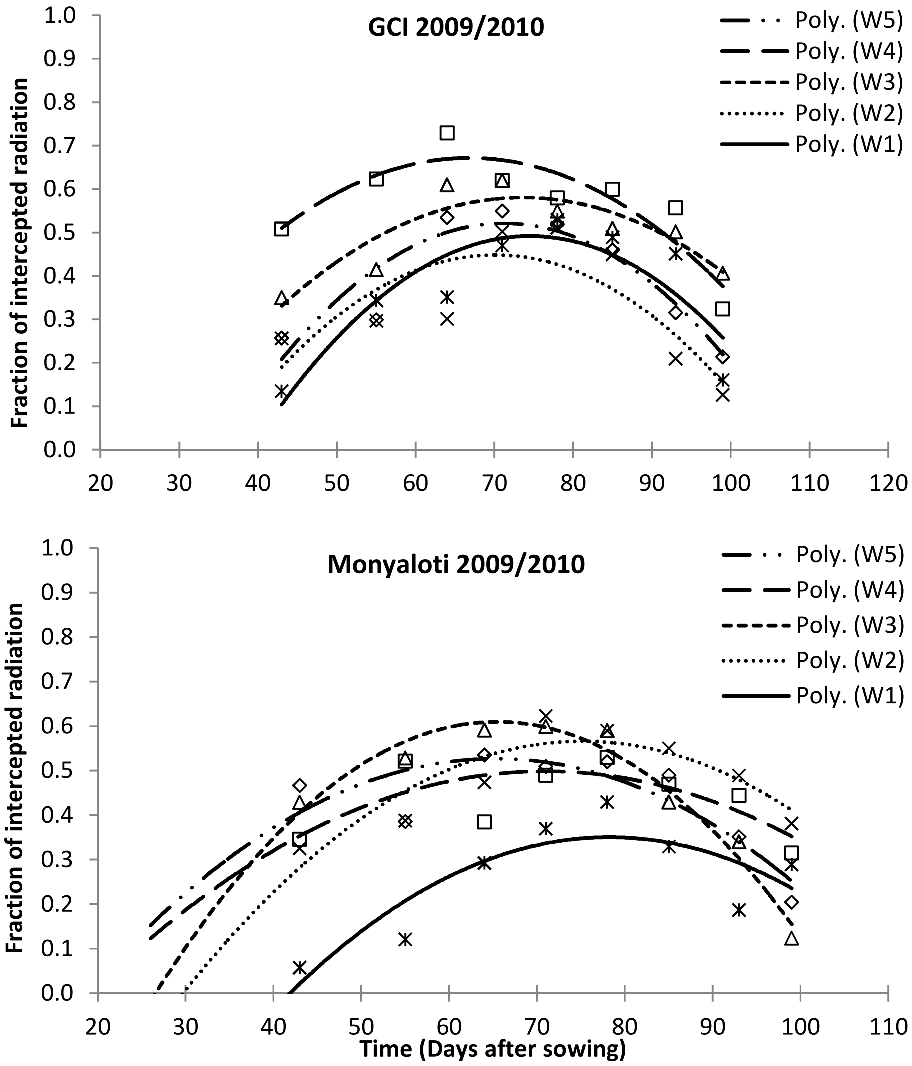

Figure 6.23: Fraction of intercepted radiation of canopies of the two lines of pearl millet during the 2009/10 season

6.4 Conclusion

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 significant information on water influence on amaranth and pearl millet production. Efficient production of amaranth through irrigation requires a small amount of water but at a sufficient level. Irrigation can improve both biomass and grain yield of the crop for 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 with the irrigated crop. 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 a large amount of water but with high water use efficiency. This line proved 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 7

Drought tolerance of selected taro (*Colocasia esculenta* L. Schott) landraces from KwaZulu-Natal, South Africa

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7.1 Introduction

Taro is thought to be one of the oldest domesticated crops, with a history of cultivation in the Indo-Pacific dating back to more than 10, 000 years (Cable, 1984; Plucknet, 1984; Haudricourt & Hédin, 1987 cited in Lebot, 2009; Rao *et al*., 2010). In South Africa, taro is an important NUS cultivated by subsistence farmers using landraces. Its production remains confined to mostly rural coastal areas of KwaZulu-Natal and the Eastern Cape provinces (Shange, 2004). Over the last decade, semi-commercialisation of taro by subsistence farmers (Modi, 2003; Agargaad & Birch-Thomsen, 2006) has contributed to an increase in taro production. As such, there is growing interest to promote it among small-scale farmers in other parts of the country, which may be drier than the coastal areas. Lack of scientific information describing effects of drought on growth, development and yield of diverse taro landraces remains a stumbling block to its successful expansion.

There has been limited research on drought tolerance of this crop. Snyder and Lugo, (1980) reported that drought tolerance existed in some wild relatives of taro, suggesting it was possible to develop drought tolerant hybrids. In India, Sahoo *et al*. (2006), using taro hybrids concluded that development of drought tolerant varieties of taro was a possibility after observing tolerance to osmotic stress with negligible yield reduction in the taro hybrid.

Local research on taro has primarily focussed on propagate quality and storage (Shange, 2004; Modi, 2007), with limited research on growth, and yield quality (Mare, 2006, 2010; Modi, 2007; Mare & Modi, 2012) as well as nutritional quality (McEwan, 2008). There has been no research describing taro's drought tolerance and there are currently no improved varieties of taro, hence local subsistence farmers still use landraces. Availability of information describing drought tolerance in these landraces could lead to development of drought tolerant varieties. Therefore, this study is aimed to evaluate the growth responses to water stress and mechanisms of drought tolerance of local taro landraces.

7.2 Materials and Methods

7.2.1 Planting material

Three landraces of taro (*Amadumbe*) were collected from two locations in KwaZulu-Natal (KZN); one from KwaNgwanase (KW) (27°1'S; 32°44'E) in northern KZN, and two from Umbumbulu [UM and Dumbed Limuli (DL): 29°36'S; 30°25'E] in the midlands of KZN, in April, 2010. The KW and DL landraces were classified as dasheen types characterised by a large central corm and no side cormels (Shange, 2004). The DL landrace was obtained from the wild where it was growing in shallow streams. The KW landrace was semi-domesticated and cultivated on stream-banks. The UM landrace is an upland landrace and is an eddoe type landrace characterised by a central corm and numerous side cormels which are the edible parts (Lebot, 2009). In order to eliminate propagule size effects, planting material was initially selected for uniform plant size (Singh *et al*., 1998). Propagules were then treated with a bactericide and fungicide (Sporekill®) to prevent rotting during sprouting. Thereafter, propagules were sprouted in vermiculite (30°C, 90% RH) for 21 days before being planted out in the field. KwaNgwanase was propagated using head-setts (huli), Umbumbulu and DL using sprouted corms and cuttings, respectively.

7.2.2 Description of experimental sites

Field trials were conducted at the University of KwaZulu-Natal's Ukulinga Research Farm, Pietermaritzburg (29°37'S; 30°16'E) during the summer planting seasons of 2010/11 and 2011/12. Ukulinga represents a semi-arid environment and is characterised by clay-loam soils (USDA taxonomic system). Weather parameters were monitored by an automatic weather station (AWS) (ARC – Institute for Soil, Climate and Water) situated within a 100 m radius of the trials.

7.2.3 Experimental designs

A factorial experiment with a split-plot layout arranged in a completely randomised block design was used at both experimental sites. Irrigation [full irrigation (FI) versus rainfed (RF)] was the main factor, while landrace type (DL, KW and UM) was the sub-factor. The sub-factor was replicated three times. The trials were planted on an area of 499.8 m^2. Main plots measured 207.4 m^2 each, with 15 m spacing between them to prevent water from sprinklers in the FI treatment from reaching RF plots – sprinklers had a maximum range of 6 m radius. The sub-plot size was 17 m^2 with an inter-plot spacing of 1 m, and plant spacing of 1 x 0.5 m, translating to 20 000 plants per hectare. Irrigation scheduling for the full irrigation treatment was based on ET_o from the AWS and was applied using sprinklers on 1 m high risers. In order to allow for maximum possible crop stand, the RF treatment was established under irrigation until plants had reached 90% emergence. Thereafter, irrigation was withheld from the RF treatment.

7.2.4 Agronomic practices

Prior to commencement of trials, soil samples were taken for soil fertility and textural analysis. Results of soil texture analysis were used to define soil physical parameters of field capacity (FC), permanent wilting point (PWP) and saturation (K_{sat}) using the Soil Water Characteristics Hydraulic Properties Calculator (http://hydrolab.arsusda.gov/soilwater/Index.htm). Land preparation involved disking and rotovating the fields to achieve a fine seedbed. Fertiliser was applied using an organic fertiliser, Gromor®, at a rate of 5 330 kg ha^{-1} (Mare, 2010). Since taro takes long to mature, fertiliser application was split into two: half at planting and the remainder 20 weeks after planting, to ensure nutrient availability throughout the trials. Weeding and ridging were done by hand-hoeing.

7.2.5 Data collection

The experimental designs and data collection were specifically designed to collect empirical data and observations for taro, which could later be used to model taro using AquaCrop (Steduto *et al*., 2009). Data collection included emergence until at least 90% of the plants had emerged. Canopy characteristics [plant height, leaf number and leaf area index (LAI)] were determined starting from when the plants had reached 90% emergence. Plant height was measured from the bottom of the plant up to the base of the 2nd youngest fully unfolded leaf. Leaf number was counted only for fully unfolded leaves with at least 50% green leaf area. Leaf area index was measured using the LAI2200 Canopy Analyser (LI-COR, Inc. USA & Canada). During the 2010/11 season, only the KW and UM landraces were measured since the crop stand in the DL landrace was too low to allow good measurements to be taken. Stomatal conductance (SC) was determined using a steady state leaf porometer (Model SC-1, Decagon Devices, USA). During 2011/12 planting season, leaf chlorophyll content index (CCI) was determined using a chlorophyll content meter (CCM-200 *PLUS*, Opti-Sciences, USA). Stomatal conductance (SC) and CCI were measured from the abaxial and adaxial leaf surfaces, respectively, of the 2nd youngest fully unfolded leaf for the entire duration of the trial as described for SC by Sivan (1995). Soil water content (SWC) was monitored weekly using a PR2/6 profile probe connected to a handheld HH2-moisture meter (Delta-T Devices, UK). The vegetative growth index (VGI) was measured in field trials as described by Lebot (2009) with minor modifications (Equation 1):

$$VGI = [((\text{leaf width x leaf length})*\text{leaf number})*H/100] – (\text{suckers + stolons})^2 \qquad \text{Equation 8.1}$$

where VGI = vegetative growth index, and

H = plant height

7.2.6 Statistical analysis

Data collected from all trials were analysed using analysis of variance (ANOVA) with GenStat® (Version 14, VSN International, UK). Thereafter, least significant differences (LSD) were used to separate means at the 5% level of significance.

7.3 Results

During the first season (2010/11), the average temperature was 19.5°C, with measured total rainfall of 939.2 mm against a calculated reference evapotranspiration (ET_o) of 878.1 mm. As such, rainfall received during this period was greater (by 61.1 mm) than ET_o. Most of the rainfall was received during the vegetative periods (Dec-March) and generally exceeded or matched ET_o (Figure 7.1). During the 2011/12 season, the average temperature was similar to that of 2010/11, however, total rainfall (647.2 mm) received in 2011/12 was less than that received in the previous season. Furthermore, total rainfall received was less (280.6 mm) than ET_o, suggesting that the crop may have suffered evaporative demand stress during the 2011/12 season. Lastly, rainfall distribution showed that rainfall during the whole growing season was lower than ET_o, except for March and November (Figure 7.1).

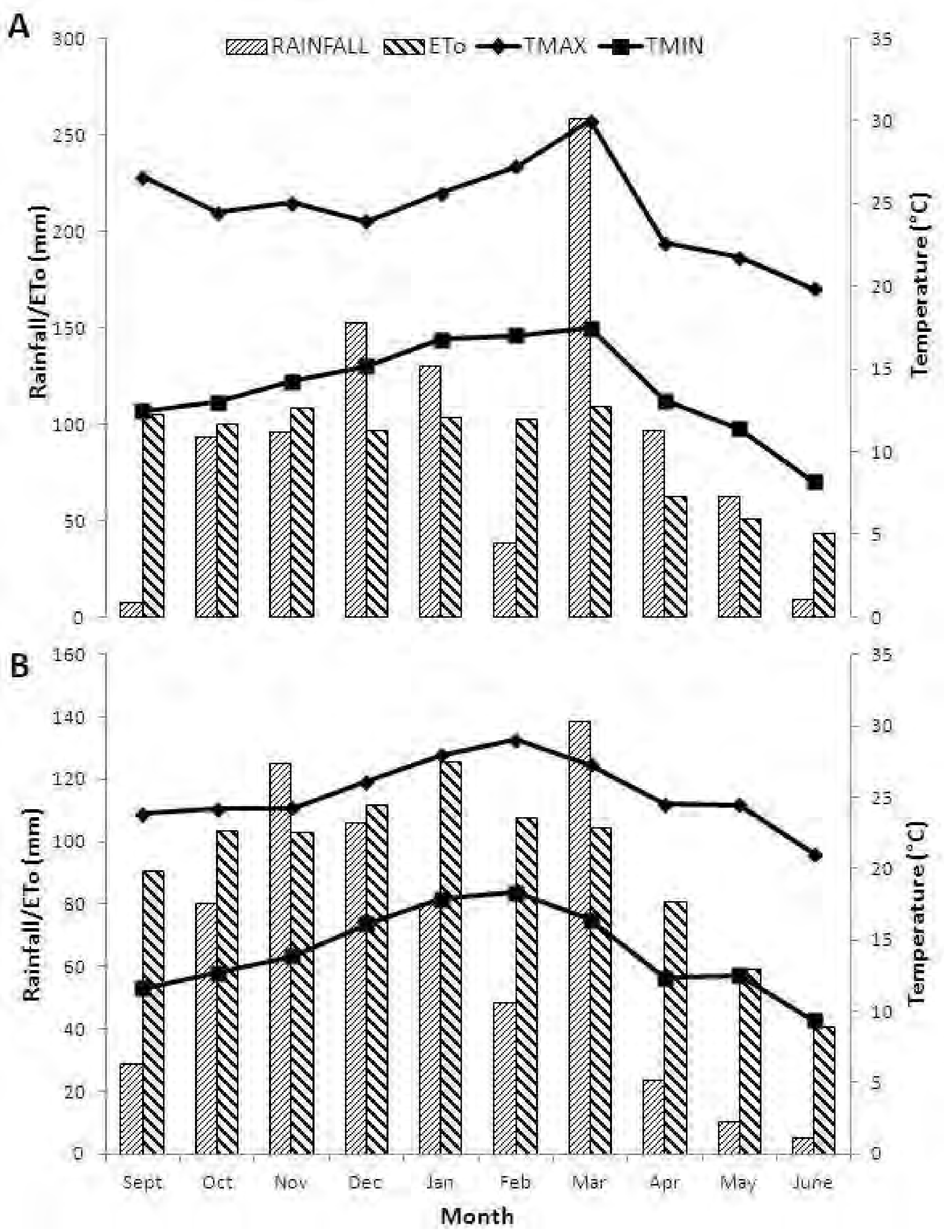

Figure 7.1: Maximum (Tmax) and minimum (Tmin) temperatures, rainfall and reference evapotranspiration (ET_o) recorded at Ukulinga (Sept-June) during A. 2010/11 and B. 2011/12 planting seasons. Note the difference in rainfall and (ET_o) recorded during 2011/12.

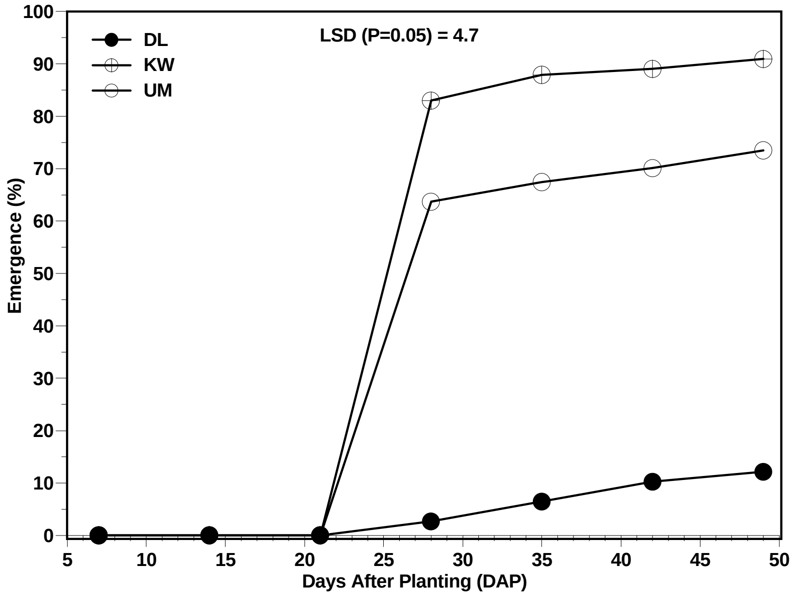

Figure 7.2: Emergence of taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] based on mean values for both seasons. Note that DL was slow to emerge.

In order to allow for maximum possible crop stand, trials (irrigated and rainfed) were established under full irrigation. Results presented here show differences between landraces for both planting seasons. Taro landraces emerged slowly during the first 21 days after planting (DAP). Thereafter, emergence proceeded relatively faster, reaching 90% establishment at about 49 DAP, on average (Figure 7.2). Results of emergence showed highly significant differences ($P<0.001$) between landraces, with KW emerging faster compared to the UM and KW landraces. The DL landrace showed the lowest emergence, failing to reach 25% emergence throughout the season (Figure 7.2).

Stomatal conductance (SC) was measured at the onset of the rapid vegetative stage (4 months after planting). Across both seasons, results showed highly significant differences ($P<0.001$) between irrigation treatments and landraces (Figure 7.3). During the 2010/11 season, there was a significant interaction ($P<0.05$) between irrigation treatments while in the subsequent season (2011/12), the interaction was not significant. Stomatal conductance was lower under rainfed, after 17 weeks, compared to irrigated conditions: it was almost twice as high under irrigated relative to rainfed conditions (Figure 7.3). On average, for both irrigation treatments, the DL landrace had higher SC than the UM landrace. Under rainfed conditions, based on mean values for both seasons, SC for DL, KW and UM was 34%, 52% and 58% lower, respectively, compared with irrigated conditions. Under rainfed conditions, the UM landrace was shown to have the lowest SC compared to the DL and KW landraces, suggesting a greater degree of stomatal control in the UM landrace.

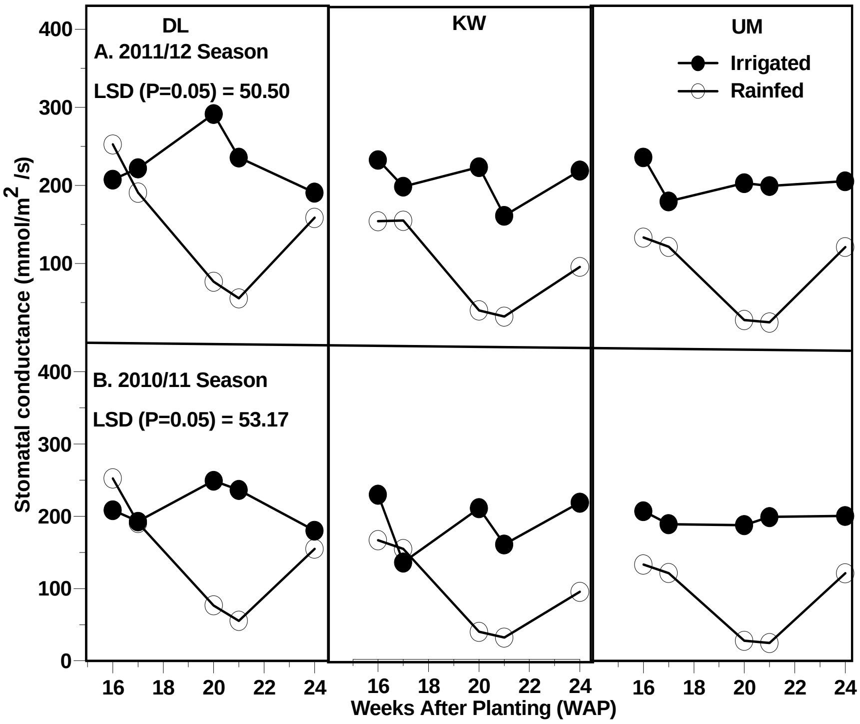

Figure 7.3: Stomatal conductance of taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] grown under irrigated and rainfed conditions at Ukulinga during (B) 2010/11 and (A) 2011/12 planting seasons.

The trend in chlorophyll content index (CCI) was in line with observations of SC (Figure 7.3). Chlorophyll content index was shown to decrease significantly (P<0.001) under rainfed relative to irrigated conditions (Figure 7.4). Based on mean values, CCI was about 40% lower under rainfed compared with irrigated conditions. Landraces were shown to differ significantly (P<0.001) with respect to CCI. The UM landrace had the highest CCI compared with KW and DL landraces, respectively, under both irrigated and rainfed conditions. Results of CCI showed that DL had the greatest decrease (49%) while KW and UM had similar decreases (36%) under rainfed relative to irrigated conditions. This meant that, even though the UM landrace had lower CCI under rainfed conditions; it retained a higher CCI under rainfed (stress) conditions than the DL and KW landraces.

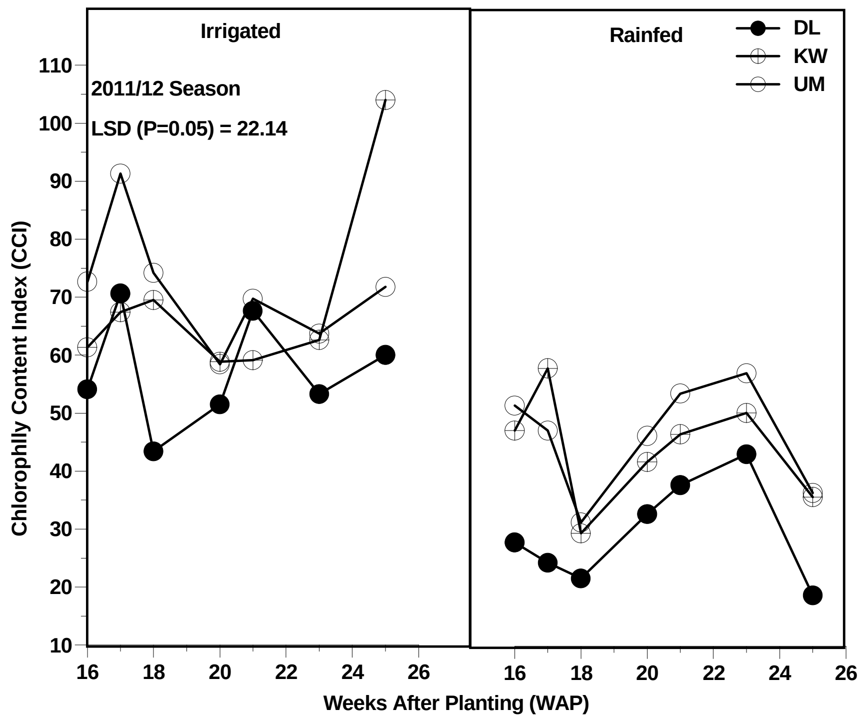

Figure 7.4: Chlorophyll content index (CCI) of taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] grown under (a) irrigated and (b) rainfed conditions at Ukulinga during the 2011/12 planting season.

Results collected from both seasons (2010/11 and 2011/12) showed that measured growth parameters of plant height, leaf number and LAI were negatively affected by limited water availability under rainfed conditions. Plant height results for both seasons recorded highly significant differences (P<0.001) between irrigation treatments, landraces and their interaction (Figure 7.5). Based on mean values of irrigated plots, DL had the tallest plants (117 cm) compared with KW (107 cm) and UM (82 cm), respectively. During 2010/11, plant height of KW, UM and DL was respectively 42%, 32% and 29% lower under rainfed relative to irrigated conditions. While for the subsequent season (2011/12), plant height of UM, KW and DL was respectively 33%, 31% and 26% lower under rainfed relative to irrigated conditions. Results showed that UM and KW landraces were more inclined to attain a lower maximum plant height under water limited conditions.

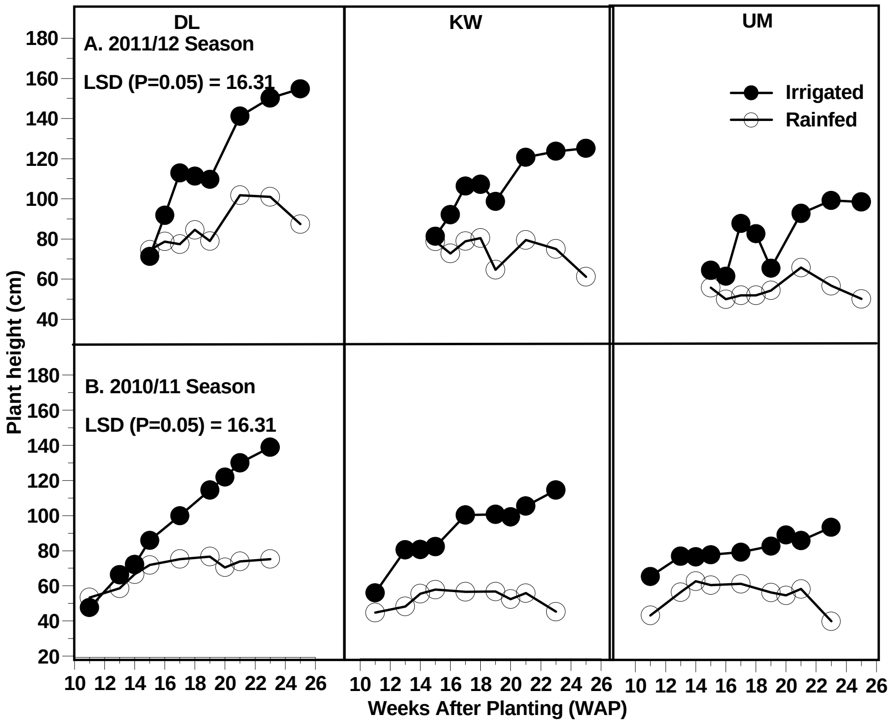

Figure 7.5: Plant height (cm) of taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] grown under irrigated and rainfed conditions at Ukulinga during (b) 2010/11 and (a) 2011/12 planting seasons.

Results of leaf number measured for both seasons showed highly significant differences (P<0.001) between irrigation treatments and landraces. During the 2011/12 planting season there was a highly significant (P<0.001) interaction between irrigation treatments and landraces (Figure 7.6). Leaf number was, on average, higher during the 2011/12 season than the 2010/11 season although less rainfall was received during the former season. The observed trend of results, across both seasons, showed that, on average, DL and KW landraces had a higher leaf number than the UM landrace. Leaf number was shown to be consistently lower under rainfed relative to irrigated conditions. On average, for both seasons, leaf number of DL, KW and UM landraces was lower by 29%, 36% and 28%, respectively, under rainfed relative to irrigated conditions. The KW landrace had the greatest decrease in leaf number compared to the DL and UM landraces. This was consistent with lower plant height observed in the KW landraces under rainfed conditions.

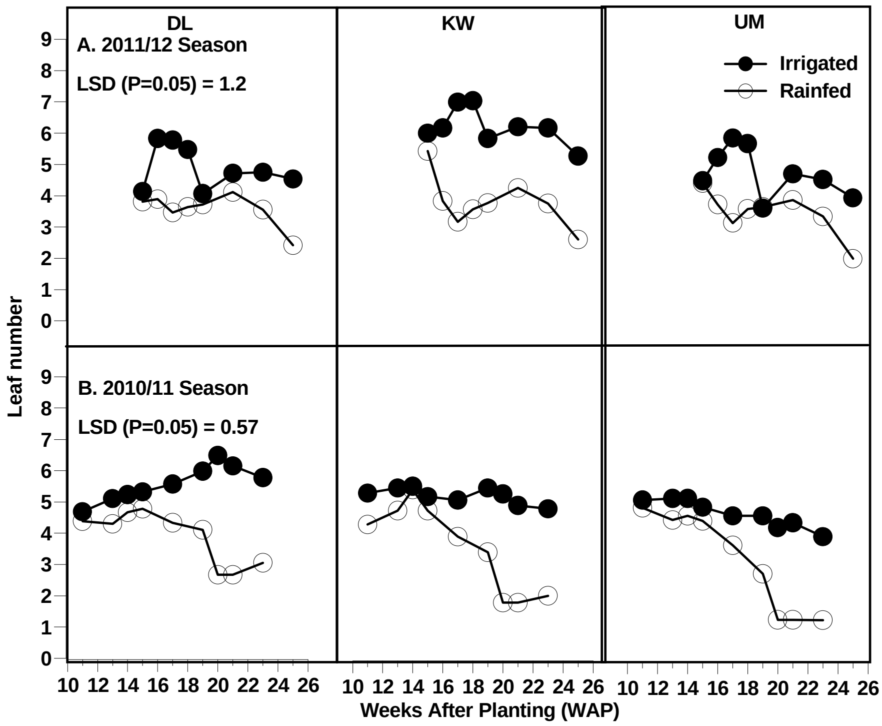

Figure 7.6: Leaf number of taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] grown under irrigated and rainfed conditions at Ukulinga during (b) 2010/11 and (a) 2011/12 planting seasons.

Leaf area index measured during 2010/11 showed highly significant differences (P<0.001) between irrigation treatments and landraces (Figure 7.7). It was 70% lower under rainfed compared with irrigated conditions; the greatest reductions in LAI were observed in the KW landrace (Figure 7.7). The UM landrace had significantly higher LAI than the KW landrace. In the subsequent season (2011/12), results were consistent in that there were highly significant differences (P<0.001) between irrigation treatments. Based on mean values for irrigation treatments, LAI was 66% lower under rainfed compared to irrigated conditions. There were no significant differences between landraces. However, the KW and UM landraces had higher LAI than the DL landrace under both irrigated and rainfed conditions. The KW landrace was shown to have the greatest reductions in LAI under rainfed conditions compared with the UM landrace. The results of LAI observed in the KW landrace were consistent with decreased plant height and leaf number. Although the UM landrace showed a decreased plant height and leaf number, its reduction in leaf number were minimal; hence, it had better LAI under rainfed conditions.

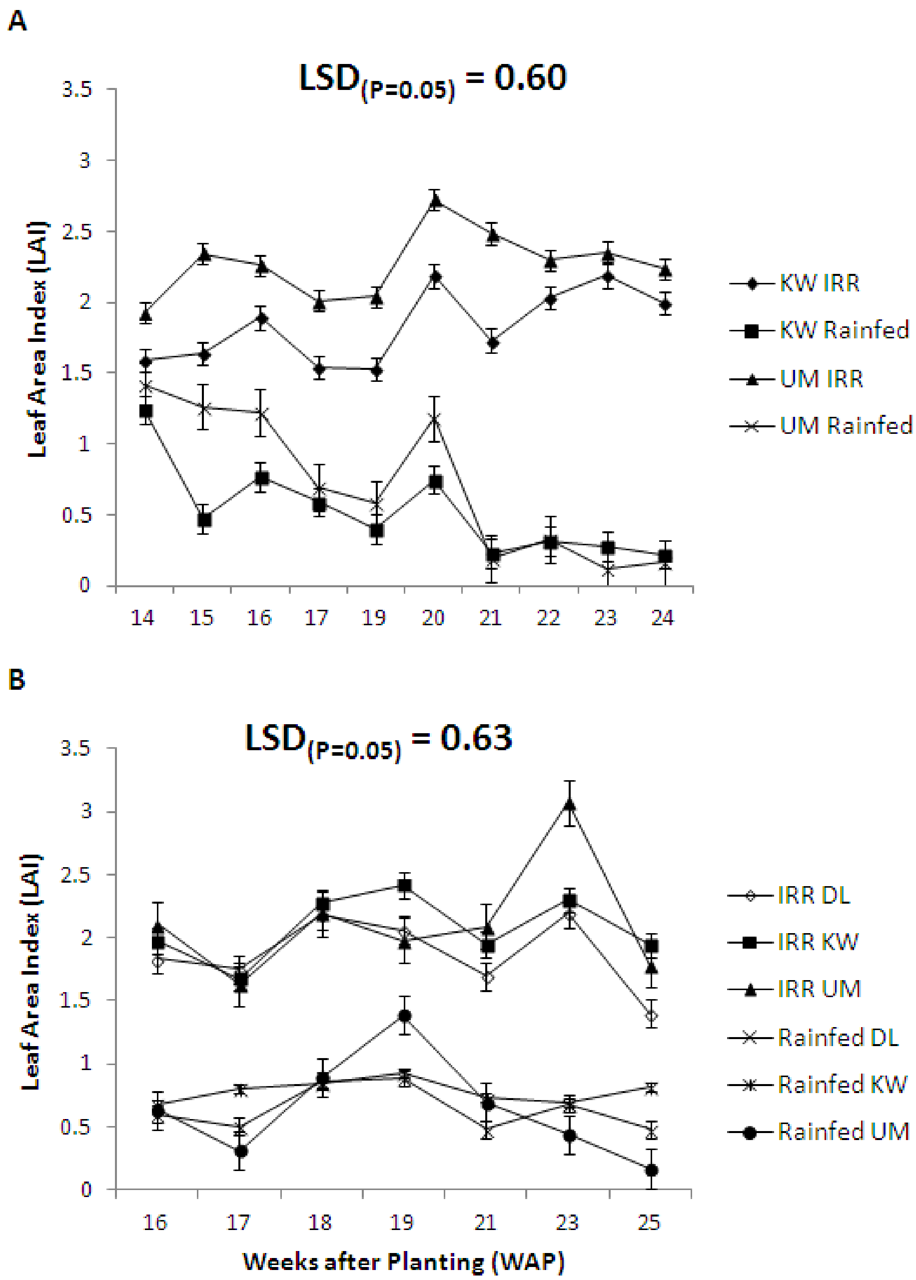

Figure 7.7: Leaf area index (LAI) of taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] grown under irrigated (IRR) and rainfed conditions at Ukulinga during (b) 2010/11 and (a) 2011/12 planting seasons.

The vegetative growth index (VGI) which considers all parameters related to vegetative growth (i.e. plant height, leaf number and area, suckers and stolons) was significantly lower under rainfed compared with irrigated conditions (Figure 7.8). Results for the VGI showed highly significant differences ($P<0.001$) between treatments and landraces. The interaction between irrigation treatments and landraces was also highly significant (Figure 7.8). Under rainfed conditions, VGI was 91% and 87% lower during the 2010/11 and 2011/12 planting seasons, respectively, relative to irrigated conditions. Decreases in VGI were highest in the KW and UM landraces (94% and 89%), respectively, compared with the DL landrace (86%). Lower VGI under rainfed conditions was consistent with results of reduced plant height, leaf number and leaf area index compared with irrigated conditions.

Results of crop phenology, observed as time to harvest maturity, showed highly significant differences ($P<0.001$) between irrigation treatments as well as between landraces (Figure 7.9). Only the KW and UM landraces were evaluated for this parameter, because the DL landrace, a perennial, was not exhibiting any signs of harvest maturity. Time to harvest maturity decreased significantly under rainfed relative to irrigated conditions. Based on mean values, it took 32 weeks after planting (WAP) for taro to mature under irrigated conditions compared with 30 WAP under rainfed conditions. The UM landrace had a shorter crop duration under both irrigated and rainfed conditions compared with the KW landrace (Figure 7.9).

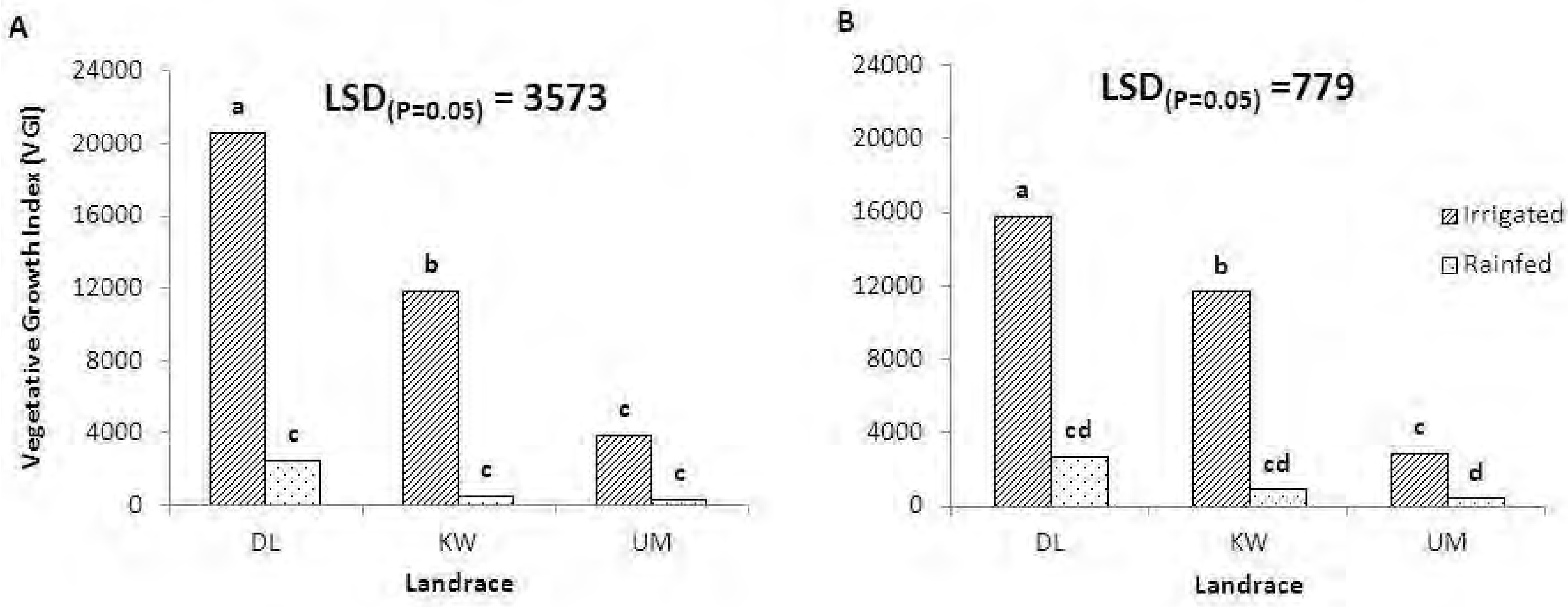

Figure 7.8: Vegetative growth index (VGI) of taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] grown under irrigated and rainfed conditions at Ukulinga during A. 2010/11 and B. 2011/12 planting seasons.

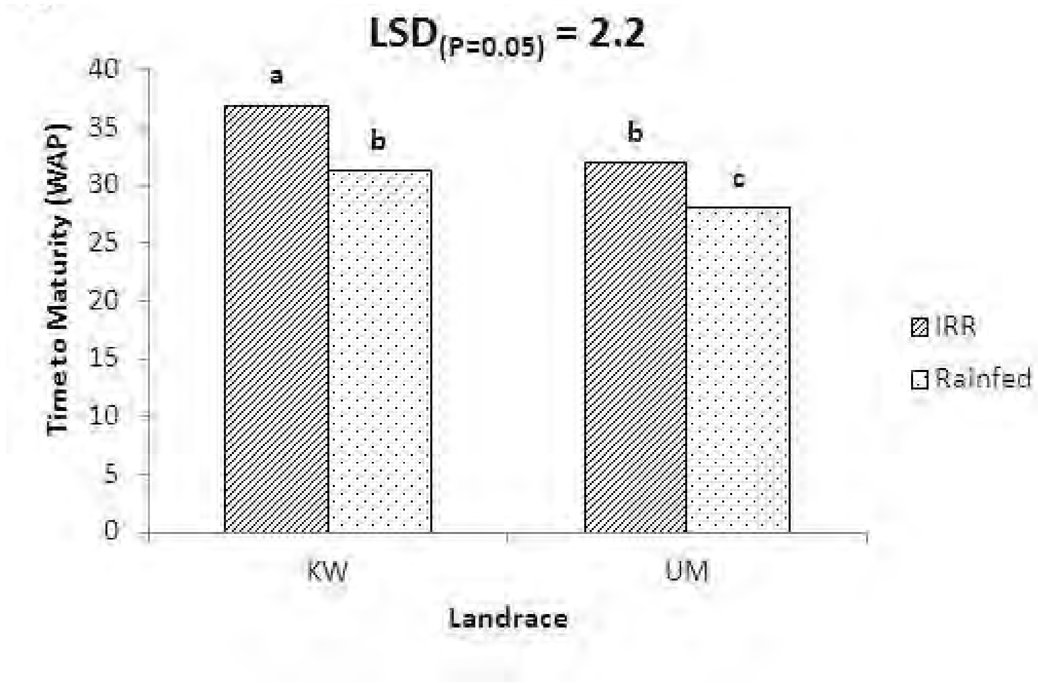

Figure 7.9: Time to harvest maturity, in weeks after planting, of taro landraces [KwaNgwanase (KW) & Umbumbulu (UM)] grown under irrigated (IRR) and rainfed conditions at Ukulinga during 2010/11 planting season. Note that DL is not included in this graph.

The DL landrace failed to produce any yield across either season. This is most likely because the DL landrace is a non-domesticated perennial crop which normally grows in shallow rivers. As such our attempt to take it out of its natural habitat was unsuccessful. Results only show the KW and UM landraces (Tables 1 & 2). Due to differences in weather parameters between the two seasons, results presented here do not show the interaction between seasons. During the 2010/11 planting season, results of yield components and final yield were lower under rainfed relative to irrigated conditions (Table 7.1). Biomass, HI, corm number and corm mass were all lower under rainfed compared to irrigated conditions (Table 7.1). Results of biomass, corm mass and yield all showed highly significant differences ($P<0.001$) between irrigation treatments. Only biomass and HI showed significant differences between landraces (Table 7.1). Overall, yield (t ha^{-1}) was higher under irrigated relative to rainfed conditions; yield was, on average, 65% lower under rainfed compared to irrigated conditions. The KW landrace had higher yield under irrigated conditions than the UM landrace only in 2010/11. This was consistent with the longer crop duration (Figure 7.9). The opposite was true under rainfed conditions, with the UM landraces having better yield than the KW landrace during both seasons. Under rainfed conditions, yield of the KW landrace was 75% lower compared with 52% in the UM landrace. The pattern of lower yield between the two landraces was consistent with trends in VGI; vegetative growth of the UM landraces was less affected by limited water availability under rainfed conditions (Figure 7.8). As such, lowering of final yield was mainly related to lower biomass per plant (Table 7.2). Correlation and path analysis of yield and yield determinants confirmed that biomass was highly correlated with yield (r = 0.9572) and that biomass had the greatest direct contribution to yield (1.081931**)** (Table 7.2).

During the subsequent season (2011/12), the trend was similar, with respect to differences between water treatments (Table 7.1). Yield components and final yield decreased under rainfed compared with irrigated conditions (Table 7.1). Yield in the irrigated treatment during 2011/12 was comparatively lower than that observed during 2010/11. Contrary to results from the first season, the UM landrace had higher biomass and yield than the KW landrace under both irrigated and rainfed conditions during the second season. Secondly, based on percentage yield decline under rainfed conditions, the UM landrace was shown to have performed better than the KW landrace under rainfed conditions (Table 7.1). Correlation and path analysis of yield and yield determinants for the second season were consistent with results of the first season (Table 7.2). Biomass was highly correlated to final yield (r = 0.8707) and contributed highly (0.817524) towards final yield. The contribution of HI to final yield was minimal while corm number had the least contribution (Table 7.2). Corm number generally was not much lower under rainfed relative to irrigated conditions. This suggested that while corm number may be relatively consistent, individual corm size and mass decreased in response to limited water availability. Since biomass was shown to contribute most to yield, the UM landrace may be more suited to rainfed production due to a higher biomass (and consequently yield) under rainfed relative to irrigated conditions (Table 7.1).

Table 7.1: Yield and yield components (biomass, harvest index, corm number and corm mass) of two taro landraces (KwaNgwanase (KW) and Umbumbulu (UM) grown under irrigated and rainfed conditions during 2010/11 and 2011/12 summer seasons. Numbers in the same column not sharing the same letter differ significantly at LSD (P = 0.05).

Season	Water Treatment	Landrace	Biomass plant^{-1} (kg)	Harvest Index (%)	Corm number plant^{-1}	Corm mass plant^{-1} (kg)	Yield (t ha^{-1})
2010/11	IRRIGATED	Umbumbulu	1.03b	82.46a	13.72a	0.86b	17.14b
		KwaNgwanase	1.95a	65.49b	20.56a	1.21a	24.16a
	RAINFED	Umbumbulu	0.56b	74.23ab	12.14a	0.41c	8.26c
		KwaNgwanase	0.52b	65.91b	13.11a	0.31c	6.13c
	LSD (P=0.05) Water		0.36	8.34	7.47	0.19	3.76
	LSD (P=0.05) Landrace		0.36	8.34	7.47	0.19	3.76
	LSD (P=0.05) WT*Landrace		0.50	11.79	10.56	0.27	5.31
2011/12	IRRIGATED	Umbumbulu	1.32a	67.26a	14.97a	0.73a	14.63a
		KwaNgwanase	0.89b	51.07a	7.29b	0.52ab	10.43ab
	RAINFED	Umbumbulu	0.63bc	59.01a	15.19a	0.36b	7.27b
		KwaNgwanase	0.49c	59.63a	8.11b	0.27b	5.39b
	LSD (P=0.05) Water		0.20	21.61	4.82	0.25	5.01
	LSD (P=0.05) Landrace		0.20	21.61	4.82	0.25	5.01
	LSD (P=0.05) WT*Landrace		0.28	30.56	6.82	0.35	7.09

Table 7.2: Correlation matrix and path coefficients showing direct and indirect contributions of biomass, harvest index and corm number per plant to yield for both KwaNgwanase (KW) and Umbumbulu (UM) landraces during 2010/11 and 2011/12 planting seasons. Values in bold represent the direct contribution; ^{i} represents the indirect contribution and * denotes the correlation coefficient.

Season		Harvest index	Corm number plant^{-1}	Biomass	Correlation Coeff. Yield*
2010/11	**Harvest index**	**0.260343**	0.029004^{i}	-0.27925^{i}	0.0101
	Corm number plant^{-1}	-0.09942^{i}	**-0.07595**	0.819671^{i}	0.6443
	Biomass	-0.06719^{i}	-0.05754^{i}	**1.081931**	0.9572
2011/12	**Harvest index**	**0.422679**	-0.02087^{i}	0.17119^{i}	0.573
	Corm number plant^{-1}	0.088974^{i}	**-0.09914**	0.291366^{i}	0.2812
	Biomass	0.088509^{i}	-0.03533^{i}	**0.817524**	0.8707

7.4 Discussion

The findings of this study showed that taro landraces took at least 7 weeks to emerge. The KwaNgwanase (KW) (dasheen) and Umbumbulu (UM) (eddoe) landraces were better than the Dumbe Lomfula (DL) (wild unclassified) landrace. It should be noted that DL is a wild landrace naturally adapted to wetlands; hence this may have affected its performance. Slow emergence of taro landraces would imply that a lot of water is lost to soil evaporation during the establishment stage. Mare (2010) reported even longer establishment periods (≈ 10 weeks) for several eddoe type landraces. Time taken to emerge may be reflective of different propagules used for each of the three landraces. KwaNgwanase was propagated using head-setts (huli), Umbumbulu and DL using sprouted corms and cuttings, respectively. This may have resulted in propagule type and size effects (Singh *et al*., 1998; Lebot, 2009); thus explaining differences observed between landraces.

Levitt (1972) is credited with categorising the different plant strategies to drought tolerance as escape, avoidance and tolerance. Stomatal closure, a drought avoidance mechanism (Levitt, 1979; Turner, 1986), is one of crops' initial responses to drought stress. The strategy is to minimise transpirational water losses (Chaves *et al*., 2003). It is widely accepted as the major limitation to photosynthesis and biomass production under drought stress (Chaves *et al*., 2002, 2003). Our findings showed that stomatal conductance decreased under rainfed compared with irrigated conditions. This was indicative of stomatal regulation. Under rainfed conditions, the UM landrace had the greatest decreases in stomatal conductance, indicating greater control of stomatal aperture than the KW and DL landraces. Sivan (1995) reported similar findings of decreasing stomatal conductance under water stress in two dasheen and eddoe taro varieties. Stomatal regulation may play a role in stress acclimation of taro landraces to water stress, specifically the UM landrace.

Under non-limiting conditions, plants (C_3 plants in particular) utilise a large proportion of absorbed solar radiation for photosynthesis and photorespiration (Maroco *et al*., 1998). However, under conditions of limited water availability, plants have to find ways of getting rid of excess radiation. Loss of chlorophyll is one such strategy (Havaux & Tardy, 1999). The strategy is to effect a down-regulation of photosynthesis in response to decreased availability of intracellular CO_2 resulting from stomatal closure. In this study it was shown that chlorophyll content index decreased under rainfed relative to irrigated conditions, in line with decreasing stomatal conductance. This was evidence of energy dissipation mechanism in taro landraces. Our findings concur with Sahoo *et al*. (2006) who reported decreased chlorophyll stability index in a taro hybrid subjected to water stress. This response was clear in the UM landrace, suggesting the UM landrace was able to down-regulate its photosynthesis in line with decreasing CO_2 availability.

Plants also cope with limited water availability through reductions in plant size and surface area available for transpiration (Mitchell *et al*., 1998) as a drought avoidance strategy (Levitt, 1979; Turner, 1986). This study has shown that plant height, leaf number, LAI and VGI of landraces were lower under rainfed relative to irrigated conditions. Our findings were consistent with findings by Sahoo *et al*. (2006) that water stress decreased plant height, leaf number and leaf area of a taro hybrid. According to Lebot (2009), VGI is a unique taro specific index in that it considers all aspects of taro morphology – leaf number and area, plant height as well as suckers and stolons. It has been reported to be positively correlated to corm yield (Lebot, 2009). Our findings showed that VGI decreased under limited water availability compared with irrigated conditions. This was more pronounced during the 2011/12 season which was classified as a drought season. The reduction in VGI was due to failure by landraces to form suckers, coupled with reduced plant height, leaf number and leaf area under rainfed conditions. Over-all, the KW landrace was shown to be most sensitive to water stress compared to the UM and DL landraces. The UM landrace showed moderate decreases in vegetative components under stress suggesting that it was able to strike a balance between minimising water losses through transpiration while allowing for biomass production to continue. This was consistent with UM's degree of stomatal control and accompanying lowering of CCI.

Another plant strategy for coping with limited water availability is escape (Levitt, 1979; Turner, 1986). Plants that escape drought generally exhibit a degree of phenological plasticity through completing their life cycle before water stress becomes terminal. In this regard, taro landraces, especially the UM landrace, showed a degree of phenological plasticity in response to limited water availability under rainfed conditions. The UM landrace matured earlier under rainfed relative to irrigated conditions. This was consistent with decreased vegetative growth under rainfed conditions. Rainfed conditions resulted in enhanced leaf shedding (reduced leaf number) which resulted in shortened crop duration. Blum (2005) associated drought avoidance with reduced season duration due to reduced leaf number. While reduction in leaf number is a drought avoidance mechanism, phenological plasticity is an escape mechanism. This agrees with Ludlow (1989) who suggested that drought tolerance strategies do not necessarily work in isolation.

Our findings on yield response to limited water availability were consistent with results of crop growth. Yield components and final yield were all lower under rainfed conditions relative to irrigated conditions. This concurs with Blum (2005) that plant drought responses that favoured avoidance and escape were often to the detriment of yield due to reduced crop duration and biomass production. Rainfed production resulted in yield losses of at least 50%, on average, in the KW and UM landraces while the DL landrace failed to form yield under both irrigated and rainfed conditions. It is worth noting that the DL landrace was obtained from the wild where it grows as a perennial. Our objective was to evaluate if it could be domesticated as an annual crop as has been done with the KW and UM landraces over a long period of time.

According to Farooq *et al.* (2009), many yield-determining plant processes are affected by water stress. Findings of the current study showed that the greatest contributor to yield attainment was biomass. However, biomass production was affected by reduced stomatal conductance and chlorophyll content, reduced vegetative growth and crop duration under rainfed conditions. Therefore, management practices that favour biomass production should be considered in order to maximise yield under conditions of limited water availability. The UM landrace which consistently produced relatively higher biomass under rainfed conditions may be suited for rainfed conditions where water is the primary limitation to crop production.

7.5 Conclusion

This study showed that taro landraces were susceptible to drought stress under rainfed conditions. Attempts to domesticate the DL out of its native habitat were unsuccessful as the crop failed to produce yield. Future studies, which may include breeders, should evaluate whether there are any useful traits in the DL landrace that could be useful to future crop improvement. Nonetheless, the study managed to index drought strategies in taro landraces. Drought adaptation in taro landraces involved a combination of drought avoidance and escape mechanisms. Drought avoidance was achieved through stomatal regulation, energy dissipation and reduced canopy size. These responses had the net effect of reducing crop water losses to transpiration. Escape was demonstrated through phenological plasticity such that under water limited conditions, taro matured earlier. The KW landrace is more suited to irrigated conditions and therefore should be cultivated where supplementary irrigation is available. The UM landrace showed greater adaptability to water stress under rainfed conditions. As such, the UM landrace may be suited for rainfed production given that management practices that favour biomass accumulation are practised.

Chapter 8

Water-use of taro (*Colocasia esculenta* L. Schott) landraces

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8.1 Introduction

There were few reports in the literature describing drought tolerance of taro and its water-use (Sivan, 1995; Sahoo *et al*., 2006; Uyeda *et al*., 2011). Sivan (1995) studied drought tolerance in two dasheen and eddoe taro varieties, as well as tannia (*Xanthosoma sagittifolium*) and observed that stomatal conductance, leaf number and leaf area of both cultivars all decreased in response to water stress. In a separate study, Sahoo *et al*. (2006) subjected a taro hybrid to water stress using polyethylene glycol (PEG) and observed significant differences in plant growth parameters of height, leaf number and area as well as minimum yield reduction in response to water stress. Elsewhere, Uyeda *et al*. (2011) evaluated the response of three commercial taro varieties to five irrigation rates based on reference evapotranspiration (ET_o) and found that irrigating taro at 150% of ET_o could maximise yield. Sahoo *et al*. (2006) went on to conclude that development of drought tolerant taro cultivars was possible while Uyeda *et al*. (2011) stated that upland taro varieties may be adapted to water-limited production. Therefore, evaluating responses of previously unstudied taro landraces to water stress may aid in identifying genotypes with drought tolerance and suitability for production in water-limited areas.

Taro production has been mainly confined to the coastal areas of KwaZulu-Natal and Eastern Cape provinces (Shange, 2004) where farmers still rely on landraces for planting material. It is possible that, over hundreds of years of farmer and natural selection, these landraces may have acquired drought tolerance and evolved to be productive under conditions of limited water availability under upland cultivation. However, this assumption remains to be tested rigorously, as has been done for other established crops. There is a need to evaluate responses of local taro landraces to water stress and determine their water-use under varying water regimes. Such information would allow for promotion of taro in areas with limited rainfall, but with access to irrigation. Furthermore, if indeed certain landraces have adapted to low levels of water-use that would contribute towards local and international breeding efforts for drought tolerance in taro. Therefore, the aim of this study was to evaluate the growth, yield and water-use efficiency of three taro landraces under varying water regimes.

8.2 Material and methods

8.2.1 Plant material

South African taro landraces were sourced from KwaNgwanase (KW) (27°1'S; 32°44'E) in northern KwaZulu-Natal (KZN) province, and Umbumbulu [UM and Dumbe Lomfula (DL): 29°36'S; 30°25'E] situated in the midlands of KZN. The KW and DL landraces were classified as dasheen types characterised by a large edible central corm with few side cormels (Shange, 2004). The UM landrace was classified as an eddoe type landrace characterised by a central corm and numerous side cormels which are the edible part (Lebot, 2009). Propagules were initially selected for uniform size (Singh *et al*., 1998) before being treated with a bactericide and fungicide (Sporekill®) to prevent rotting during sprouting. Propagules were then sprouted in vermiculite (30°C; 90% RH) for 21 days before being planted.

8.2.2 Site description

Trials were planted under a rainshelter at Roodeplaat, Pretoria (25º60′S; 28º35′E), South Africa, over two summer seasons (14 October, 2010 to June, 2011 and 8 September, 2011 to May, 2011). In both seasons, the duration of the experiments was eight months. The rainshelter is designed to stay open when there is no rainfall, but to close when a rainfall event occurs, thus excluding the effect of rainfall from the experiment. Soil in the rainshelter was classified as sandy clay loam (USDA taxonomic system). The Soil Water Characteristics Hydraulic Properties Calculator (http://hydrolab.arsusda.gov/soilwater/Index.htm) was used to calculate the amount of water available at field capacity (FC), permanent wilting point (PWP), and saturation (SAT), as well as the saturated hydraulic conductivity (Table 8.1). Daily weather parameters [maximum and minimum air temperature, relative humidity, solar radiation, wind speed, rainfall and reference evapotranspiration(ET_o)] for the duration of the experiments were monitored and collected from an automatic weather station located within a 100 m radius from the rainshelter.

8.2.3 Experimental designs

The experimental design was a factorial experiment with two factors: irrigation level and landrace type, replicated three times. The three irrigation levels were 30%, 60% and 100% of crop water requirement (ETa). There were three landraces: Dumbe Lomfula (DL), KwaNgwanase (KW) and Umbumbulu (UM). The experiment was laid out in a randomised complete block design; individual plot size in the rainshelter was 6 m^2, with plant spacing of 0.6 m x 0.6 m.

8.2.4 Irrigation

Irrigation in the rainshelter was delivered using drip irrigation. The irrigation system comprised a pump, filters, 3 solenoid valves (one for each irrigation level), 3 water meters, a control box, online drippers, 200 litre JOJO tank, main line, sub-main lines and laterals. The maximum allowable operating pressure of the system was 200 kPa, with an average discharge rate per dripper of 2 l/hour. Dripper line spacing was based on actual plant spacing (0.6 m x 0.6 m). In order to prevent seepage and lateral movement of water between plots, a double-folded black, 200 µm thick polyethylene sheet, was trenched at a depth of 1 m between plots.

Irrigation scheduling was based on reference evapotranspiration (ET_o) and a crop factor (K_c) (Allen *et al*., 1998). Reference evapotranspiration (ET_o) values were obtained from an automatic weather station (AWS); the AWS calculates ET_o on a daily basis according to the FAO Penman-Monteith's method (Allen *et al*., 1998). Taro is about 7 months (210 days) duration crop and authors differ on how these may be divided based on growth stages (Lebot, 2009). Crop coefficient (K_c) values for taro were as described by Fares (2008) whereby $Kc_{initial}$ = 1.05 (2 months), Kc_{med} = 1.15 (4 months) and Kc_{late} = 1.1 (1 month). Using these values of K_c and ET_o from the AWS, crop water requirement (ETa) was then calculated as follows as described by Allen *et al*. (1998);

$$ETa = ET_o * K_c \qquad \text{Equation 8.1}$$

Where ETa = crop water requirement

ET_o = reference evapotranspiration, and

K_c = crop factor

Initially, at the beginning of the study, all treatments were irrigated to field capacity (Table 8.1). Thereafter, the treatments were imposed. Irrigation was applied three times every week. Irrigation was applied during the mornings to ensure water availability during peak periods of demand in the day. The total actual amount of irrigation water applied, taking into consideration the initial watering, ranged from 1 288 mm (100% ETa) to 1 009 mm and 800 mm for 60% and 100% ETa, respectively. The soil water status during the growing period was monitored using Theta probes (Figure 8.1).

Table 8.1: Soil physical properties in the rainshelter. ^{v}PWP – permanent wilting point; ^{w}FC – field capacity; ^{x}SAT – saturation; ^{y}TAW – total available water; ^{z}Ksat – saturated hydraulic conductivity**.**

Textural class	^{v}**PWP**	^{w}**FC**	^{x}**SAT**	^{y}**TAW** (mm m^{-1})	^{z}**Ksat** (mm day^{-1})
	——— vol % ———				
Sandy clay loam	16.1	24.1	42.1	80	324.2

8.2.5 Agronomic practices

Soil samples were taken from the rainshelter prior to planting and submitted for soil fertility and texture analyses. Based on soil fertility results, an organic fertiliser (Table 8.2), Gromor Accelerator® (30 g kg^{-1} N, 15 g kg^{-1} P and 15 g kg^{-1} K) was applied at a rate of 5 330 kg ha^{-1} (Mare, 2010), with half being applied at planting and the balance applied 20 weeks after emergence. Routine weeding and ridging inside the plots were done by hand. Agronomic practices were similar for both planting seasons.

Table 8.2: Chemical properties of soil in the rainshelter.

Fe	**Mn**	**Cu**	**Zn**	**K**	**Ca**	**Mg**	**Na**	**P**	**pH (H_2O)**	**Org. C**	**Total N**
----------mg kg^{-1}----------									Water	-----%-----	
7.09	120.56	3.50	19.56	165.86	804.26	262.57	27.65	41.44	7.89	0.73	0.048

8.2.6 Data collection

Soil water content in the plots was monitored using ML-2x Theta Probes connected to a DL-2 data logger (Delta-T Devices, UK). In each plot, two probes were carefully inserted within the root zone at an angle (< 90°) at depths of 30 cm and 60 cm, respectively, and then buried with soil. Data collection for SWC using the Theta probes was done every 4 hours.

Parameters determined during the course of the experiments were emergence [up to 49 days after planting (DAP)]. Thereafter, plant height, leaf number, leaf area index (LAI) and stomatal conductance (SC) were determined up to 30 weeks after planting (WAP). Plant height was measured from the base of the plant up to the base of the 2^{nd} youngest fully unfolded leaf. Leaf number was counted only for fully unfolded leaves with at least 50% green leaf area. Leaf area index was measured using the LAI2200 Canopy Analyser (Li-Cor, USA & Canada) by taking one measurement above the canopy and four below canopy readings taken in a diagonal (1 m) in each plot using a 270° view cap. Stomatal conductance was measured between 10 am and midday using a steady state leaf porometer (Model SC-1, Decagon Devices, USA); measurements were taken on the abaxial leaf surface of the 2^{nd} youngest fully unfolded leaf (Sivan, 1995). Upon termination of the experiments, biomass (B), harvest index (HI) and corm yield (Y) were determined. Biomass was measured as the whole plant mass (shoot, corms and roots), corm yield was measured as the mass of edible corms; HI was then calculated as the proportion of Y to B. Stomatal conductance was only determined in 2011/12.

Plant samples were randomly taken from the non-experimental plants in each plot at four, five and six months after planting for determination of biomass accumulation and root length. Plants were carefully dug out to avoid damaging roots and thereafter root length was determined by measuring from the base of the plant to the tip of the longest root.

Water-use efficiency (WUE): water-use efficiency was determined as follows:

$$WUE = Biomass / ETa \qquad \text{Equation 8.2}$$

Where: WUE = water-use efficiency in kg m^{-3},

Biomass = above ground biomass plus below ground portion in kg, and

ETa = crop evapotranspiration/ water-use/ crop water requirement in m^3.

8.2.7 Data analysis

Analysis of variance (ANOVA) was used to statistically analyse data using GenStat® (Version 14, VSN International, UK). Least significant difference (LSD) was used to separate means at the 5% level of significance.

8.3 Results

Table 8.3 summarises the weather conditions that prevailed during the growing season months (September to May). The two seasons' weather patterns were similar to long-term weather characteristics for Roodeplaat, where the experimental site was located. Temperatures were cooler in April and May, which represents the onset of winter. These two months were also characterised by low wind speed, solar radiation and total reference evapotranspiration (ET_o). Warmer temperatures (December to March) coincided with rapid vegetative growth stages of taro (Figures 8.3 and 8.4). This period was characterised by, high solar radiation and ET_o. Hence, the conditions were optimum for growth of taro. Figure 1 shows the soil water content measurements from the three water regimes. The measurements confirmed that there were indeed differences between the three water regimes.

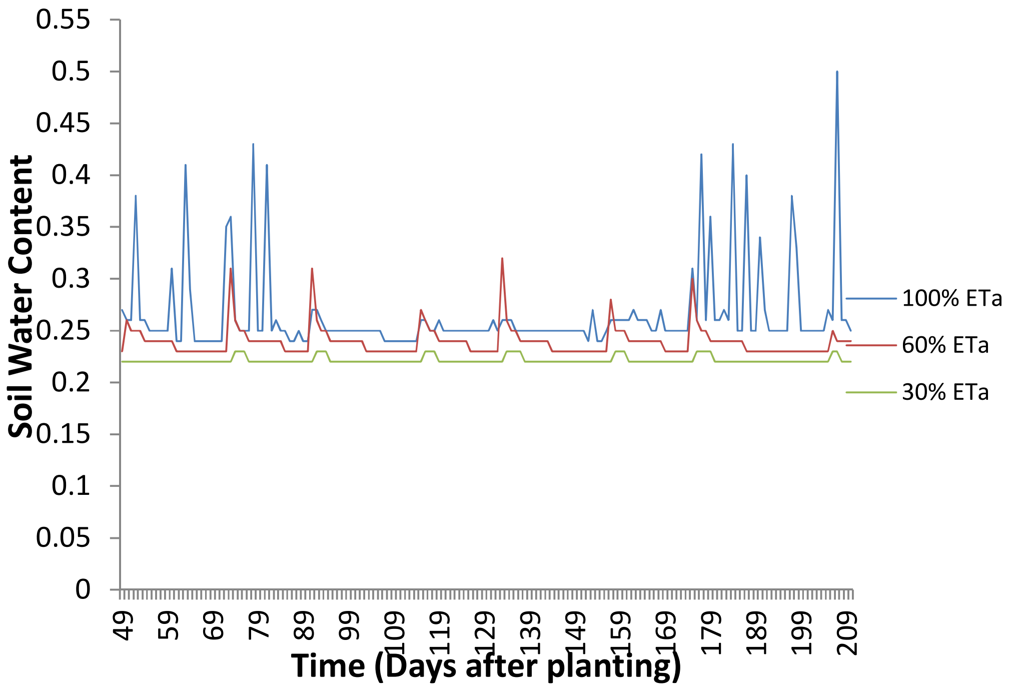

Figure 8.1: Volumetric soil water content observed in the rainshelter from 49 DAP showing differences between the 30%, 60% and 100% ETa water regimes.

Table 8.3: Summary of monthly averages for meteorological variables during the taro growing seasons.

Season Month	$^{a}T_x$ (°C)	$^{b}T_n$ (°C)	Wind speed ($m\ s^{-1}$)	Total radiation ($MJ\ m^{-2}\ day^{-1}$)	$^{c}ET_o$*
2010-11					
September	29.61	8.89	1.08	22.58	140.12
October	31.59	13.58	1.22	25.86	171.36
November	29.79	15.73	1.07	23.64	148.63
December	29.11	16.25	0.95	24.31	152.61
January	28.25	17.25	0.69	21.73	134.92
February	29.40	15.84	0.57	24.47	136.55
March	30.08	14.97	0.47	22.62	136.03
April	24.52	11.77	0.48	15.28	85.85
May	23.77	6.3	0.47	15.43	84.31
2011-12					
September	28.86	8.2	1.09	24.26	146.59
October	29.49	11.92	0.99	25.84	161.56
November	30.31	14.46	1.12	26.93	169.54
December	28.91	16.51	0.73	23.45	147.79
January	30.67	16.78	0.92	25.59	169.37
February	31.23	17.07	0.54	24.51	130.1
March	29.94	14.12	0.78	22.94	145.51
April	26.26	8.88	0.66	21.28	118.42
May	26.23	6.09	0.46	18.53	103.83

[a]Maximum temperature; [b]Minimum temperature; [c]FAO reference evapotranspiration; *Monthly total. Monthly averages and totals were calculated from hourly data. Note: meteorological variables do not include rainfall, because it was excluded in the rainshelter.

Results of crop emergence showed differences between varieties (Figure 8.2). Irrigation treatment effects are not reported because all landraces were established under optimum 100% ETa treatment. Landraces were slow to emerge showing no uniformity (Figure 8.2), with zero emergence observed during the first 4 weeks after planting (WAP). There were highly significant differences ($P<0.001$) between landraces' emergence. The interaction between landraces and time (WAP) was also highly significant ($P<0.001$). The KW landrace was shown to emerge better (44.44%), with regards to emergence rate and uniformity, compared with the UM (38.89%) and DL (20.37%) landraces; DL had the lowest emergence rate over the time period observed.

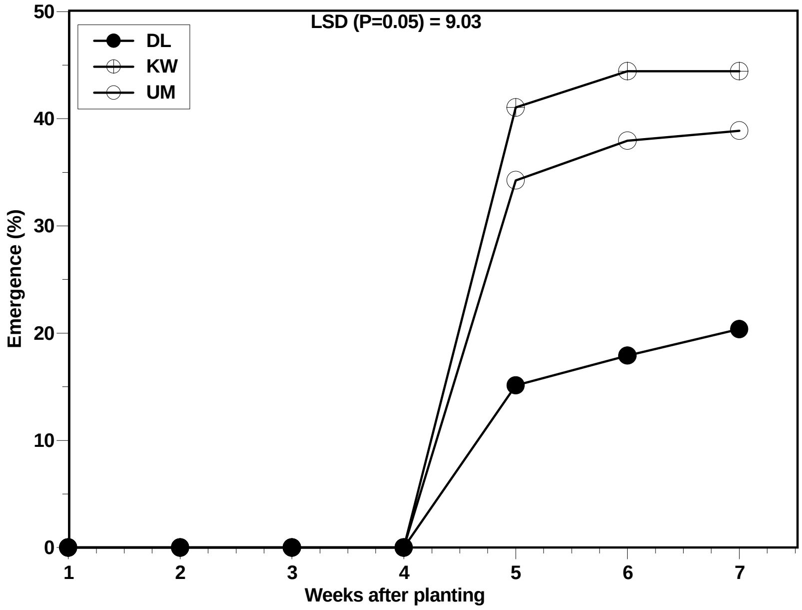

Figure 8.2: Emergence of taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] based on mean values for both seasons (2010/11 and 2011/12).

Stomatal conductance was significantly affected ($P<0.001$) by irrigation treatments (Figure 8.3). It was lower by about 4% and 23% at 60% and 30% ETa than at 100% ETa treatment. There were significant differences ($P<0.05$) between landraces; KW (204.6 mmol m^{-2} s^{-1}) and DL (204.4 mmol m^{-2} s^{-1}) landraces were similar while stomatal conductance of the UM landrace was 19% lower than the two landraces. The interaction between irrigation treatments and landraces was significant ($P<0.05$). Stomatal conductance of the DL and KW landraces was between 3-30% higher at 60% ETa compared to 100% and 30% ETa. Stomatal conductance of the UM landrace was lower by 25% and 40% at 60% ETa and 30% ETa than at 100% ETa. In addition, stomatal conductance of the UM landrace was 25% and 32% lower than the KW and DL landraces, respectively, at 30% ETa. Stomatal conductance of the DL and KW landraces, measured at 30% ETa, was respectively 6% and 15% higher than stomatal conductance of the UM landrace at 60% ETa. Overall, results of stomatal conductance pointed to the UM landrace having greater stomatal regulation, in response to decreasing water availability, than the KW and DL landraces.

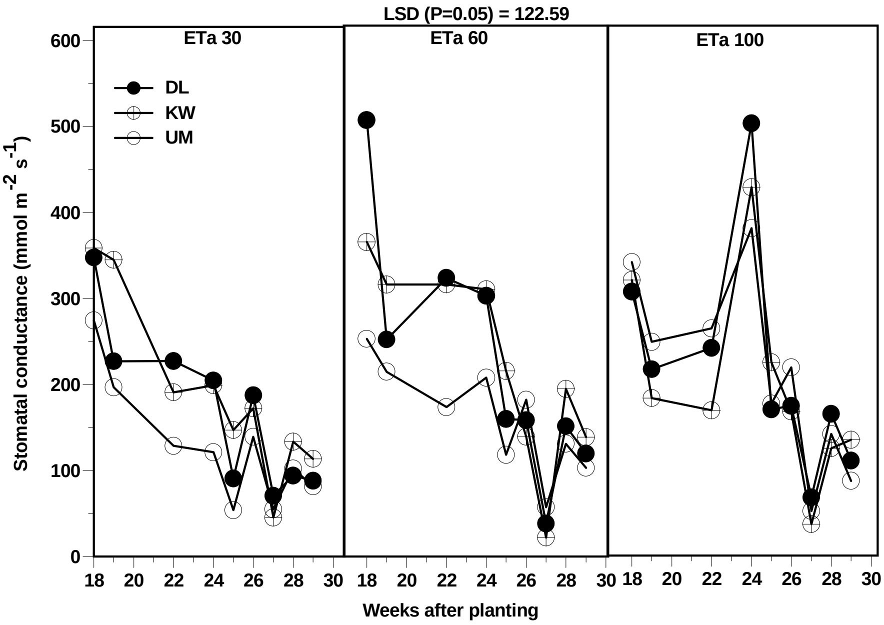

Figure 8.3: Stomatal conductance of taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] in response to three levels of irrigation (30%, 60% and 100% ETa) during 2010/11 and 2011/12 seasons.

Plant height showed highly significant differences (P<0.001) between irrigation treatments (Figure 8.4). Plant height was 15% and 19% lower at 60% ETa and 30 ETa than at 100% ETa. There were also highly significant differences (P<0.001) between landraces; the trend was DL > KW > UM during 2010/11 season and DL > UM > KW during 2011/12. The DL landrace was the tallest at 100% ETa at the end of the season while the KW landrace showed the greatest reduction (≈15%) in plant height (after 16 weeks) in response to decreasing water availability at 60% and 30% ETa, respectively. The UM landrace showed moderate reduction (≈7%) in plant height under conditions of decreasing water availability.

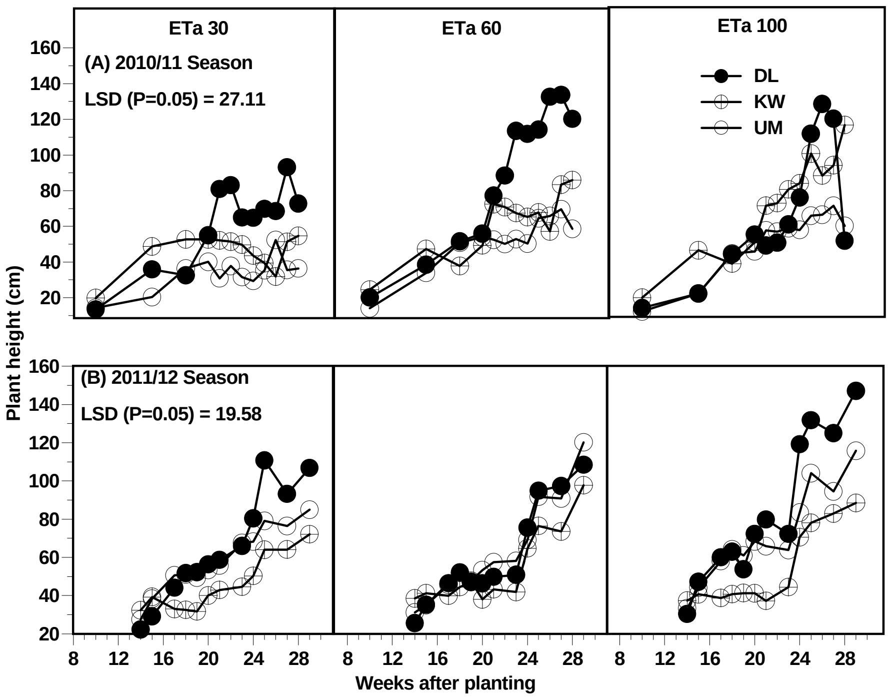

Figure 8.4: Plant height (cm) of taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] in response to three levels of irrigation (30%, 60% and 100% ETa) during 2010/11 and 2011/12 seasons.

Leaf number followed the same trend as plant height. Highly significant differences (P<0.001) were shown between irrigation treatments as well as between landraces, with respect to leaf number (Figure 8.5). During 2010/11, the trend observed for leaf number was 100% ETa > 60% ETa > 30% ETa; however, during 2011/12 the trend was 60% ETa > 100% ETa > 30% ETa. Mean separation showed that leaf number at 100% ETa was statistically similar to 60% ETa but significantly less by 6% at 30% ETa. Thus, irrigation at 30% ETa consistently resulted in plants with the least number of leaves. With respect to differences observed between landraces, the trend was such that UM > DL > KW, while in 2011/12 the trend showed that KW > UM > DL. Similar to plant height, the KW landrace showed the greatest reduction (≈5%) in leaf number in response to limited water availability at 30% ETa. As with plant height, the UM landrace showed moderate reduction in leaf number in response to decreasing water availability.

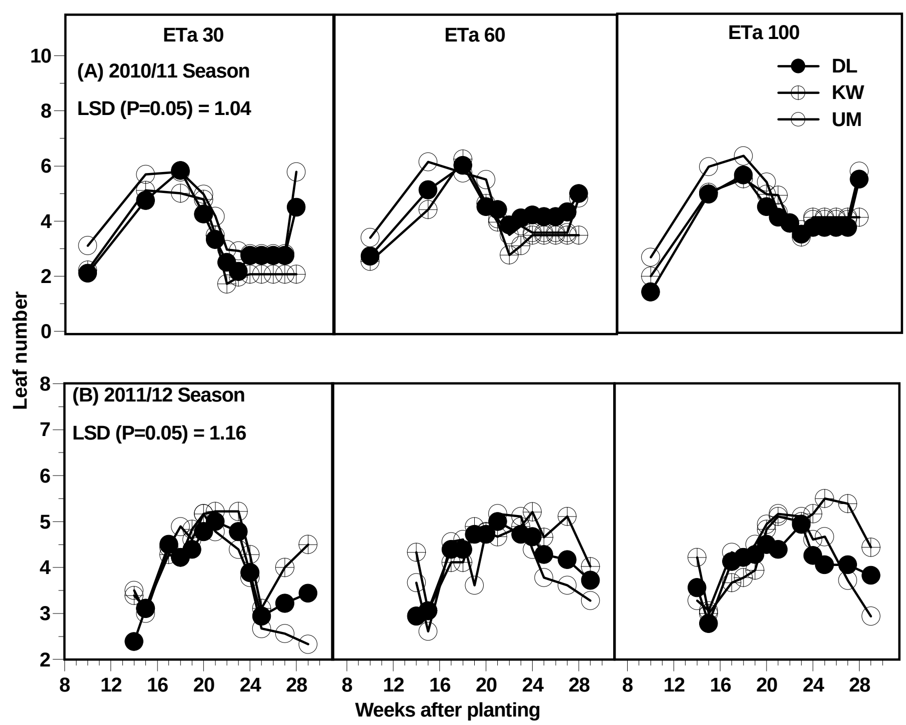

Figure 8.5: Leaf number of taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] in response to three levels of irrigation (30%, 60% and 100% ETa) during 2010/11 and 2011/12 seasons.

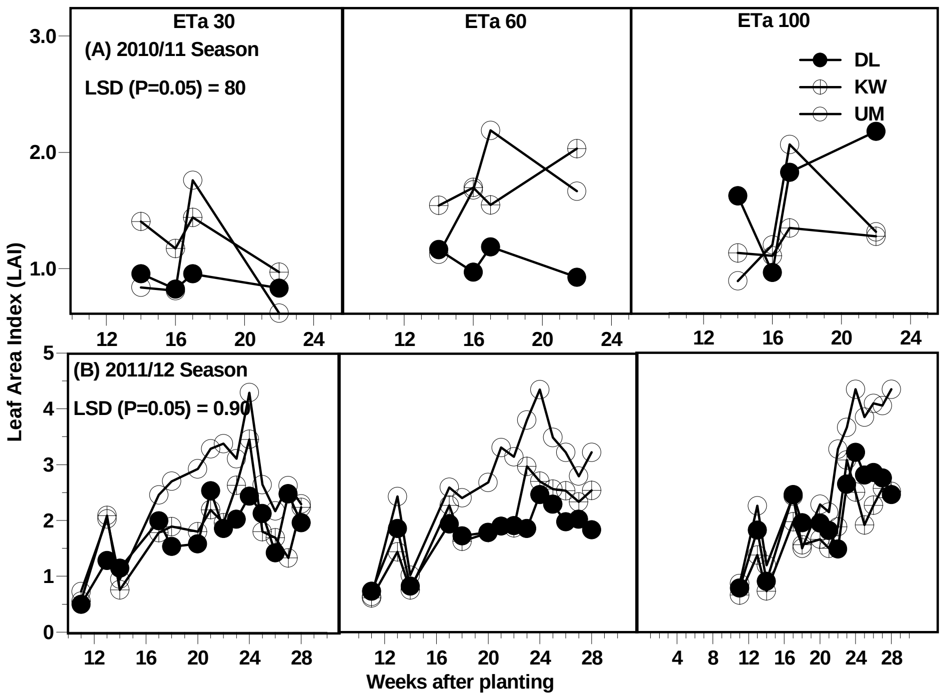

Figure 8.6: Leaf area index (LAI) of taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] in response to three levels of irrigation (30%, 60% and 100% ETa) during 2010/11 and 2011/12 seasons.

Leaf area index (LAI), which represents the whole canopy size, was shown to be significantly (P<0.001) affected by water availability (Figure 8.6). This was clearer during the 2011/12 season, possibly due to an increased number of observations compared to 2010/11 season. Leaf area index was 5% and 12% lower at 60% ETa and 30% ETa than LAI at 100% ETa treatments. This was consistent with measurements of plant height and leaf number which showed much lower values at 30% ETa. There were highly significant differences (P<0.001) between landraces (UM > KW > DL) during the 2011/12 season. There was a significant ((P<0.001) interaction between the irrigation treatments and landraces. The UM landrace's LAI was shown to be similar at 100% and 60% ETa but it was statistically lower (≈14%) at 30% ETa. Consistent with observations on plant height and leaf number, lower water application resulted in lower LAI for all landraces; the extent of such reduction differed between landraces.

A fluctuating growth pattern was observed for plant height, leaf number and LAI (Figure 8.4, 8.5 and 8.6). This was possibly due to the nature of taro vegetative growth. Taro landraces continuously shed older leaves, replacing them with younger ones. As such, this distorts measurements of growth parameters (Section 2.6), resulting in the observed fluctuations.

Destructive sampling was done for the 2011/12 season, at monthly intervals (5-7 months after planting), to determine plant fresh mass (FM), dry mass (DM), root length and the ratio between dry to fresh mass (DM:FM) (Figure 8.7 and 8.8). Results showed huge variability. Fresh mass was significantly ($P<0.05$) affected by irrigation treatments giving 15% and 37% lower values at 60% ETa and 30% ETa (Figure 8.8). Although there were no significant differences ($P>0.05$) between landraces, their interaction with irrigation treatments was shown to be significant. The UM landrace had 2% and 40% more fresh mass at 100% ETa than the DL and KW landraces, respectively; KW had 8% and 25% lower fresh mass than UM and DL at 30% ETa. Dry mass per plant showed no significant differences ($P>0.05$) between irrigation treatments Results showed that DM was respectively 77% and 12% higher at 60% ETa relative to 100% and 30% ETa (Figure 8.7). The ratio between fresh and dry mass (FM:DM) showed the same trend as that observed for DM with respect to differences between irrigation treatments and landraces (Figure 8.8).

Plant root length was significantly ($P<0.05$) affected by irrigation treatment (Figure 8.8). Decreasing water application resulted in lower root length; landraces had 2% and 19% less root length at 60% ETa and to 30% than at 100% ETa. There were also highly significant differences ($P<0.001$) between landraces (DL > KW > UM) while the interaction of the two factors was also highly significant ($P<0.001$). On average the UM landrace had 3% and 24% shorter roots than the KW and DL landraces, respectively.

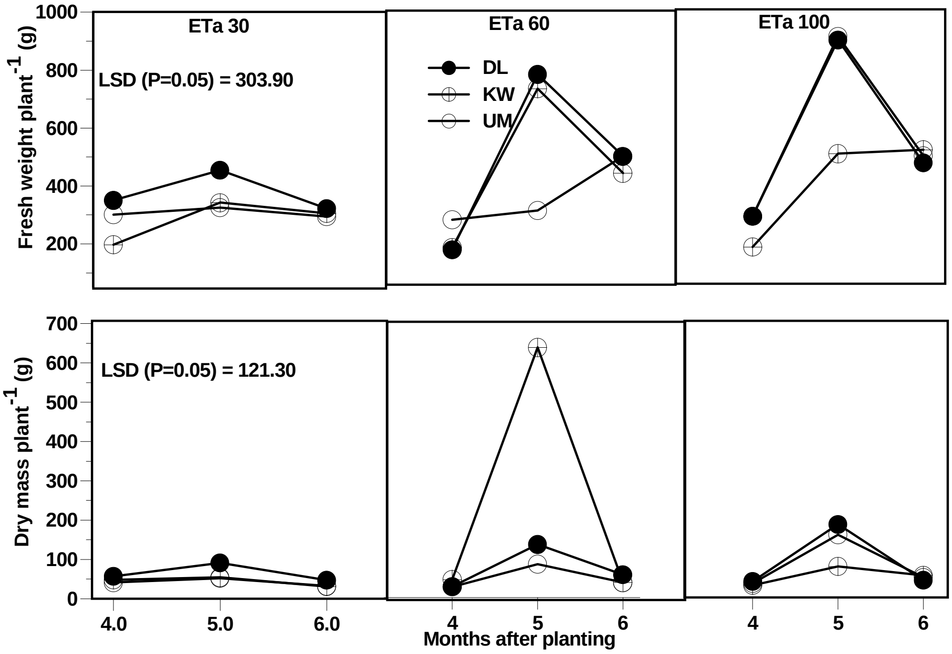

Figure 8.7: Fresh and dry mass (g plant-[1]) of taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] in response to three levels of irrigation (30%, 60% and 100% ETa) during 2010/11 and 2011/12 seasons.

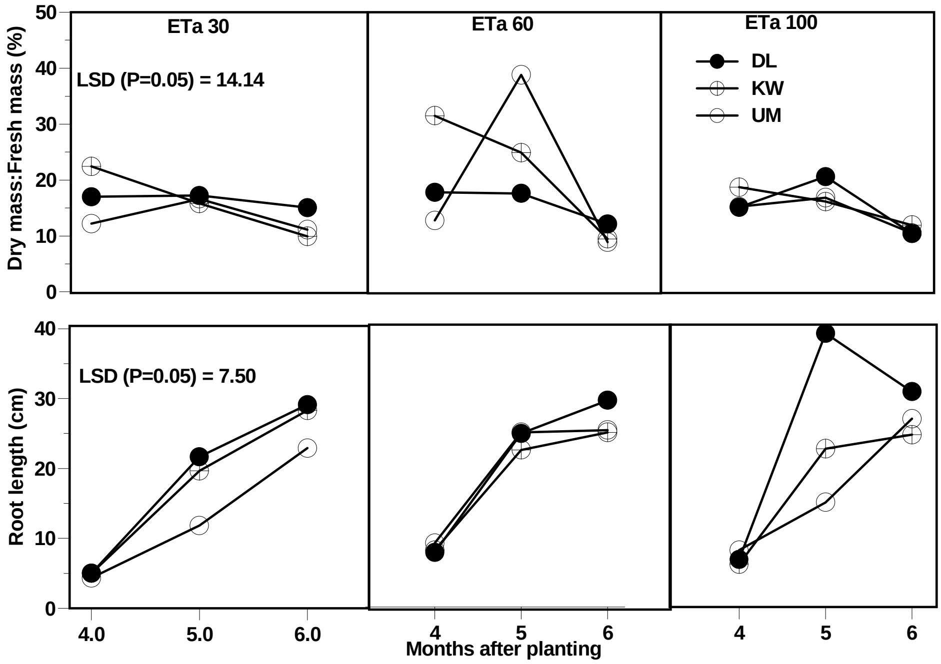

Figure 8.8: Root length (cm) and fresh: dry mass ratio (%) taro landraces [Dumbe Lomfula (DL), KwaNgwanase (KW) & Umbumbulu (UM)] in response to three levels of irrigation (30%, 60% and 100% ETa) during 2010/11 and 2011/12 seasons.

Results of yield and yield components reported in this chapter are only for the KW and UM landraces (Table 8.4). The DL landrace produced no yield, most likely because it is a wild landrace whose natural habitat is in shallow streams. Results of final biomass, for the two landraces, showed highly significant differences ($P<0.001$) between seasons (Table 8.4). Based on mean values for the seasons, final biomass during 2011/12 was at least 68% greater than that observed during 2010/11. Results of final biomass also showed significant differences ($P<0.05$) between irrigation treatments as well as between landraces. Final biomass was shown to be lower in response to decreasing water application rates (100% ETa > 60% ETa > 30% ETa). With regards to differences between landraces, the UM landrace had about 69% higher final biomass relative to the KW landrace under all three irrigation treatments. The trend in final biomass was consistent with results for plant growth, whereby the KW landrace was shown to be most affected by limited water availability.

Another key yield component was corm number per plant, especially for the UM landrace whereby the side cormels are consumed. The trend of results was similar to that observed for biomass. There were highly significant differences ($P<0.001$) between the two seasons, and significant differences ($P<0.05$) between irrigation treatments as well as between landraces (Table 8.4). On average, corm number per plant was 78% higher in 2011/12 than that in 2010/11. Interestingly, treatment means showed that corm number was respectively 13% and 11% higher at 60% ETa than at 100% and 30% ETa; this was also confirmed by mean separation using LSD ($P=0.05$) (Table 8.4). The UM landrace had about 92% higher corm number per plant than the KW landrace; this was due to morphological differences between the two landraces (Section 2.1).

Table 8.4: Yield and yield components (biomass, harvest index, corm number and corm mass) of two taro landraces (KwaNgwanase (KW) and Umbumbulu (UM) grown under a rainshelter at three irrigation levels (30, 60 and 100% ETa) during 2010/11 and 2011/12 summer seasons. *Numbers in the same column not sharing the same letter differ significantly at LSD (P = 0.05).

Season / Water Levels	Landrace	Biomass plant^{-1} (kg)	Corm number plant^{-1}	Corm mass plant^{-1} (kg)	Harvest Index (%)	Yield (t ha^{-1})	WUE (kg m^{-3})
2010/11 Season							
30% ETa	**UM**	0.248e	9.06c	0.220cd	87a	6.10cd	0.15c
	KW	0.183e	3.88e	0.156d	86a	4.32d	0.11c
60% ETa	**UM**	0.370de	8.11cd	0.336cd	90a	9.31cd	0.17c
	KW	0.164e	6.20cde	0.138d	86a	3.83d	0.07c
100% ETa	**UM**	0.377de	9.06c	0.324cd	85a	9.00cd	0.12c
	KW	0.227e	3.46e	0.152d	57c	4.23d	0.06c
2011/12 Season							
30% ETa	**UM**	0.886bc	16.56b	0.467bc	62bc	12.96ab	0.53a
	KW	0.288e	2.44e	0.205cd	71abc	5.70cd	0.17c
60% ETa	**UM**	1.086ab	22.56a	0.804a	74abc	22.32a	0.49a
	KW	0.478cde	3.28e	0.386bcd	82ab	10.70bcd	0.22c
100% ETa	**UM**	1.368a	21.78a	0.861a	63bc	23.90a	0.44ab
	KW	0.822bcd	4.28de	0.625ab	79ab	17.33ab	0.27bc
LSD (P=0.05) Season		0.179	1.53	0.102	8	2.82	0.08
LSD$_{(P=0.05)}$ Water Treatment		0.220	1.874	0.124	9	3.45	0.10
LSD$_{(P=0.05)}$ Landrace		0.179	1.53	0.102	8	2.82	0.08
LSD$_{(P=0.05)}$ WT*Landrace		0.311	2.65	0.176	13	4.88	0.14
LSD$_{(P=0.05)}$ Ssn*WT*Landrace		0.440	3.75	0.249	19	6.90	0.20

Corm mass per plant also differed significantly ($P<0.001$) between seasons, being higher (≈150%) during 2011/12 compared with 2010/11. Irrigation treatments were also shown to have a significant effect on plant corm mass; based on treatment means alone, corm mass per plant was lower at lower water application rates (100% ETa > 60% ETa > 30% ETa). Although corm number per plant was respectively 13% and 11% higher at 60% ETa compared with 100% and 30% ETa, this did not correlate with corm mass, suggesting that the numerous corms were small. The two landraces also differed significantly ($P<0.001$), with respect to corm mass (UM > KW). Mean separation using LSD ($P=0.05$) showed that corm mass of the UM landrace at 100% and 60% ETa were statistically similar, while corm mass was statistically less (44%) at 30% ETa. The general trend in corm mass showed much variation, although corm mass was less affected at 60% ETa (Table 8.4).

In line with observations on biomass, corm number and corm mass, harvest index (HI) showed significant differences ($P<0.05$) between the two seasons. Unlike other yield components, HI was 14% higher during 2010/11 compared with 2011/12. This was due to reduced vegetative growth and biomass (the denominator) during 2010/11. There were significant differences ($P<0.05$) between the three irrigation treatments only in 2011/12. Contrary to the trend observed for the other parameters, HI was respectively 14% and 7% lower at 100% ETa than at 60% and 30% ETa; mean separation confirmed this trend (Table 8.4). The fact that HI was higher under conditions of limited water availability implied a positive effect of stress on HI. Additionally, HI seemed to be more sensitive to changes in biomass than corm mass. There were no significant differences ($P>0.05$) between the landraces; based on mean values for landraces, they both had an average HI of 77%.

Consistent with results of yield components reported above, final yield (t ha^{-1}) showed highly significant differences ($P<0.001$) between seasons. On average, yield was higher (≈150%) during 2011/12 compared to 2010/11 (Table 8.4). Irrigation treatments were shown to have a significant effect ($P<0.05$) on final yield, with yield being lower at lower water application rates (100% ETa > 60% ETa > 30% ETa). The extent of yield reduction was greater at 30% ETa than at 60% ETa; based on mean values for irrigation treatments, yield was 15% and 47% lower at 60% ETa and 30% ETa than at 100% ETa. This re-affirmed the trend observed so far indicating that differences between 100% and 60% ETa were minimal, while 30% ETa had the greatest effect on all parameters measured. With respect to differences between landraces, analysis of variance showed highly significant differences ($P<0.001$) between landraces, with the UM landrace out-yielding the KW landrace under all conditions. The performance of UM, especially under limited water availability, was consistent with the moderate reductions observed for growth parameters.

Water-use efficiency (WUE) also showed highly significant differences (P<0.001) between seasons, in line with the trend observed for yield components and final yield (Table 8.4). Interestingly, results showed that there were no significant differences (P>0.05) between the three irrigation treatments. A closer look at irrigation treatment means showed that, on average, WUE was slightly higher (9%) and similar at 30% and 60% ETa (0.24 kg m^{-3}) compared to 100% ETa (0.22 kg m^{-3}). Results also showed highly significant differences between landraces, with the UM landrace (0.32 kg m^{-3}) having higher (113%) WUE than the KW landrace (0.15 kg m^{-3}); mean separation also confirmed this.

Results of biomass, harvest index, corm number per plant (CMN) and WUE were subjected to correlation and path analysis to identify the parameter(s) that contributed most to final yield (Table 8.5). Biomass (r = 0.92), CMN (r = 0.73) and WUE (r = 0.67) were shown to be highly correlated to final yield (Table 8.5). The parameter that had the greatest contribution to final yield was biomass, followed by harvest index (Table 8.5). Corm number had the least contribution to final yield, while WUE had a negative contribution to yield. The low contribution of corm number per plant relates to observations that high CMN did not translate to high yield (Table 8.4). This suggests that any selection effort should target a landrace with minimum biomass reduction under limited water availability.

Table 8.5: Correlation matrix and path coefficients showing direct and indirect contributions of biomass, harvest index and corm number per plant to yield for both KwaNgwanase (KW) and Umbumbulu (UM) landraces. ^{x} CMN = corm number per plant; ^{y} WUE = water-use efficiency. Values in bold represent the direct contribution; ^{i} represents the indirect contribution and * denotes the correlation coefficient.

	Biomass	**Harvest index**	**^{x}CMN**	**^{y}WUE**	**Yield***
Biomass	**1.21**	-0.18^{i}	0.06^{i}	-0.16^{i}	0.92
Harvest index	-0.65^{i}	**0.34**	-0.03^{i}	0.13^{i}	-0.22
^{x}CMN	0.93^{i}	-0.14^{i}	**0.08**	-0.14^{i}	0.73
^{y}WUE	1.03^{i}	-0.23^{i}	0.06^{i}	**-0.19**	0.67

8.4 Discussion

Emergence of taro landraces was slow and erratic, with landraces failing to reach 50% emergence by 49 days after planting. Previously, Mare (2010) reported that it took about 70 days after planting for taro landraces to emerge under dryland conditions. Vigorous and uniform emergence is important for canopy cover (Passioura, 2006; Blum, 2012); thence the ability to quickly emerge (vigour) and start photosynthesising is important (Harris *et al*., 2002; Passioura, 2006). Good seedling establishment ensures rapid ground cover (Passioura, 2006) thereby reducing loss of water to soil evaporation. Slow emergence of taro landraces implies that a significant amount of water is lost to soil evaporation (unproductive) as opposed to being lost through transpiration during establishment (Blum, 2012). This would result in a significant amount of water being lost to evaporation in cases where the crop is irrigated using sprinkler or surface irrigation methods that have a high percentage of soil surface wetted. The use of drip irrigation, which has a smaller percentage wetted soil surface, would save water (Phene *et al*., 1994; Unlu *et al*., 2006).

A plant's ability to tolerate dry conditions is intricately linked to its ability to acclimatise (Anjum *et al*., 2011). Stomata facilitate water loss through transpiration as well as uptake of CO_2 from the atmosphere. In the current study, stomatal conductance was shown to decrease in response to decreasing water availability; this pattern was lucid for the UM landrace. Sivan (1995) reported similar findings of declining stomatal conductance in taro varieties subjected to water stress. Under limited water availability, stomatal conductance decreases as a mechanism to minimise transpirational water losses (Chaves *et al*., 2003) – this is dehydration avoidance (Levitt, 1979; Turner, 1986). In this regard, it can be assumed that the UM landrace is the most water-efficient of the three landraces as evidenced by its greater degree of stomatal control.

Limited water availability has been reported to result in reduced plant growth due to impairment of cell division and expansion (Hussain *et al*., 2008). The trend observed showing lower canopy size (plant height, leaf number and LAI) under limited water availability (60% and 30% ETa) was consistent with reports by Sivan (1995) and Sahoo *et al*. (2006) who also observed reduced growth in taro varieties subjected to water stress. Reduction in leaf number was also due to premature senescence of leaves. Canopy size represents surface area available for transpiration; plants cope with reduced water availability through reductions in canopy size (Mitchell *et al*., 1998) – a dehydration avoidance mechanism (Levitt, 1979; Turner, 1986). In addition, reduced LAI has previously been ascribed to reduction in photosynthesis and assimilate supply under water limited conditions (Anjum *et al*., 2011) which curtail leaf expansion.

Reduction in canopy size in response to limited water availability is an attribute of water-use efficiency; however, this should not be excessive as leaf area directly correlates to biomass production and yield (Blum, 2005, 2012). Hypothetically, a plant that shows moderate reduction in canopy size is capable of striking a balance between minimising water loss and allowing for reasonable biomass production to continue. In this regard, the UM landrace was efficient in achieving both aspects – while the crop reduced its canopy size under limited water conditions, such reduction was moderate compared with the DL and KW landraces. This allowed the UM landrace to have higher biomass compared with the other landraces.

Under limited water availability, roots grow until demand for water is met. However, genetic variations may limit potential maximum rooting depth (Blum, 2005). A well-developed root system allows for enhanced capture of soil water (Passioura *et al*., 2006) an important adaptation (dehydration avoidance) to water limited conditions (Vurayai *et al*., 2011). This study showed that taro landraces are shallow-rooted (< 30 cm); this suggests that taro landraces are unable to utilise water from deeper areas of the soil profile. Root length of taro landraces decreased with decreasing water availability. This was contrary to other studies that have reported increased root length under conditions of limited water availability – sunflower (Tahir *et al*., 2002) and *Populus sp* (Wullschleger *et al*., 2005). Moreover, this was also contrary to reports by Sivan (1995) of increased root: shoot in taro varieties subjected to water stress. We can only hypothesise that perhaps the constant re-wetting of the root zone, at all water levels, due to frequent irrigation by drip may have kept the root zone reasonably moist enough to discourage root growth.

Most plant adaptations associated with increased WUE under limited water availability are often detrimental to yield attainment, which is the goal of farming (Blum, 2005; Jaleel *et al*., 2009). Yield and yield components all decreased in response to reduced water availability. Despite the fact similar agronomic practices were done for both seasons, yield was significantly higher during 2011/12 compared with 2011/11. Differences in yield between seasons may be due to landrace variability. Yield decreased by 15% and 47% in response to reduced water availability at 60% ETa and 30% ETa, respectively, compared with the 100% ETa treatment. The trend was similar to recent reports on yield and water use efficiency of potato grown under different irrigation levels (Badr *et al*., 2012). They reported that tuber yield of potatoes decreased with decreasing amount of irrigation applied.

Water-use efficiency of taro landraces was shown to be constant across water regimes (0.22-0.24 kg m^{-3}). The increase in WUE under limited water availability was marginal. Under limited water availability, WUE increases through either increasing yield (biomass) or decreasing water-use through the amount of irrigation applied (Pandey *et al*., 2000). Over-all, WUE of taro landraces was low compared to that reported for other crops such as potato (Badr *et al*., 2009). In the present study, decreasing the amount of irrigation applied, did not significantly improve WUE. This was shown in corresponding reductions in biomass and yield. Percentage yield reduction may have been equal to percentage reduction in water-use (water applied). On average, the UM landrace's WUE (0.32 kg m^{-3}) was twice as high as that of the KW landrace (0.15 kg m^{-3}). Uyeda *et al*. (2011) reported that upland taro was more efficient at using water than varieties which are more adapted to flooded conditions. The UM landrace is an upland variety while the KW landrace is cultivated along the coast in swamps and other waterlogged areas.

Correlation and path analysis of taro yield determinants showed that biomass was highly correlated to yield and had the greatest contribution to yield. Corm number per plant had less contribution to final yield, suggesting that it is corm mass, not number, which is more critical under limited water availability. This partly explains why the UM landrace was able to out yield the KW landrace under all conditions. Yield reduction under limited water availability is a function of reduced canopy growth and biomass production (Badr *et al*., 2012). The UM landraces had moderate reductions in plant growth compared with the KW landrace and therefore, was able to produce more biomass which translated to higher yield. Yield of the UM landrace in the 30% ETa treatment during both seasons was higher than the global average yield estimate for taro (6.5 t ha^{-1}) (FAOSTAT, 2012).

8.5 Conclusion

Given the importance of vigorous emergence, strategies to improve emergence of taro should be a key objective of future studies. This would improve water-use and possibly yield. Under conditions of limited water availability, taro landraces were able to reduce their water-use through reductions in stomatal conductance and canopy size. The extent of reduction in canopy size was greater in the KW landrace compared with the UM landrace suggesting that the KW landrace was more sensitive to limited water availability. The UM landrace was shown to have a greater degree of stomatal control, thus minimising water loss through transpiration. Yield was shown to decrease in response to limited water availability while WUE remained relatively unchanged across water treatments. The UM landrace was shown to have higher WUE and to be better adapted for cultivation in areas with limited water availability.

Chapter 9

Drought tolerance of a bambara groundnut (*Vigna subterranea* L. Verdc) landrace

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9.1 Introduction

In South Africa, bambara groundnut is cultivated under dryland conditions in the KwaZulu-Natal, Mpumalanga, Limpopo and North-West Provinces (Swanevelder 1998). Under these conditions, water stress through insufficient and/or uneven rainfall, remains a significant limitation to crop production. Water stress occurring at any stage can have a negative impact on yield. Several studies described the germination, growth and yield responses of bambara groundnut landraces to water stress (Collinson *et al*. 1996, 1997, 1999, Sesay *et al*. 2004, Mwale *et al*. 2007, Vurayai *et al*. 2011a, 2011b, Berchie *et al*. 2012). In South Africa, s study by Spreeth *et al*. (2004) screened some bambara landraces for drought tolerance; however, information describing local bambara groundnut landraces remains limited in extent.

There is need to characterise local landraces and identify them for drought tolerance in South Africa. There are currently no improved bambara groundnut cultivars. The crop is sown using landraces, of which little is known regarding their agronomy and water use. Previous studies have associated seed colour with seed quality and vigour in landraces of maize (Mabhaudhi & Modi, 2010, 2011), wild mustard (Mbatha & Modi, 2010) and wild water melon (Zulu & Modi, 2010), and recently in bambara groundnut (Sinefu, 2011). Although seed coat colour may not necessarily imply genotypic differences, it may be a useful criterion for initial selection of bambara groundnut landraces for improved varieties. This may be especially true for landraces which typically exhibit large variations in seed coat colour but little is known about their seed quality.

In this study, it was hypothesised that local bambara groundnut landraces may have acquired drought tolerance through years of natural and farmer selection under often harsh conditions. It was further hypothesized that such drought tolerance may be linked to seed coat colour. Hence, the specific objectives of this study were to evaluate growth, phenological and yield responses of a local bambara groundnut landrace characterised into three selections according to seed coat colour under irrigated and rainfed field conditions over two seasons.

9.2 Materials and Methods

9.2.1 Planting material

Seeds of a locally grown bambara groundnut landrace were collected from subsistence farmers in Jozini (27°26'S; 32°4'E; < 500 masl), northern KwaZulu-Natal, South Africa. The mean annual rainfall for Jozini is > 1000 mm. Information describing the growing period as well as any assumed drought tolerance of the landrace was unavailable. The landrace was characterised into three selections according to seed colour based on previous studies that suggested seed coat colour may have an effect on early establishment performance (Mabhaudhi & Modi 2010, 2011, Mbatha & Modi 2010, Zulu & Modi 2010, Sinefu 2011). The seeds were sorted into three distinct seed coat colours: Red, Brown and Light brown.

9.2.2 Description of experimental sites

Field trials were planted at Roodeplaat, Pretoria (25º60´S; 28º35´E; 1168 masl) during the summer seasons of 2010/11 and 2011/12. During 2010/11, trials were planted on 12 September, 2010 while during 2011/12, trials were planted on 6 September, 2011. The soil was classified as a sandy loam (USDA taxonomic system). The average seasonal rainfall (November to April) of Roodeplaat is ~500 mm, and is highly variable with maximum precipitation in December and January. Daily maximum and minimum temperature averages are 34℃ and 8℃, respectively, in summer (November – April) (Agricultural Research Council – Institute for Soil, Climate and Water).

9.2.3 Experimental design

The experimental design was a split-plot design, with irrigation (full irrigation vs. rainfed) being the main factor and landrace colour being the sub-plot, arranged in a randomised complete block design with three replicates. Main plots were 52 m^2 each with spacing of 10 m between them and sprinklers were designed to have a maximum range of 6 m radius to prevent water sprays from reaching rainfed plots; the sub-plots measured 3 m^2. Plant spacing was 0.3 m (inter-row) x 0.2 m (intra-row). Trials were irrigated using sprinkler irrigation. Irrigation scheduling, during both seasons, was based on reference evapotranspiration (ET_o) obtained from an automatic weather station located within a 100 m radius from the experimental site at Roodeplaat, and a crop factor (Kc). The total amount of rainfall received during the experiments was 678 mm during 2010/11 and 466 mm during 2011/12 growing season. The 2011/12 growing season was characterised by less than average rainfall and was therefore a dry season. Supplementary irrigation supplied to the irrigated treatment amounted to 526 mm during 2010/11 and 890 mm during 2011/12. The higher amount of supplementary irrigation applied during 2011/12 was because this was a drier season compared to 2010/11.

9.2.4 Agronomic practices

The experiments during 2010/11 and 2011/12 were sown before the onset of the rainy season. Soil samples were obtained from the field trial site prior to planting for determination of soil fertility and texture. Based on soil fertility results, 167 kg N ha^{-1}, 23.4 kg P ha^{-1} and 78.6 kg ha^{-1} were applied at planting using an organic fertiliser, Gromor Accelerator® (30 g kg^{-1} N, 15 g kg^{-1} P and 15 g kg^{-1} K) to meet crop nutritional requirements (Swanevelder 1998). Weeding and ridging were done by hand hoeing.

9.2.5 Data collection

Data collection included emergence up to 35 days after planting. Thereafter, plant height, leaf number, leaf area index, stomatal conductance, chlorophyll content index were determined either weekly or every fortnight. Crop phenology was observed as days to flowering, flowering duration, days to leaf senescence, days to maturity, biomass and yield. A phenological event was deemed to have occurred if it was observed in at least 50% of plants. Days to leaf senescence was described as when at least 10% of leaves had senesced without new leaves being formed to replace them – this stage indicates beginning of canopy decline. Days to maturity was defined in terms of physiological maturity or when at least 50% of leaves in at least 50% of plants had senesced. Leaf area index was measured using the LAI2200 canopy analyser (Li-Cor, USA & Canada). Stomatal conductance was measured using a steady state leaf porometer (Model SC-1, Decagon Devices, USA). Chlorophyll content index was measured using a chlorophyll content meter (CCM-200 *PLUS*, Opti-Sciences, USA); chlorophyll content index data were only measured during the 2011/12 season. Stomatal conductance and CCI were measured from the abaxial (lower) and adaxial (upper) leaf surfaces, respectively, on young fully unfolded leaves. Stomatal conductance was measured on the abaxial surface because it was higher there relative to the adaxial surface. In addition, measurements of stomatal conductance and CCI were taken around midday in-between irrigation and/or rainfall events when the soil was drying. Soil water content was monitored gravimetrically, weekly, at depths of 30 and 60 cm. Weather data for the duration of the experiments was recorded and obtained from the Agricultural Research Council – Institute for Soil, Climate and Water's automatic weather stations network.

9.2.6 Description of statistical analysis

Data were analysed using analysis of variance (ANOVA) (GenStat® Version 14, VSN International, UK). Duncan's multiple range test was used to separate means at the 5% level of significance.

9.3 Results

Weather data recorded over the two seasons (2010/11 and 2011/12) showed a significant ($P < 0.05$) difference in rainfall, although temperatures (maximum and minimum) observed were similar (Figure 9.1). Comparing rainfall received during the two seasons with the average long-term rainfall for Roodeplaat showed that total rainfall received during 2010/11 (766 mm) was 13% more than the long-term rainfall (678 mm). However, in the subsequent season (2011/12), significantly less rainfall was measured (466 mm) compared to the long-term (31% less) and the previous season's rainfall (39% lower).

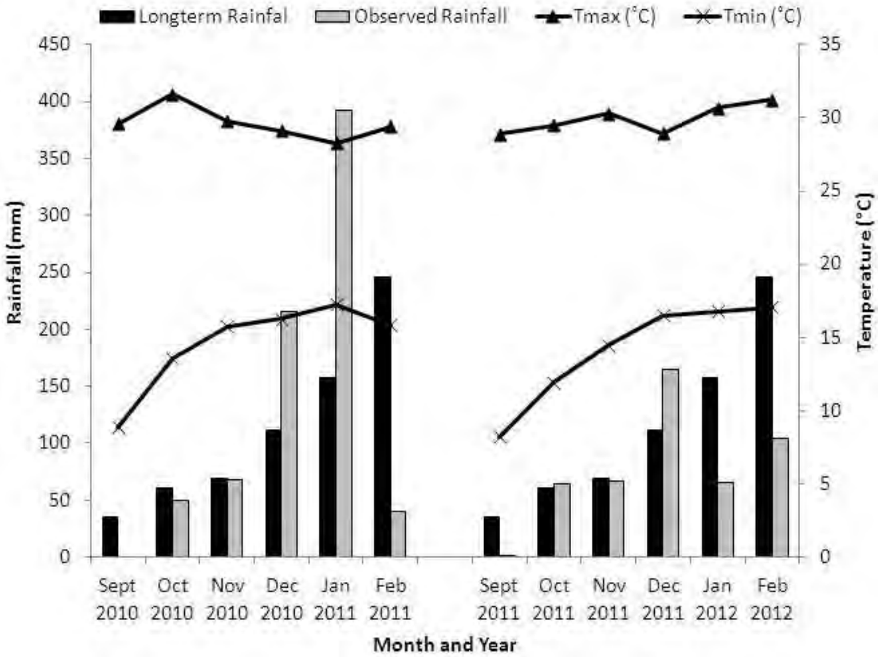

Figure 9.1: Variations in monthly rainfall and maximum (Tmax) and minimum (Tmin) temperatures (°C) recorded during (A) 2010/11 and (B) 2011/12 planting seasons at ARC-Roodeplaat, Pretoria, South Africa.

Bambara groundnut landrace selections were slow to emerge. During both the 2010/11 and 2011/12 seasons, it took an average of 35 DAP (days after planting) for the crop to achieve 90% emergence (Figure 9.2). The trend of slow emergence was consistent over both seasons. During 2010/11, there were highly significant differences ($P < 0.001$) between landrace selections; the 'Brown' landrace had the highest emergence, followed by 'Red' and 'Light brown' landrace selections, respectively. The only difference during 2011/12 was that 'Red' performed better than 'Brown'. However, for both seasons, performance of the 'Light-brown' landrace selection, with regard to emergence, was less than that of the darker coloured landrace selections.

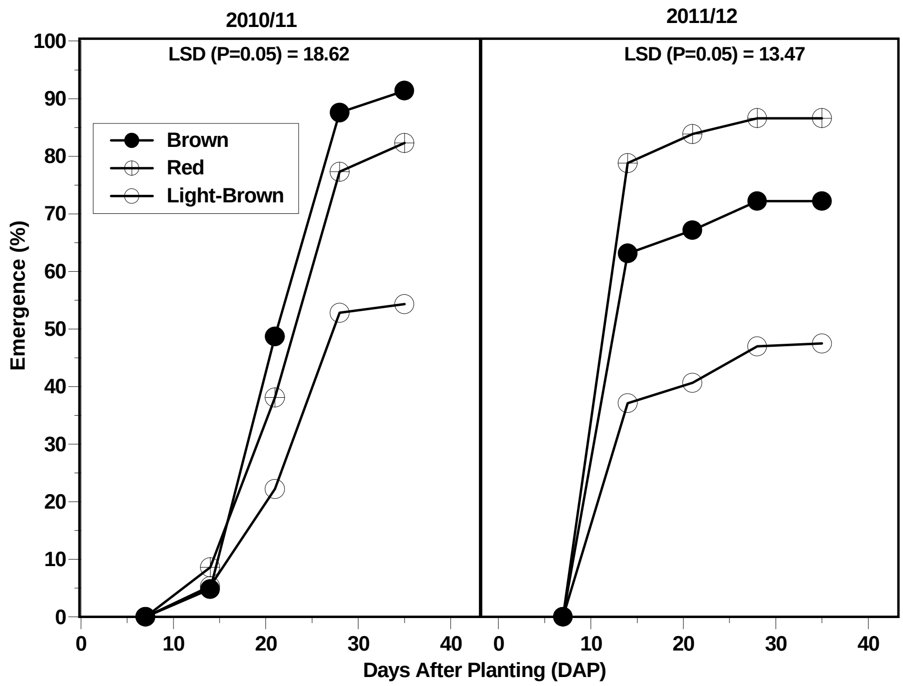

Figure 9.2: Daily emergence of three bambara groundnut landrace selections (Brown, Red and Light brown) under field conditions during 2011/11 and 2011/12 planting seasons.

Although not significantly different, stomatal conductance (SC) was lower under rainfed conditions relative to irrigated conditions (Figure 9.3). The trend of decline in SC was clearer during 2010/11; under rainfed conditions, SC decreased by 1%, 8% and 6% in 'Brown', 'Red' and 'Light-brown' landrace selections, respectively.

Chlorophyll content index (CCI) was only measured during the 2011/12 season; measurements of were typically observed during periods between irrigation and/or rainfall events when the soil was drying. Results showed significant differences ($P < 0.001$) between rainfed and irrigated water regimes (Figure 9.4). Chlorophyll content index, on average, was about 25% lower under rainfed conditions relative to irrigated conditions. There were no differences ($P > 0.05$) between landrace selections. The interaction between landrace and water regime was not significant ($P > 0.05$). The trend in CCI was clearer during the early part of the season. Chlorophyll content index for 'Brown', 'Red' and 'Light-brown' decreased by 29%, 25% and 20%, respectively, under rainfed relative to irrigated conditions.

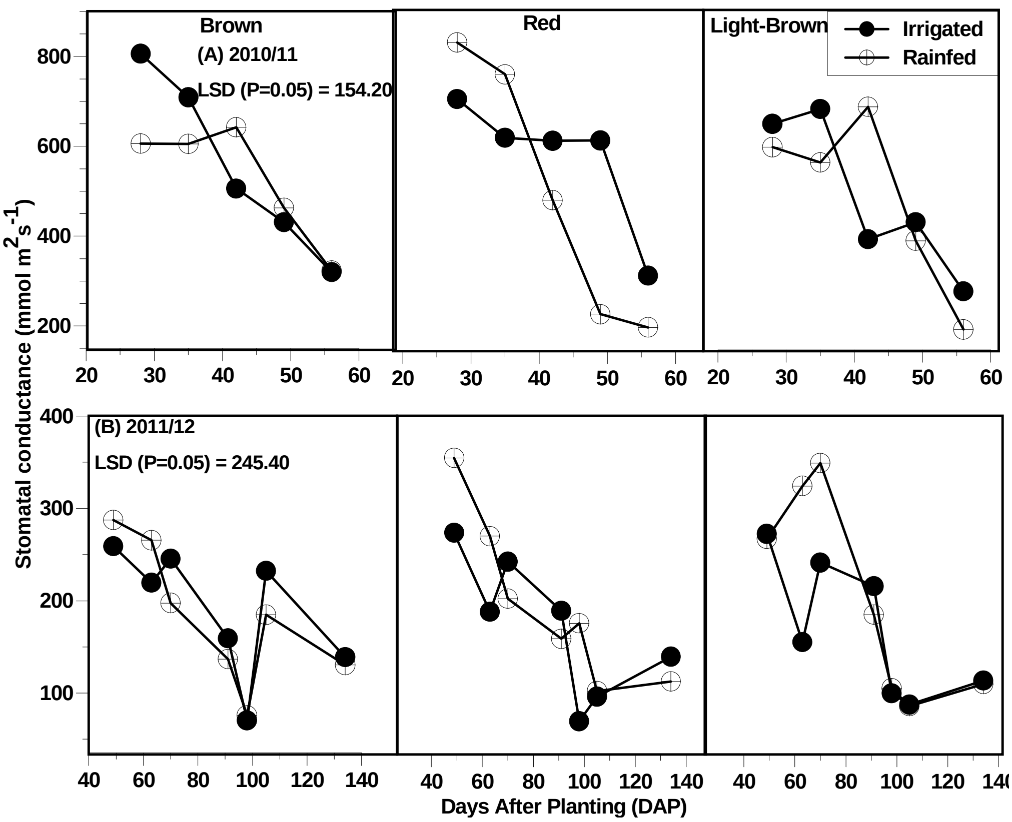

Figure 9.3: Stomatal conductance (mmol m^{-2} s^{-1}) of bambara groundnut landrace selections (Brown, Red & Light-brown) under irrigated and rainfed field conditions during 2011/11 and 2011/12 planting seasons. Measurements were taken in-between irrigation and/or rainfall events when the soil was drying.

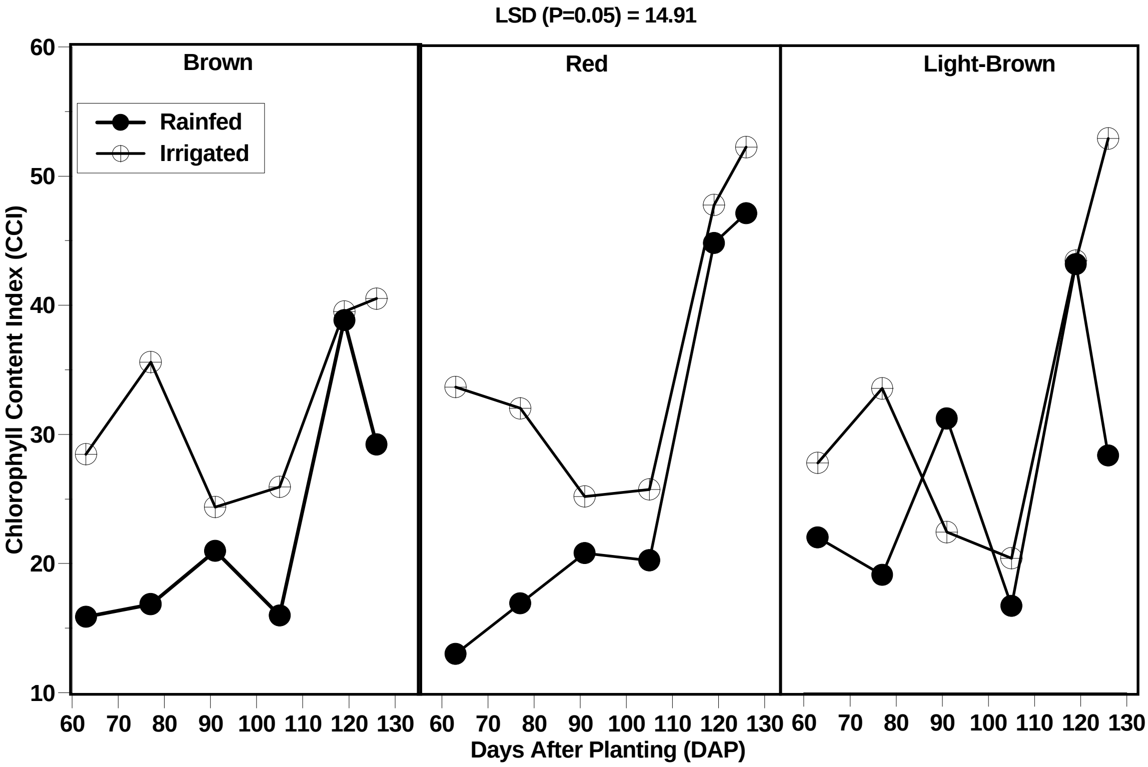

Figure 9.4: Chlorophyll content index (CCI) of bambara groundnut landrace selections (Brown, Red & Light-brown) under irrigated and rainfed field conditions during the 2011/12 planting season.

Plant height and leaf number, observed during 2010/11, showed highly significant differences ($P < 0.001$) between seed colours although there were no significant differences ($P > 0.05$) between water regimes as well as the interaction between landraces and water regime (Figure 9.5). During 2011/12, results of plant height and leaf number showed highly significant differences ($P < 0.001$) between landraces, water regimes and their interaction (Figure 9.5). For both seasons, plant height was lower under rainfed conditions compared to irrigated conditions. Leaf number was more affected by water stress than plant height during 2011/12 compared with 2010/11.

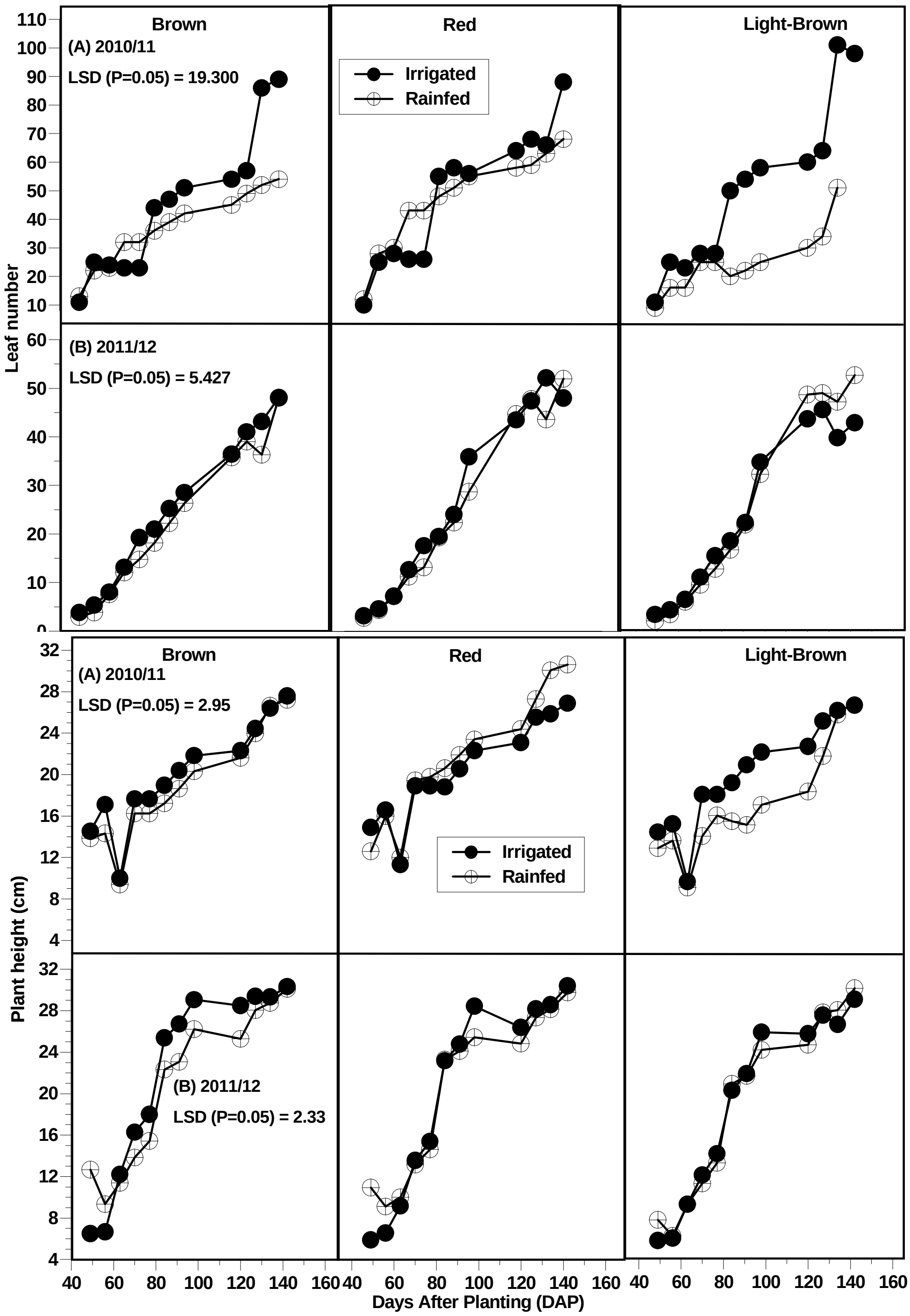

Figure 9.5: **A.** Plant height (cm), and **B.** Leaf number of bambara groundnut landrace selections (Brown, Red & Light-brown) grown under irrigated and rainfed conditions during 2010/11 and 2011/12 planting seasons.

There were no significant differences between landraces or water regimes during 2010/11, with respect to leaf area index (LAI). However, there was a significant interaction ($P < 0.05$) between the two factors. Nonetheless, during 2011/12, there were highly significant differences ($P < 0.001$) between landraces and water regimes (Figure 9.6). This was consistent with observations of plant height and leaf number during the same season. Based on mean values for landraces across water regimes for both seasons, LAI was lower in 'Brown' (18% and 9%) and 'Red' (5% and 8%) under rainfed than irrigated conditions (Figure 9.6).

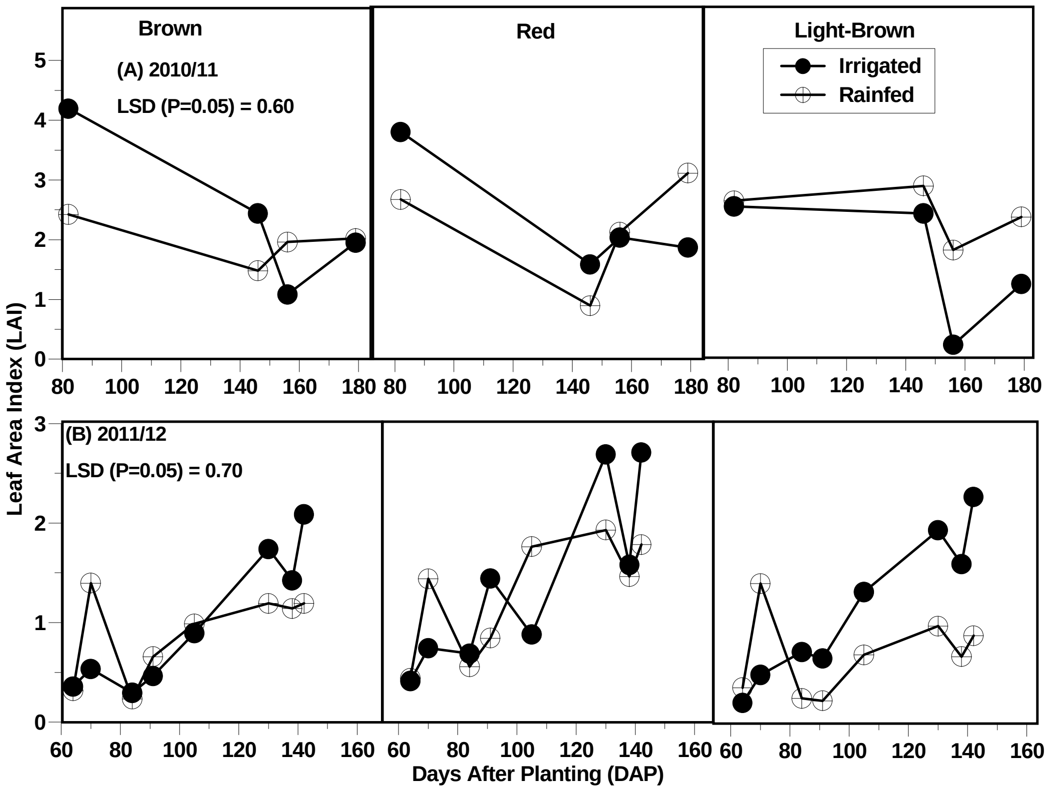

Figure 9.6: Leaf area index (LAI) of bambara groundnut landrace selections (Brown, Red & Light-brown) grown under irrigated and rainfed conditions during 2010/11 and 2011/12 planting seasons.

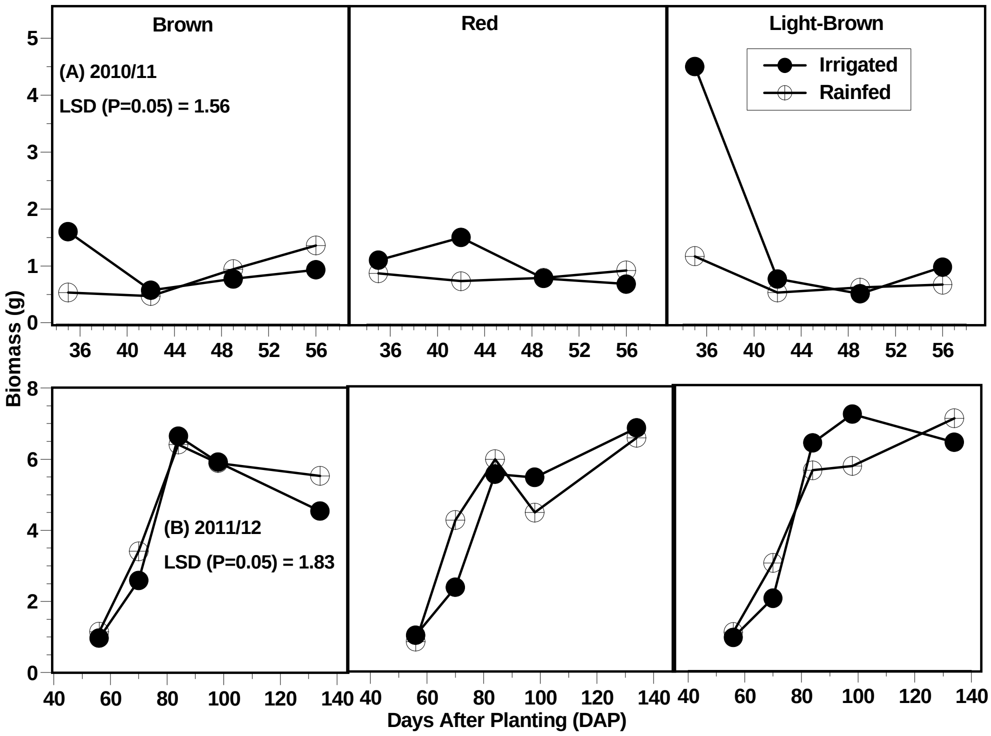

Figure 9.7: Biomass accumulation (per plant per dry matter basis) of bambara groundnut landrace selections (Brown, Red & Light-brown) grown under irrigated and rainfed conditions during 2010/11 and 2011/12 planting seasons.

Results of biomass accumulation, for both seasons, showed no differences (P > 0.05) between landrace selections, water regimes as well as their interaction (Figure 9.7). However, despite lack of statistical difference, biomass accumulation, with the exception of the 'Light-brown' landrace selection, was lower under rainfed than irrigated conditions (Figure 9.7).

Crop development, defined in terms of occurrence of phenological stages under field conditions, was shown to be significantly affected by different water regimes (Table 9.1). Days to flowering showed highly significant differences (P<0.001) between landrace selections and between water regimes. Based on mean values for landrace selections, 'Red' flowered earlier than 'Brown' and 'Light-brown', respectively. In addition, mean values for water regimes showed that flowering occurred earlier (~11 days) under rainfed relative to irrigated conditions. The interaction between landrace and water regime was not significant (P > 0.05) for flowering (Table 9.1).

Table 9.1: Phenological stages of bambara groundnut landrace selections (Brown, Red and Light-brown) grown under irrigated and rainfed conditions during 2010/11 and 2011/12 seasons.

Year	Treatment	Landrace Selection	Flowering (^{x}DAP*)	Flowering Duration (^{x}Days)	Leaf Senescence (^{x}DAP*)	Maturity (^{x}DAP*)
2010/11 Season	Irrigated	Brown	88ab	47cd	135b	178b
		Red	86bcde	49bc	135b	174c
		Light-brown	93a	47cd	140a	182a
	Rainfed	Brown	75g	39ef	114cd	157d
		Red	72g	43cde	115cd	157d
		Light-brown	82cdef	31g	113d	155e
2011/12 Season	Irrigated	Brown	87bc	56a	143a	150f
		Red	87bc	56a	143a	150f
		Light-brown	87bcd	54ab	141a	148g
	Rainfed	Brown	77fg	40ef	117c	136h
		Red	75g	42de	117c	136h
		Light-brown	81cef	35fg	116cd	134i
$LSD_{(P=0.05)}$ Landrace			2.574	2.9	1.5	0.663
$LSD_{(P=0.05)}$ Treatment			2.101	2.3	1.2	0.542
$LSD_{(P=0.05)}$ Year			2.101	2.3	1.2	0.542
$LSD_{(P=0.05)}$ Landrace*Treat*Year			5.147	5.7	3.0	1.326

*DAP = Days after planting; ^{x}DAP values were rounded off to the nearest integer. Values in the same column not sharing the same letter differ significantly at LSD (P=0.05).

With respect to days to leaf senescence, results showed no significant differences (P > 0.05) between landrace selections while there were highly significant differences (P < 0.001) between water regimes. Mean values for water regimes showed that under rainfed conditions bambara groundnut landraces flowered at least 15 days earlier than under irrigated conditions. There was no significant (P > 0.05) interaction between landrace and water regimes with respect to days to leaf senescence (Table 9.1).

Flowering duration showed highly significant differences (P < 0.001) between landrace selections as well as between water regimes. Based on mean values for landrace selections only, the 'Red' landrace had the longest flowering duration (~48 days) followed by, 'Brown' (~46 days) and 'Light-brown' (~42 days) landrace selections, respectively. Bambara groundnut landrace selections, on average, had a shorter flowering duration under rainfed relative to irrigated conditions. The interaction between landrace and water regime was also significant ($P < 0.05$). 'Brown' and 'Light-brown' landrace selections had the greatest reduction in flowering duration under rainfed compared to irrigated conditions (Table 9.1).

Days to maturity showed significant differences ($P < 0.05$) between landrace selections and highly significant differences ($P < 0.001$) between water regimes. Means of landraces showed that, on average, 'Red' matured earlier than 'Light-brown' and 'Brown' landrace selections, respectively. Under rainfed conditions, bambara groundnut landrace selections matured earlier (~18 days) than under irrigated conditions. The interaction between landrace and water regime was shown to be highly significant ($P < 0.001$). Although all landrace selections matured earlier under rainfed relative to irrigated conditions, 'Light-brown' and 'Brown' landrace selections matured earlier than the 'Red' landrace selection (Table 9.1).

Results for measured yield components, harvest index (HI), pod mass, pod number per plant, biomass and yield, during the 2010/11 planting season, showed highly significant differences ($P < 0.001$) between water regimes. There were no differences ($P > 0.05$) between landrace selections and the interaction between landrace and water regime was not significant ($P > 0.05$) (Table 9.2). Harvest index was significantly ($P < 0.001$) lower under rainfed conditions. This was due to the lower corresponding pod mass (Table 9.2) under rainfed conditions. The effect of poor podding was shown in yield losses of, on average, 50% for all landraces under rainfed conditions relative to irrigated conditions.

During the 2011/12 season, which was drier than the 2010/11 planting season, results of yield components showed no significant differences ($P > 0.05$) between water regimes and landrace selections; the exception was that for biomass there were significant differences ($P < 0.05$) between water regimes and landrace selections (Table 9.2). Biomass and yield were significantly lower under rainfed relative to irrigated conditions.

Table 9.2: Yield components of bambara groundnut landrace selections (Brown, Red and Light-brown) grown under irrigated and rainfed conditions during 2010/11 and 2011/12 seasons.

Year	Water	Landrace Selection	HI* (%)	Pod Mass (g $plant^{-1}$)	Pod No. $Plant^{-1}$	Biomass (t ha^{-1})	Yield (t ha^{-1})
2010/11 Season	Irrigated	Brown	25.75abc	21.21ab	25ab	12.98abcd	2.44ab
		Red	31.46ab	24.37a	27ab	11.80bcde	3.34a
		Light-brown	32.46ab	27.53a	35ab	16.79a	3.22ab
	Rainfed	Brown	6.21c	4.27b	10b	10.60bcde	0.66c
		Red	17.48bc	12.94ab	17ab	11.69bcde	1.52bc
		Light-brown	13.29bc	9.89ab	15ab	14.81ab	1.43bc
$LSD_{(P=0.05)}$ Landrace*Water (2010/11)			**9.22**	**11.76**	**17.16**	**3.722**	**1.359**
2011/12 Season	Irrigated	Brown	32.61ab	16.04ab	21ab	8.23de	2.28abc
		Red	30.75ab	22.35a	32ab	12.14abcde	2.84ab
		Light-brown	20.76bc	20.74ab	36a	13.44abc	2.60ab
	Rainfed	Brown	25.19abc	11.66ab	15ab	7.90de	1.62abc
		Red	30.36ab	15.26ab	22ab	8.75cde	1.84abc
		Light-brown	42.11a	23.22a	24ab	10.23bcde	1.99abc
$LSD_{(P=0.05)}$ Landrace*Water (2011/12)			**18.809**	**11.042**	**19.876**	**4.331**	**1.085**
[z]Yield correlation (r)			0.657	0.873	0.860	0.396	---------
[z]$LSD_{(P=0.05)}$ Landrace			8.949	7.582	11	2.192	0.775
[z]$LSD_{(P=0.05)}$ Treatment			7.307	6.191	9	1.790	0.633
[z]$LSD_{(P=0.05)}$ Year			7.307	6.191	9	1.790	0.633
[z]$LSD_{(P=0.05)}$ [z]Landrace*Treat*Season			17.898	15.164	21	4.384	1.549

*HI = harvest index; [x] Pod number per plant values were rounded off to the nearest integer since pod number represents discrete data. Values in the same column not sharing the same letter differ significantly at LSD (P=0.05). Mean separation was done using the LSD value for the Landrace selection*Treatment*season interaction. [z]Statistics refer to the comparison between the 2010/11 and 2011/12 planting seasons for the three bambara groundnut landrace selections under irrigated and rainfed conditions.

Results of yield components (HI, pod mass, pod number per plant) over the two planting seasons (2010/11 and 2011/12) showed much variability between season and landrace selection. Weather data showed that 2011/12 was a drought season with less than average rainfall received. There was a trend of lower HI under rainfed conditions relative to irrigated conditions, for both seasons. Overall, the 'Brown' and 'Red' landraces were more sensitive to lower HI compared with the 'Light-brown' landrace. Despite 2011/12 receiving less than average rainfall, HI under rainfed conditions was higher than during 2010/11, indicating a positive effect of water stress on HI. With respect to final yield, there were highly significant differences ($P < 0.001$) between irrigated and rainfed production, while there were no differences ($P > 0.05$) between the seasons (Table 9.2). The 'Red' landrace selection, on average, had 3% and 48% higher yield compared with the 'Light-brown' and 'Brown' landrace selections, respectively.

9.4 Discussion

Bambara groundnut landrace selections were slow to emerge under both irrigated and rainfed conditions, taking an average of 28-35 DAP to emerge. This was much longer than the 7-14 days reported by Swanevelder (1998). Slow emergence observed in this study may be due to poor seed quality of landraces used in this study. Landraces often lack the same vigour as hybrids or other improved varieties (Mabhaudhi & Modi, 2010). Thence, there is a need to come up with strategies to improve or enhance seed quality in landraces. In a study on maize landraces, Mabhaudhi and Modi (2011) showed hydropriming could be used to improve seed vigour and emergence of maize landraces.

In addition, slow emergence may have been the result of planting early in September when temperatures were still relatively cool. Sinefu (2011) observed similar results showing that bambara groundnut landraces were slow to emerge (taking up to 35 DAP) for trials planted in September (early); emergence improved with later plantings in November and January when temperatures were warmer.

The fact that 'Red' and 'Brown' landrace selections consistently emerged better than 'Light-brown'; further strengths our initial hypothesis that darker coloured seeds may have better vigour compared with light coloured seeds (Mabhaudhi & Modi 2010, Zulu & Modi 2010, Mbatha & Modi 2010). The effect of seed coat colour on seed quality has previously been related to levels of phenolic compounds (Anuradha *et al*. 2009) and seed coat thickness (Sinefu 2011). Darker coloured seeds may contain high levels of phenolic compounds (Anuradha *et al*. 2009). High phenolic content in darker coloured seeds may be the reason for the association between dark seed colour and seed quality since phenolic compounds have antioxidant properties. As such, seed coat colour may be a useful indicator of seed quality (Anuradha *et al*. 2009).

Although our results of stomatal conductance were not statistically significant, stomatal conductivity was lower under rainfed than irrigated conditions. Under water limited conditions, stomatal closure is designed to reduce water losses through transpiration. This means that the bambara groundnut landrace selections used in this study were able to adapt to limited water availability under rainfed conditions by closing their stomata. The fact that stomatal conductance was lower under rainfed relative to irrigated conditions implies that bambara groundnut landraces demonstrated a degree of stomatal control hence regulation of transpirational losses. Stomatal closure is widely thought to be a plant's first line of defence in response to developing water stress (Mansfield and Atkinson 1990, Cornic and Massacci 1996). Similar observations of stomatal regulation in bambara groundnut were reported by Collinson *et al*. (1997). They stated that drought tolerance in bambara groundnuts may be due to greater stomatal regulation which is a drought avoidance mechanism. Recently, Jørgensen *et al*. (2010) observed stomatal closure in two bambara groundnut landraces from two diverse locations in Africa. They also concluded that stomatal closure in bambara groundnut was an important strategy for survival during intermittent stress.

In addition to reducing transpiration, stomatal closure also decreases flow of CO_2 into leaves, followed by a parallel decline in net photosynthesis, ultimately resulting in reduced plant growth. Decreased CO_2 availability necessitates a down-regulation of photosynthesis. This involves lowering the levels of photosynthetic pigments, chiefly – chlorophyll. Results of this study showed that chlorophyll content was lower in rainfed plants relative to irrigated plants. Chlorophyll content of 'Brown', 'Red' and 'Light-brown' landrace selections was respectively 29%, 25% and 20% lower under rainfed than irrigated conditions. 'Brown' and 'Red' landrace selections were therefore shown to be able to reduce chlorophyll content better than the 'Light-brown' landrace selection. Reduction in chlorophyll content, results in less energy captured for photosynthesis. If this down-regulation was not to occur, the plant would have more energy than required to fix CO_2 resulting in increased levels of free radicals which would in turn damage the chloroplast membranes (Chaves & Oliveira 2004). As such, bambara groundnut landraces demonstrated an ability to down-regulate photosynthesis in line with reduced CO_2 availability caused by stomatal closure. Several experiments conducted on barley (Anjum *et al*. 2003) and sunflower (Kiani *et al*. 2008, Farooq *et al*. 2009) showed that water stress decreased chlorophyll content. Rainfed production led to lower plant height, leaf number and LAI relative to irrigated conditions. On average, irrigated plants were shown to have taller plants, greater leaf number and LAI relative to rainfed plants. Although there was much variability within and between landrace selections, 'Brown' and 'Red' bambara groundnut landrace selections responded to rainfed production by reducing their canopy size as defined by plant height, leaf number and LAI. Canopy size results during 2010/11 showed no differences between water treatments in the field trials due to a favourable rainfall season; however, there were differences during 2011/12 when rainfall was below the long-term average. The lower plant growth observed under rainfed conditions may have been due to reduced photosynthesis emanating from reduced CO_2 assimilation and fixation due to stomatal closure and reduced chlorophyll in the leaves. Plants, by nature, are designed to reduce water use when confronted with water stress (Blum 2005). Reduced plant height, leaf area and LAI constitute this adaptation aimed at minimising water loss under drought stress (Mitchell *et al*. 1998). Similar results showing reduction in plant height, leaf number and LAI were found in the literature (Collinson *et al*. 1996, 1997, 1999, Sesay *et al*. 2004, Mwale *et al*. 2007, Vurayai *et al*. 2011a, 2011b, Berchie *et al*. 2012).

Results of biomass accumulation and final biomass showed that, despite much variability between the landrace selections, there was a trend of declining biomass under rainfed relative to irrigated conditions. Such a trend was consistent with the trend observed for stomatal conductance, chlorophyll content and plant growth parameters. The combination of reduced CO_2 assimilation, low chlorophyll content and a smaller canopy size ultimately meant that bambara groundnut landrace selections produced less biomass under rainfed relative to irrigated conditions. This explains why researchers have previously ascribed stomatal limitations to photosynthesis as the chief yield limiting factor under conditions of limited water availability (Cornic & Massacci 1996, Chaves *et al*. 2002, 2003, Yokota *et al*. 2002). Blum (2005) stated that drought avoidance mechanisms had the down side of reduced biomass production. This is because in order for the plant to avoid drought, it would require to minimise water losses through stomatal closure and reduced canopy size, both of which ultimately reduce the amount of biomass produced by the plant.

Another important plant response to water limited conditions is the timing and duration of key phenological events such as flowering. In the current study, results of crop phenology showed clear responses, with regards to bambara groundnut landrace selections' responses to rainfed production. Under rainfed conditions, bambara groundnut landrace selections flowered much earlier, had a shorter flowering duration, and matured earlier relative to irrigated conditions. This trend was more lucid during the 2011/12 season which was a dry season. In the case of the 'Brown' and 'Light-brown' landrace selections, these observations may have been due to enhanced leaf senescence under rainfed conditions. Although the 'Red' landrace selection flowered early, it was shown to senesce later, compared with the 'Brown' and 'Light-brown' landrace selections; this phenomenon may also suggest delayed leaf senescence in the 'Red' landrace selection. Odindo (2007) also observed delayed leaf senescence in water stressed cowpeas. Blum (2005) stated that early flowering, partly due to reduced growth duration (leaf number and area), was a major mechanism for moderating water loss under drought stress. Early flowering has been classified as a drought escape mechanism (Araus *et al.* 2002). However, a crop that escapes drought cannot attain maximum yield under water stress (Blum 2005) due to reduced crop duration.

Results for measured yield components HI, pod mass, pod number per plant and yield showed much variability within landraces over the two seasons. Harvest index was lower under rainfed relative to irrigated conditions; this was due to corresponding low pod number and mass as well as total biomass under rainfed conditions. This resulted in yield losses of, on average, 50% for all landraces under rainfed conditions during 2010/11. Nonetheless, the 'Red' landrace selection consistently performed well under all conditions and hence may be described as the most stable of the three seed colour selections. The seemingly better performance of the 'Red' landrace selection may be linked to its ability to regulate stomatal closure, moderate reductions in chlorophyll content and phenological plasticity. Of the three landrace selections, the 'Red' landrace selection showed delayed leaf senescence under rainfed production, an adaptation that allowed it to have a longer flowering duration and build-up of harvest index. Blum (2005) stated that crops that avoided drought through stomatal regulation, reduced plant size, LAI, and growth duration due to early flowering, did so at the expense of attaining high yields. Jaleel *et al.* (2009) stated that crops showed variation in yield under stress while Jørgensen *et al.* (2011) noted that the variability that exists within bambara groundnut landraces necessitated the need for more research on drought tolerance. Such variability may be a reason for low yields and may explain why farmers do not cultivate bambara groundnut extensively. Our results or reduced yield under rainfed conditions concur with other reports in the literature where limited water availability was shown to reduce yield of bambara groundnuts (Mwale *et al.* 2007, Sinefu 2011, Vurayai *et al.*

2011b). In addition, values of HI observed in this study for the 'Red' and 'Brown' landrace selections were similar to those reported by Mwale *et al*. (2007).

Pod number, pod mass and HI, respectively, were shown to contribute significantly to yield attainment or loss. Bambara groundnut landrace selections yielded significantly better under rainfed conditions during 2011/12 which was a drier season compared to 2010/11. The above average rainfall received during 2010/11 may have resulted in periods of intermittent water logging. Since bambara groundnut is sensitive to water logging (Swanevelder, 1998), this could have resulted in yield losses during 2010/11. These results agree with reports in the literature that bambara groundnut is drought tolerant and will give reasonable yield under drought stress (Harris & Azam-Ali 1993).

9.5 Conclusion

Bambara groundnut demonstrated drought avoidance and escape mechanisms under rainfed cultivation compared with irrigated conditions. Bambara groundnut avoided drought by minimising water losses through stomatal closure, reducing plant height, leaf number and LAI in response to reduced water availability under rainfed conditions. Chlorophyll content index proved to be a useful index for evaluating crop responses to reduced water availability under rainfed conditions. It was lower under rainfed conditions relative to irrigated conditions, at least earlier in the season. However, CCI was only observed during 2011/12 hence more research is necessary on this trait. Flowering was hastened, the duration of flowering was shortened, leaf senescence started sooner, and crop duration, as shown by days to maturity, was shortened under rainfed conditions relative to irrigated conditions. Thus bambara groundnut shows a degree of phenological plasticity in response to drought. Biomass, harvest index and seed yield were all lower under rainfed conditions relative to irrigated conditions. 'Red' and 'Brown' landrace selections showed better resilience to drought stress compared with the 'Light-brown' landrace selection. While seed coat colour does not imply genotypic differences, it may be used a selection criterion for identifying bambara groundnut landraces with potential for water stress tolerance.

Chapter 10

Water-use of bambara groundnut (*Vigna subterranea* L. Verdc) landraces

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10.1 Introduction

Bambara groundnut is an African indigenous legume that has been cultivated for centuries in sub-Saharan Africa, mainly the semi-arid regions, and has in the past contributed to the food security (Swanevelder, 1998; FAO, 2001; Azam-Ali *et al*., 2001; Mwale *et al*., 2007a). Traditionally, it was cultivated in extreme, tropical environments by small-scale farmers without access to irrigation and/or fertilisers and with little guidance on improved practices. It is mainly grown by women for the sustenance of their families (Mukurumbira, 1985; Mwale *et al.,* 2007a). It has been reported to contain 17-25% protein, 42-65% carbohydrate and 6% lipid (Aykroyd & Doughty, 1982; Linnemann & Azam-Ali, 1993; Mwale *et al*., 2007a). However, germplasm improvement and management practices have mainly relied on local experience and resources (indigenous knowledge) (Mukurumbira, 1985). Consequently, the crop remains underutilised and is still mainly cultivated from landraces of which very little is known about their growth, yield and water-use responses under water stress conditions.

There are very few reports in the literature describing water-use efficiency of bambara groundnut. The growth responses of bambara groundnut to water stress have been described in several instances, using growth indices such as plant height, leaf area index and total dry matter (Collinson *et al*., 1996, 1997, 1999; Mwale *et al*., 2007; Vurayai *et al*., 2011a, 2011b). However, most of this research has been done under controlled environments (Sesay *et al*., 2010) and field conditions whereby quantifying water was not the major objective. Water use efficiency has often been equated to high yield potential under optimum and stressful conditions (Blum, 2005). Reduced plant canopy size and early maturity are often associated with increased water use efficiency and better drought tolerance. Therefore, the objective of the current study was to evaluate growth, development, yield and water-use efficiency of local a bambara groundnut landrace characterised according to seed coat colour under water stress under rain shelter conditions.

10.2 Materials and Methods

10.2.1 Plant material

Fresh seeds of local bambara groundnut landraces were collected from subsistence farmers in Jozini (27°26'S; 32°4'E), northern KwaZulu-Natal, South Africa in 2010. The same seed lot was used for both seasons during which the trials were conducted. Seeds were characterised according to seed coat colour and sorted into three distinct seed coat colours: 'Red', 'Brown' and 'Light brown'. Seed characterisation according to seed colour was based on the hypothesis that dark coloured seeds tend to be more vigorous than light coloured seeds and may thus be more drought tolerant compared with light coloured seeds (Mabhaudhi & Modi, 2010, 2011; Mbatha & Modi, 2010; Zulu & Modi, 2010).

10.2.2 Site descriptions

Trials were planted at Roodeplaat, Pretoria (25º60´S; 28º35´E) during the summer seasons of 2010/11 and 2011/12. Soils in the rain shelters were classified as loamy sand (South African taxonomic system). Soil physical characteristics were used to generate parameters for amount of water available at field capacity (FC), permanent wilting point (PWP), and saturation (SAT), as well as the saturated hydraulic conductivity using the Soil Water Characteristics Hydraulic Properties Calculator (http://hydrolab.arsusda.gov/soilwater/Index.htm). Daily maximum and minimum temperature averages are 34℃ and 8℃ in summer (November-April) (Agricultural Research Council – Institute of Soil, Climate and Weather). Rainfall was excluded since the rain shelters are designed to close when rainfall starts.

10.2.3 Experimental designs

The experimental design was a factorial experiment arranged in a completely randomised block design; individual plot size in the rain shelter was 6 m^2, with plant spacing of 0.3 m x 0.3 m. There were two factors: irrigation level and seed colour, replicated four times. During the

2010/11 season, only two seed colours, 'Brown' and 'Red', were used in the rain shelter experiments. However, in the subsequent season, 2011/12, all three colours ('Brown', 'Red' and 'Light-brown') were used. There were three irrigation levels 30%, 60% and 100% of crop water requirement (ET_a) calculated using reference evapotranspiration (ET_o) and a crop factor (K_c) as described by Allen *et al*. (1996):

$$ETa = ET_o*K_c$$

where, ETa = crop water requirement

ET_o = reference evapotranspiration, and

K_c = crop factor.

10.2.4 Irrigation

Drip irrigation was used to apply water in the rain shelter. The system consisted of a pump, filters, solenoid valves, water meters, control box, online drippers, 200 litre JOJO tank, main line, sub-main lines and laterals. The system was designed to allow for a maximum operating pressure of 200 kPa with average discharge of 2 l/hour per emitter. Drip lines were spaced according to the plant spacing (0.3 m x 0.3 m). A black 200 µm thick polyethylene sheet was trenched at a depth of 1 m to separate the plots in order to prevent water seepage and lateral movement of water between plots. Irrigation scheduling was based on reference evapotranspiration (ET_o) and a crop factor (K_c).

10.2.5 Data collection

Plant measurements: Parameters determined weekly were emergence [up to 35 days after planting (DAP)], plant height, leaf number, leaf area index (LAI), stomatal conductance (SC), chlorophyll content (CC) and days to flowering (DTF). At the end of the season, biomass and yield were determined. Whereas data for growth parameters were collected weekly from 35 DAP, destructive sampling was performed biweekly to determine dry mass. Leaf area index was measured using the LAI2200 Canopy Analyser (Li-Cor, USA & Canada). Stomatal conductance was measured using a steady state leaf porometer (Model SC-1, Decagon Devices, USA). Chlorophyll content was measured using a Chlorophyll content meter (CCM-200 *PLUS*, Opti-Sciences, USA); CC data were only measured during the 2011/12 season.

Soil water content (SWC): during the 2010/11 season, a neutron water meter was used to determine SWC at soil depths of 20, 40, 60, 80 and 100 cm, at weekly intervals. Wet and dry spot readings were determined, together with their corresponding volumetric water contents in order to obtain a best-fit regression equation (Campbell and Mulla, 1990). The equation was then used to develop a spreadsheet for the conversion of neutron probe readings to corresponding volumetric SWC readings. During the 2011/12 season, ML-2X Theta Probes connected to a DL-6 data logger (Delta-T Devices, UK) were used to monitor SWC in the rain shelters at varying depths. The frequency of data collection for SWC using the Theta probes was every 4 hours.
Water-use efficiency (WUE): water-use efficiency for the crop was determined as follows:

$$WUE = \frac{Biomass}{ET_a}$$

where: WUE = water-use efficiency, and
ETa = crop water requirement.

10.2.6 Agronomic practices

Prior to planting, soil samples were obtained from the rain shelter for determination of soil fertility and texture. Based on soil fertility results, an organic fertiliser, Gromor Accelerator® was applied at planting to meet crop nutritional requirements (Swanevelder, 1998). Routine weeding and ridging were done by hand.

10.2.7 Data analysis

Analysis of variance (ANOVA) was used to statistically analyse data using GenStat® (Version 14, VSN International, UK). Least significant difference (LSD) was used to separate means at the 5% level of significance.

10.3 Results and discussion

During the 2010/11 season, results of emergence showed significant differences ($P < 0.05$) between the ‘Red’ and ‘Brown’ landraces, with ‘Red’ emerging better than ‘Brown’ (data not shown because only two landrace selections were used). During the 2011/12 season, results showed highly significant differences (P < 0.001) between landraces, with 'Brown' and 'Red' having higher and faster emergence compared with the 'Light-brown' landrace (Figure 10.1). These results suggest a possible effect of seed colour on vigour. Over-all, for both seasons, time to 90% emergence was generally achieved 28 days after sowing, indicating that bambara groundnut landraces are slow to establish as reported by Sinefu (2011). Successful crop establishment is critical under water limited conditions; Blum (2009) stated that during crop establishment a significant amount of total available water is lost through soil evaporation not transpiration. Therefore, a significant amount of water is probably lost due to soil evaporation with this slow establishment in bambara groundnut. Researchers in Australia, working on wheat, found that about 40% of total available water was lost to soil evaporation at establishment stage (French & Schultz, 1984; Siddique *et al*., 1990). Vigorous seedling growth is thus essential in establishing canopy cover and reducing water losses to evaporation; this is now a part of an Australian wheat breeding program (Rebetzke & Richards, 1999).

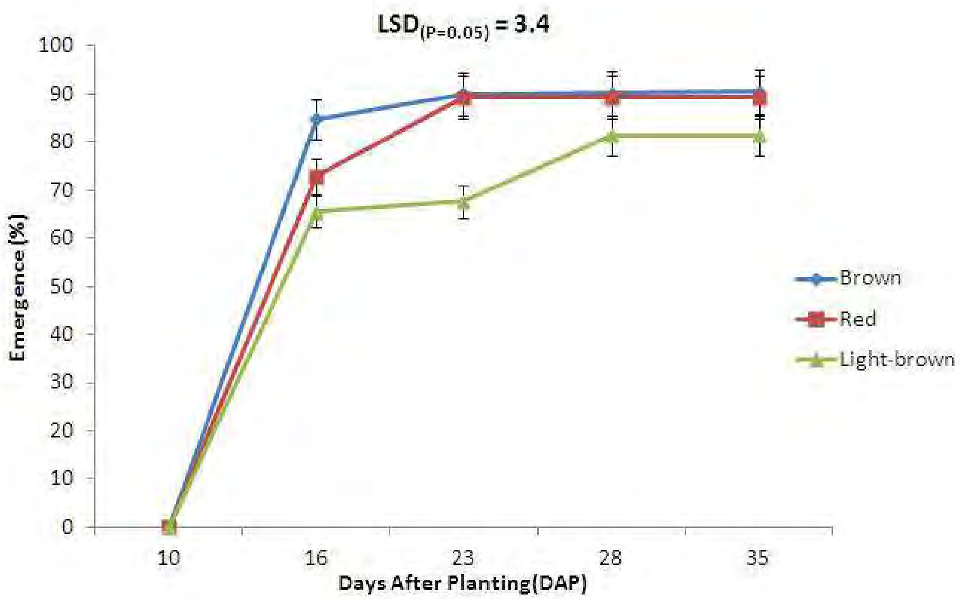

Figure 10.1: Emergence of bambara groundnut landraces ('Brown', 'Red' and 'Light brown') under rainshelter conditions during 2011/12 planting season.

Closure of stomata reduces transpirational losses, thus minimising water losses through transpiration while also lowering photosynthesis. Results of stomatal conductance (SC) were only collected during the 2011/12 planting season. The results showed highly significant differences

(P < 0.001) between water regimes as well as significant differences (P < 0.05) between landraces (Figure 10.2). The trend showed that SC decreased with increasing water stress (Figure 10.2). 'Red' and 'Brown' landraces showed the greatest decrease in response to water stress compared with the 'Light-brown' landrace (Figure 10.2), demonstrating greater stomatal regulation in response to water stress. Stomatal closure is a plant's initial response to declining soil water content and has been characterised as a drought avoidance mechanism (Farooq *et al.*, 2009) as well as being a characteristic of increased water use efficiency under drought stress (Blum, 2005, 2009). It has previously been suggested as a component of bambara groundnut's drought resistance mechanisms by Collinson *et al.* (1997). However, Blum (2005, 2009) argued that stomatal closure is a negative response to water stress in that it reduces CO_2 availability leading to yield reduction under water stress.

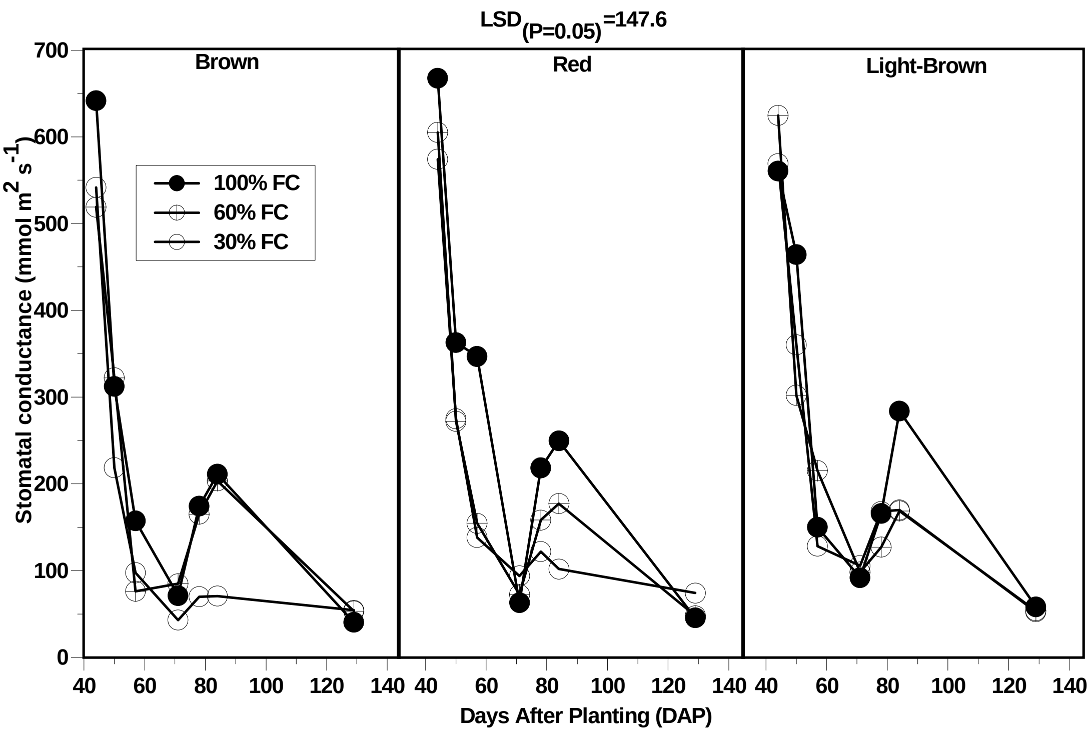

Figure 10.2: Stomatal conductance (mmol m^{-2} s^{-1}) of bambara groundnut landraces ('Brown', 'Red' and 'Light brown') grown under a rainshelter during the 2011/12 planting season.

Reduction in intracellular CO_2, due to stomatal closure, results in reduced substrate availability for photosynthesis. Therefore, there is need to down-regulate photosynthesis in line with reduced substrate availability. In this regard, chlorophyll content has been reported to decrease in water stressed plants (Farooq *et al*., 2009), for example, in barley (Anjum *et al*., 2003) and sunflower (Kiani *et al*., 2008). Results of chlorophyll content index were only collected during the 2011/12 planting season. There were no significant differences ($P > 0.05$) between landraces, water regimes as well as their interaction (Figure 10.3); suggesting that chlorophyll content in bambara groundnut landraces was not sensitive to water stress. Interestingly, with the exception of the 'Light-brown' landrace, 'Red' and 'Brown' had higher CCI at 30% ETa relative to 60% ETa, whilst all landraces had highest CCI at 100% CCI (Figure 10.3). These results once again showed the variability that exists within landraces, with respect to responses to water stress.

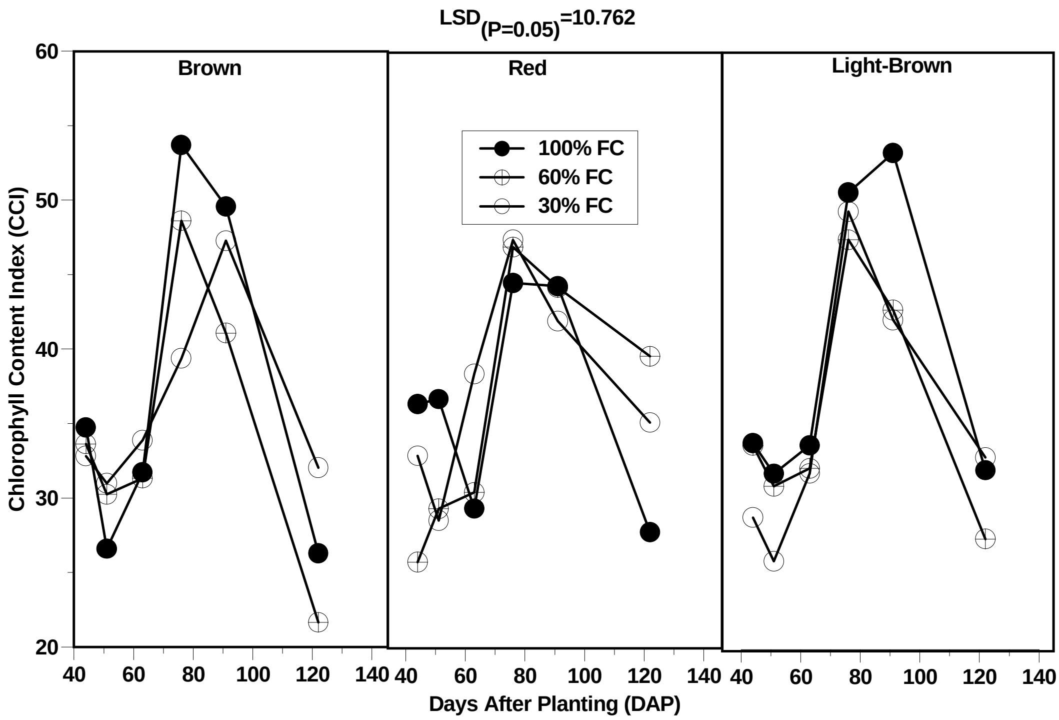

Figure 10.3: Chlorophyll content index (CCI) of bambara groundnut landraces ('Brown', 'Red' and 'Light brown') grown under a rainshelter during the 2011/12 planting season.

Results of plant height and leaf number during 2010/11 and 2011/12 were variable (Figures 10.4 & 10.5), with respect to differences between water regimes and landraces. In the 2011/12 season, the 'Light-brown' landrace performed better than the 'Brown' and 'Red' landraces, respectively. There was a trend, for both seasons, of decreasing plant height and leaf number in response to increasing water stress. The lowest values of plant height and leaf number were observed in the 30% ETa treatment, followed by 60% and 100% ETa, respectively. The 'Red' landrace was shown to have the greatest decrease in plant height and leaf number under water stress compared with 'Light-brown' and 'Brown' (Figures 10.4 & 10.5).

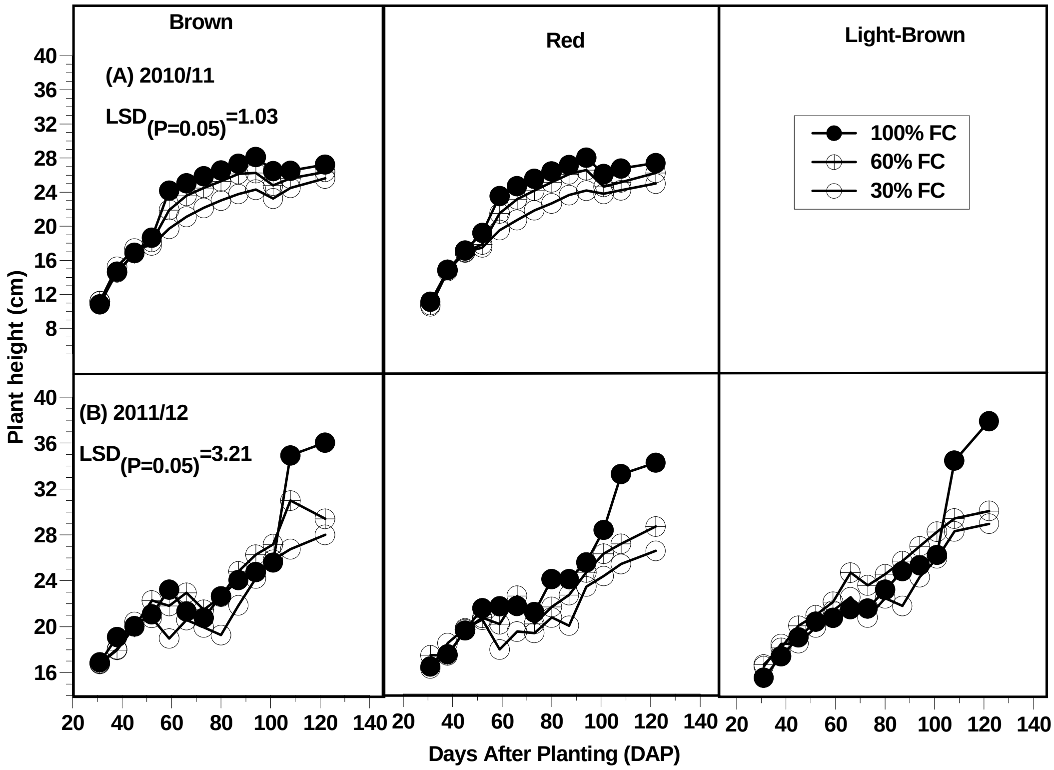

Figure 10.4: Plant height (cm) of bambara groundnut landraces ('Brown', 'Red' and 'Light brown') grown under grown under a rainshelter during 2010/11 and 2011/12 planting seasons.

With respect to LAI, for both seasons, there were no differences (P > 0.05) between landraces, although the trend (2011/12) showed that 'Brown' and 'Red' performed better than 'Light-brown' (Figure 10.6). For both seasons, results showed a decrease in LAI in response to increasing water stress; LAI was lowest at 30% ETa compared with 60% and 100% ETa, respectively, which were statistically similar (Figure 10.6). The reduction in LAI in response to water stress was assumed to be due to a corresponding reduction in plant height and leaf number (Figures 10.4 & 10.5).

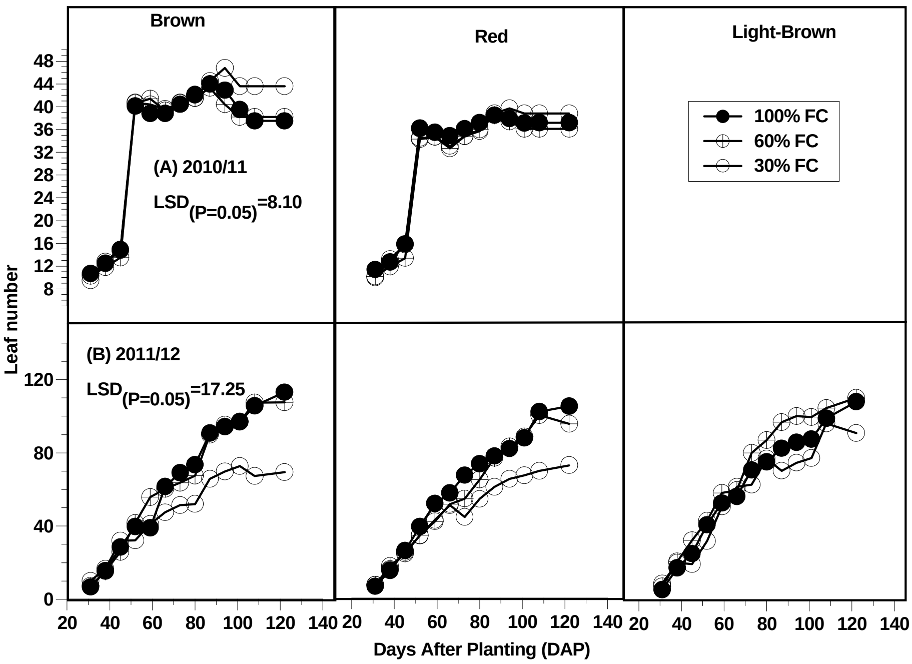

Figure 10.5: Leaf number of bambara groundnut landraces ('Brown', 'Red' and 'Light brown') grown under grown under a rainshelter during 2010/11 and 2011/12 planting seasons.

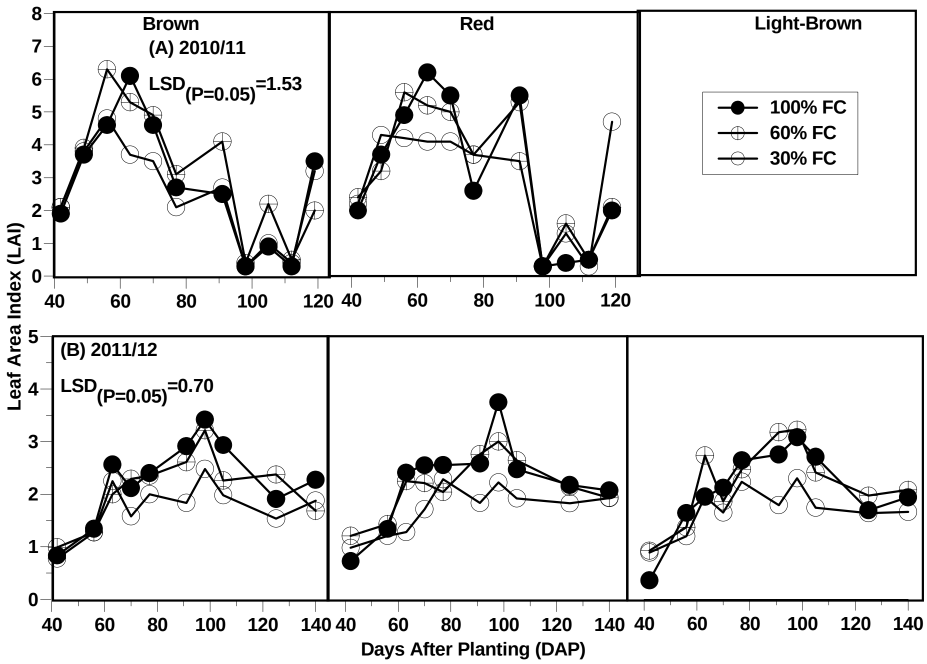

Figure 10.6: Leaf area index of bambara groundnut landraces ('Brown', 'Red' and 'Light brown') grown under a rainshelter during the 2010/11 and 2011/12 planting seasons.

The growth responses of bambara groundnut to water stress have previously been described using similar growth indices of plant height, leaf number and leaf area index (Collinson *et al*., 1996, 1997, 1999; Mwale *et al*., 2007; Vurayai *et al*., 2011a, 2011b). There was consensus among the researchers that drought tolerance in bambara groundnut involved reduction in these growth indices. Reduced plant height, leaf number and LAI are mechanisms of reducing plant water use in response to decreasing soil water availability (Mitchell, 1998). Reduced canopy size is also responsible for increased water use-efficiency, although this often occurs at the expense of yield potential (Blum, 2005).

Results of crop phenology were observed during the 2011/12 planting season when all three landraces were planted. With the exception of time to flowering, all other phenological stages showed highly significant differences ($P < 0.001$) between water regimes but no differences ($P > 0.05$) between landraces (Table 10.1). For all phenological events observed, mean separation showed that 60% and 100% ETa were statistically similar, but significantly different from 30% ETa (Table 10.1). Bambara groundnut landraces were shown to flower early, have a reduced flowering duration and mature early in response to decreasing soil water availability (Table 10.1). Water stress reduced the vegetative stage of bambara groundnut; landraces flowered earlier at 30% ETa compared with 60% and 100% ETa, respectively (Table 10.1).

Since bambara groundnut landraces took long to establish (Figure 10.1), this effectively resulted in a shortened vegetative period which may also be linked to reduced plant height and leaf number under water limited conditions (Figures 10.4 & 10.5). In addition, water stress reduced the reproductive stage; decreased water availability resulted in shortened flowering duration or reproductive period at 30% ETa compared with 60% and 100% ETa, respectively (Table 10.1). Furthermore, water stress reduced the overall length of bambara groundnut landraces' crop cycle through early leaf senescence and subsequently early maturity (Table 10.1). With respect to landraces, 'Brown' and 'Red' landraces showed a consistent trend in flowering and maturing early in response to limited water availability compared with 'Light-brown'. However, 'Red' had a longer reproductive period compared with 'Brown' and 'Light-brown', respectively; this was due to delayed leaf senescence in the 'Red' landrace (Table 10.1).

Table 10.1: Phenological stages of bambara groundnut landraces ('Brown', 'Red' and 'Light-brown') in response to three water regimes (30%, 60% and 100% ETa) during 2011/12 planting season.

Water Regime ([x]ETa)	Landrace	Flowering (DAP)	Flowering duration (Days)	Leaf senescence (DAP)	Maturity (DAP)
30%	Brown	61.00ab	35.00d	96.0b	119.8b
	Red	59.75b	42.00cd	101.8b	122.0b
	Light-brown	64.50ab	48.75abc	113.3a	126.5a
	Mean	**61.75[b]**	**41.9[b]**	**103.7[b]**	**122.75[b]**
60%	Brown	65.25ab	53.75ab	119.0a	128.0a
	Red	60.50ab	58.50a	119.0a	128.0a
	Light-brown	67.25a	46.00bc	113.2a	126.5a
	Mean	**64.33[a]**	**52.8[a]**	**117.1[a]**	**127.50[a]**
100%	Brown	65.75ab	53.25ab	119.0a	128.0a
	Red	65.25ab	53.75ab	119.0a	128.0a
	Light-brown	64.50ab	54.50ab	119.0a	128.0a
	Mean	**65.75[a]**	**53.8[a]**	**119.0[a]**	**128.00[a]**
$LSD_{(P=0.05)}$ Water regime		3.73	5.72	5.52	1.74
$LSD_{(P=0.05)}$ Landrace		3.73	5.72	5.52	1.74
$LSD_{(P=0.05)}$ Water*Landrace		6.46	9.90	9.55	3.01

[x]ETa = crop water requirement. Values in the same column not sharing the same letter differ significantly at LSD (P=0.05). DAP = Days after planting.

Early flowering, due to reduced vegetative growth (leaf number and area) is a major mechanism for moderating water loss under drought stress (Blum, 2005). According to Araus *et al*. (2002), early flowering in response to limited water availability, is a drought escape mechanism. This is equally true for reduced flowering duration, with the objective being to reproduce before water stress becomes terminal. Selection for high water use efficiency under limited water supply has tended to be biased towards plants that flower early and maintain a smaller canopy size (Blum, 2005, 2009). Hence, by definition, bambara groundnut landraces may be suitable for production under dryland conditions that require plants with a small canopy, moderated growth and short growth duration under water limited conditions.

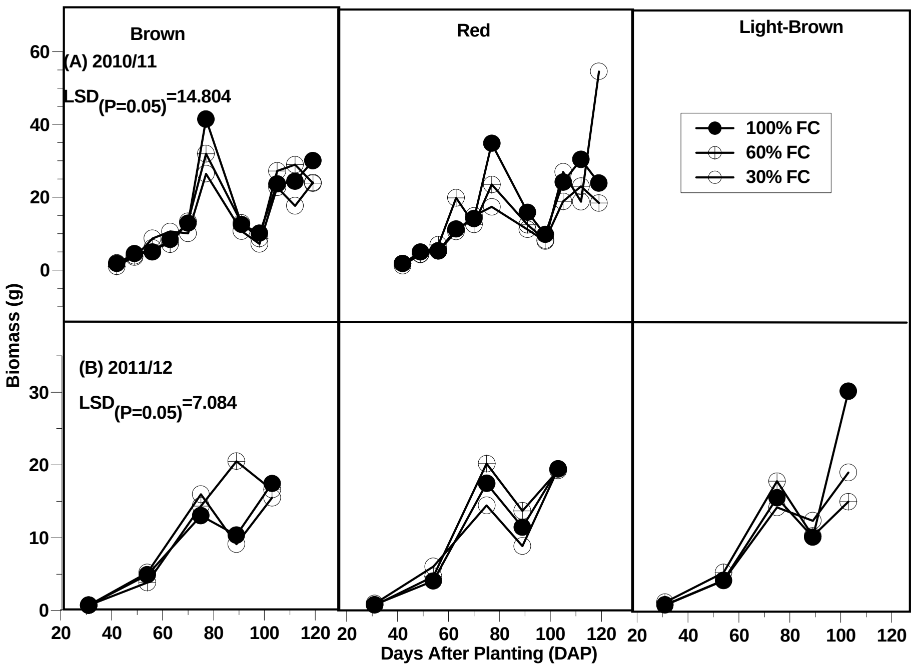

Figure 10.7: Biomass accumulation (per plant per dry matter basis) of bambara groundnut landraces (‘Brown’, ‘Red’ and ‘Light brown’) grown under a rainshelter during the 2010/11 and 2011/12 planting seasons.

Biomass accumulation, over time, for both seasons, showed no significant differences ($P > 0.05$) between water regimes as well as between landraces (Figure 10.7). However, closer inspection of results showed a trend of biomass decreasing with increasing water stress (Figure 10.7); although there was variability between landraces. During 2010/11, this observation was clear at 112 DAP, which also corresponded with the vegetative peak of the plants (Figure 10.7).

Table 10.2: Yield components of bambara groundnut landraces ('Brown' and 'Red') in response to three water regimes (30%, 60% and 100% ETa) during 2010/11 season.

Water Regime (^{x}ETa)	**Landrace**	**HI* (%)**	**Pod Mass (g)**	**^{x}Pod No. (plant^{-1})**	**Biomass (t.ha^{-1})**	**Yield (t.ha^{-1})**	**^{y}WUE (kg.m^{-3})**
30%	Brown	10.55c	2.293b	2b	3.259a	0.114c	0.262a
	Red	15.04bc	1.900b	3b	2.315a	0.215bc	0.186a
	Mean	**12.80^{c}**	**2.10^{c}**	**3^{c}**	**2.79^{b}**	**0.16^{b}**	**0.224^{a}**
60%	Brown	18.39bc	3.893b	8b	4.176a	1.078bc	0.255a
	Red	14.65bc	3.180b	7b	3.886a	1.125b	0.237a
	Mean	**16.50^{bc}**	**3.54^{b}**	**7^{b}**	**4.03^{a}**	**1.10^{b}**	**0.246^{a}**
100%	Brown	51.83a	8.883a	17a	3.062a	2.701a	0.139a
	Red	27.12b	7.712a	15a	5.011a	2.486a	0.233a
	Mean	**39.30^{a}**	**8.30^{a}**	**16^{a}**	**4.04^{a}**	**2.59^{a}**	**0.186^{a}**
Yield correlation (r)		0.295	0.649	0.869	0.943	-------	-------
$LSD_{(P=0.05)}$ Water regime		10.48	1.946	4	1.906	0.652	0.116
$LSD_{(P=0.05)}$ Landrace		8.55	1.589	4	1.556	0.533	0.095
$LSD_{(P=0.05)}$ Land*Treat		14.82	2.752	6	2.696	0.923	0.164

^{x}ETa = crop water requirement. *HI = harvest index; ^{x}Pod number values were rounded off to the nearest integer since pod number represents discrete data; ^{y}WUE = water use efficiency. Values in the same column not sharing the same letter differ significantly at LSD (P=0.05).

Crop yield during 2010/11 showed a clearer trend, with regards to differences between water regimes (Table 10.2). With the exception of final biomass, all other parameters measured showed highly significant differences ($P < 0.001$) between water regimes; there were no differences ($P > 0.05$) between the two landraces ('Brown' and 'Red') for all yield components. The results showed a trend of decline in HI, pod mass, pod number, biomass and grain yield in response to water stress. Correlations of the data showed that HI ($r = 0.649$), pod mass ($r = 0.869$) and pod number ($r = 0.943$) contributed significantly to yield. Consequently, reduction in yield under stress was due to decreased HI, pod mass and number (Table 10.2).

Table 10.3: Yield components of bambara groundnut landraces ('Brown', 'Red' and 'Light-brown') in response to three water regimes (30%, 60% and 100% ETa) during 2011/12 planting season.

Water Regime ([x]ETa)	Landrace	HI* (%)	Pod Mass (g)	[x]Pod No. ($plant^{-1}$)	Biomass ($t.ha^{-1}$)	Yield ($t.ha^{-1}$)	[y]WUE ($kg.m^{-3}$)
30%	Brown	15.7a	4.914bc	7ab	5.414c	0.362b	0.114ab
	Red	12.26ab	5.361bc	8ab	7.414bc	0.348b	0.144a
	Light-brown	14.39ab	6.446bc	10ab	7.856abc	0.652ab	0.093b
	Mean	**14.02[a]**	**5.57[a]**	**8.46[a]**	**6.91[b]**	**0.45[a]**	**0.120[a]**
60%	Brown	12.30ab	6.015bc	8ab	8.550abc	0.623ab	0.096b
	Red	11.63ab	6.084bc	8ab	8.612abc	0.319b	0.118ab
	Light-brown	15.34ab	8.761ab	11ab	9.468ab	0.712ab	0.129ab
	Mean	**13.09[a]**	**6.95[a]**	**9.02[a]**	**8.88[ab]**	**0.55[a]**	**0.110[ab]**
100%	Brown	7.82b	4.214c	5ab	8.757abc	0.419b	0.110ab
	Red	9.81ab	4.549bc	7ab	8.107abc	0.518b	0.097b
	Light-brown	15.99a	10.699a	13a	11.054a	1.013a	0.107ab
	Mean	**11.21[a]**	**6.49[a]**	**8.49[a]**	**9.31[a]**	**0.65[a]**	**0.100[b]**
Yield correlation (r)		0.541	0.592	0.853	0.697	-----	-----
$LSD_{(P=0.05)}$ Water regime		3.938	2.188	3.645	1.715	0.214	0.021
$LSD_{(P=0.05)}$ Landrace		3.938	2.188	3.645	1.715	0.214	0.021
$LSD_{(P=0.05)}$ Land*Water		6.821	3.790	6.313	2.970	0.370	0.037

[x]ETa = crop water requirement. *HI = harvest index; [x]Pod number values were rounded off to the nearest integer since pod number represents discrete data; [y]WUE = water use efficiency. Values in the same column not sharing the same letter differ significantly at LSD (P=0.05).

Yield results from 2011/12 were contrary to the trend observed during 2010/11 (Table 10.3). With the exception of biomass, all other yield components showed no differences ($P > 0.05$) between landraces and water regimes; there was also no clear trend in response to water stress. Only final biomass was significantly ($P < 0.05$) affected by water stress, with biomass decreasing in response to 60% ETa and 30% ETa, respectively (Table 10.3). Yields achieved during the 2011/12 planting season were also significantly lower than yields achieved in the previous season. Although correlations showed a similar trend as in the previous season, they were lower than those reported for 2010/11; suggesting overall poor crop performance during 2011/12.

Results of yield, for both planting seasons, showed that pod yield (pod number and mass) was the greatest influence to seed mass or yield. Even though bambara groundnut has been reported to be drought tolerant, water stress was still able to affect yield. These results are similar to other reports in the literature (e.g. Babiker, 1989; Berchie *et al.*, 2010; Berchie *et al.*, 2012) who all reported reduced seed yield in bambara groundnut landraces in response to limited water availability. In this study, reduced seed yield, through reduced pod mass and number, may be related to a shorter flowering duration, which limited pod number, while low pod mass may be linked to earlier senescence which affected pod filling. This was also observed in the number of empty pods. However, what is noteworthy is bambara groundnut's ability to still produce yield even under severe water stress (30 % ETa). According to Berchie *et al*. (2012), this confirms bambara groundnut's resilience under drought stress and further justifies the need for more research on the crop, with a view to promoting it as a food security crop.

Results of water use efficiency (WUE) showed no (significant) differences ($P > 0.05$) between water regimes as well as between landraces for both planting seasons (Tables 10.2 & 10.3). During the 2010/11 planting season, WUE was highest at 60% and 30% ETa, respectively, compared with 100% ETa, suggesting that WUE increased in response to limited water availability. The lack of clear differences between treatments during 2010/11 was due to the numerator – biomass, which also showed a trend of no differences between treatments (Table 10.2). However, during the 2011/12 planting season, the observed trend showed WUE increasing with decreasing water availability. Water use efficiency was highest in the 30% ETa treatment, followed by 60% and 100%, respectively; mean separation showed that WUE at 30% ETa was significantly higher than at 100% ETa but similar to the 60% ETa water regime. This was in line with the trend observed for final biomass during the 2011/12 season (Table 10.3), suggesting that WUE was more influenced by biomass than water use.

High water use efficiency under limited water conditions is linked to reduced canopy size (plant height, leaf number, LAI), reduced transpirational losses (low stomatal conductance) as well as a shortened growth duration (Blum, 2005, 2009). While reduced canopy size and stomatal closure directly moderate water losses by the crop, reduced crop duration effectively reduces the amount of water applied to the crop. As such, in line with observed reductions in canopy size, stomatal conductance and crop duration, WUE increased in response to declining water availability. Our results of WUE, although slightly higher, were similar to those reported in a long running project on bambara groundnut (BAMFOOD), where it was found bambara groundnut's WUE is about 2.1 g mm^{-1} m^{-2}, a value which was comparable to that of other legumes (Azam-Ali *et al*., 2004). However, as argued by Blum (2005, 2009), increased WUE often occurs at the expense of yield potential.

10.4 Conclusion

This study showed that bambara groundnut landraces have some resilience to reduced water availability. Increased water use efficiency in bambara groundnut landraces in response to water stress was achieved through canopy size and crop duration adjustments. Limited water availability resulted in reduction in growth indices of plant height, leaf number and leaf area index, thus minimising water losses. In addition, bambara groundnut landraces were shown to respond to limited water availability through closure of stomata, thus reducing transpirational losses. Furthermore, imposition of stress resulted in early flowering, reduced flowering duration, early senescence and ultimately, early maturity. These responses are characteristic of drought avoidance and escape mechanisms. Water stress was shown to reduce seed yield through reduced pod number and mass, although bambara groundnut landraces were shown to be still productive under limited water conditions. While bambara groundnut landraces showed growth and phenological responses to water stress, slow establishment in bambara groundnut landraces may result in water losses through soil evaporation during the establishment stage. Lastly, although there was much variability between ‘Brown’, ‘Light-brown’ and ‘Red’ landraces, the trend showed that the darker coloured bambara groundnut landrace selections were more drought tolerant than the light-brown bambara groundnut landrace selection. This suggests that there is a possible association between seed coat colour and drought tolerance in bambara groundnut. Future studies should investigate the physiological basis for such an association.

Chapter 11

The FAO AquaCrop Model

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11.1 Introduction

The purpose of this chapter is to give a detailed model description of the FAO's AquaCrop model. A review on crop modelling, types of models and approaches to modelling as well as justification for selecting this model, has been given in Chapter 1. AquaCrop is a water-driven, canopy level, engineering (functional) type model whose primary focus is to simulate attainable crop biomass and yield in response to water (Steduto *et al*., 2012). The model is an evolution of Doorenbos and Kassam's (1979) initiative, published in FAO's Irrigation and Drainage Paper No.33. At the core of their paper was the following equation:

$$\left(\frac{Yx-Ya}{Yx}\right) = Ky\left(\frac{ETx-ETa}{ETx}\right) \quad \text{Equation 11.1}$$

where Yx = maximum yield

Ya = actual yield

ETx = maximum evapotranspiration

ETa = actual evapotranspiration, and

Ky = proportionality factor between relative yield loss and relative reduction in evapotranspiration.

The FAO's irrigation scheduling model CROPWAT (Smith, 1992) uses Eq. 11.1 to simulate yield under water deficit. In South Africa, SAPWAT (Crosby and Crosby, 1999) also uses this approach to calculate crop yields. The successes of both CROPWAT and SAPWAT, with regard to uptake by end-users, speak volumes about Eq. 11.1. In South Africa, SAPWAT, and now SAPWAT 3, have been fully adopted by the former Department of Water Affairs and Forestry (DWAFF) as a tool for determining irrigation water allocations in relation to licensing of agricultural water use (Singels *et al*., 2010). However, as progress in understanding plant water relations would dictate, and also due to the need for increased water productivity as a result of increasing water scarcity, the FAO had to upgrade Eq. 11.1. A decision was taken to develop a new crop model as an evolution from Doorenbos and Kassam (1979). The new model would remain water-driven, as well as retain the broad spectrum applicability of Eq. 11.1, while also making ground breaking improvements in accuracy and still maintaining the hallmark of a robust and simple model. It is to this end that FAO has developed AquaCrop (Raes *et al*., 2009; Steduto *et al*., 2009; Steduto *et al., 2012*).

According to Steduto *et al*. (2009) (Figure 11.1), the evolution lies in AquaCrop's capacity to:

I. separate ET into crop transpiration (Tr) and soil evaporation (E). Previously, in Eq. 11.1 these were combined and this caused challenges with regards to the unproductive use of water lost through E, especially during crop establishment when ground cover is still very low,

II. estimate Tr and E based on a simple canopy growth and decline model,

III. treat final yield (Y) as a function of biomass (B) and harvest index (HI), thus allowing for the distinction of functional relations between the environment and B, and between the environment and HI,

IV. segregate responses to water stress into four separate components –

   a. canopy growth
   b. canopy senescence
   c. Tr, and
   d. HI.

The above changes led to the equation at the core of AquaCrop:

$$B = WP \times \Sigma Tr \qquad \text{Equation 11.2}$$

Where, B = biomass,

WP = water productivity (biomass per unit of cumulative transpiration), and

Tr = crop transpiration.

Fundamental to Eq. 11.2 is the WP parameter which tends to be constant over different soils and climatic conditions as described by De Wit (1985), Hanks (1983) and Tanner and Sinclair (1983). In addition, normalization of WP for different climatic conditions further makes it a conservative parameter (Steduto *et al.,* 2007), implying greater applicability, robustness and transferability of the model between and among users in varying regions of the world. The other important improvement from Eq. 11.1 is that Eq. 11.22 can operate on a daily time step thus approaching the time scale of plant responses to water stresses (Acevedo *et al*., 1971), while Eq. 11.1 operated on a seasonal time scale.

There are, however, similarities between AquaCrop and other established models with regards to structure of the SPAC. As with other models, AquaCrop includes the soil (soil water balance), the plant and the atmosphere as structural components of the model (Steduto *et al*., 2009). The atmosphere and soil components bear similarities to other models. It is the relationship between the crop and soil components that distinguishes AquaCrop from other known models. Under its management component, there is particular emphasis on irrigation, with soil fertility also being considered to a limited extent. AquaCrop, however, does not consider other biotic factors such as pests and diseases (Steduto *et al*., 2009).

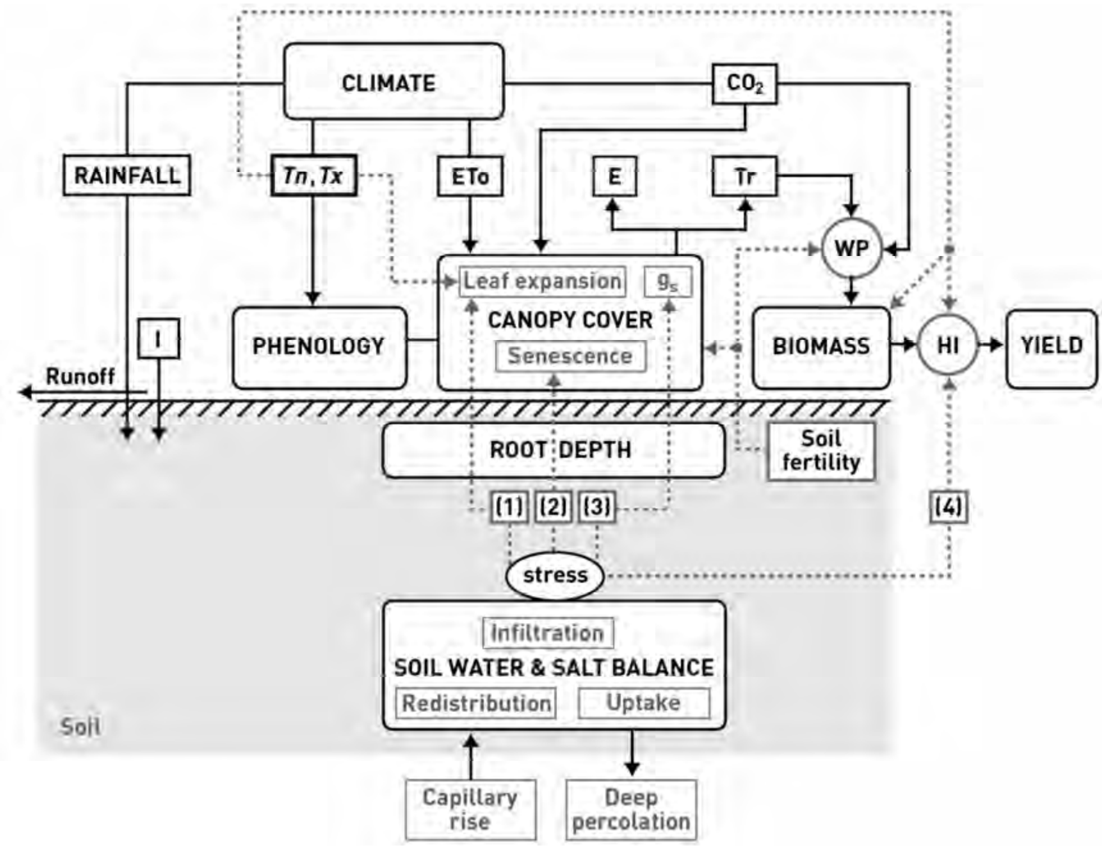

Figure 11.1: Flowchart of AquaCrop indicating the structural relationships in the SPAC (adapted from Raes *et al*., 2009).

AquaCrop models the crop based on five major components and their associated responses to water stress (Figure 11.1). These are, phenology/development, canopy cover, rooting depth, biomass production and harvestable yield (Raes *et al*., 2009). The crop responds to water stress by (1) limiting canopy expansion, (2) early canopy senescence, and (3) closure of stomata (Raes *et al*., 2009). Under continued water stress, the (4) WP and (5) HI parameters may also be affected. It is important to note that three of these responses occur at the canopy level, hence the importance of the canopy in AquaCrop. Collectively, these five responses form the background framework of the crop component of AquaCrop (Steduto *et al*., 2009).

In AquaCrop, the canopy, through green canopy cover and canopy duration, represents the source of Tr. It is Tr that gets translated to biomass (B) through WP (Eq. 11.3). Following this, yield (Y), which is a constituent of B is then determined as a function of HI;

$$Y = B*HI \qquad \text{Equation 11.3}$$

The canopy, through its expansion, ageing, conductance and senescence, is very important in AquaCrop. The canopy is directly linked to Tr, which is directly related to B through Eq. 11.2, and indirectly to Y through Eq. 11.3. Under non-limiting conditions, canopy growth is exponential during the period from emergence to maximum canopy cover (CC_x). Canopy cover duration is also a function of time and is dependent on the determinacy of the crop, aspects all of which can be varied by the user in AquaCrop. Beyond this point, the canopy follows an exponential decay (Raes *et al*., 2009).

Unlike all other models, AquaCrop uses canopy cover (CC) not leaf area index (LAI) – a distinctive feature of AquaCrop. The use of CC, as opposed to LAI, is meant to introduce simplicity by reducing overall above-ground growth into just a single growth function. In the absence of water stress, amount of water transpired is proportional to CC. The crop's rooting system is also considered in AquaCrop through crop parameters for effective rooting depth (*Z*) and the crop's water extraction pattern. The effective rooting depth is defined as the depth at which the crop will conduct most of its water uptake (Raes *et al*., 2009). AquaCrop uses effective rooting depth and water extraction pattern of the roots to simulate the root system of a particular crop. All of the above mentioned components are in the form of inputs stored in climate, crop, soil and management files of AquaCrop. 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 11.2 for its calculation. The total amount of water available in the root zone throughout the crop cycle is simulated by budgeting 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 (CC) 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 (Kc_{tr}) is adjusted throughout the simulation according to the CC development. With the core equation (Equation 12.1), biomass (B) is derived from transpiration by means of the normalized water productivity (WP*) which is a conservative parameter. Conservative parameter does not change with time, management practices, and geographic locations (Raes *et al.,* 2009) once it is calibrated for a specific crop. Yield is calculated as the product of the simulated B and the adjusted HI (Raes *et al.,* 2009).

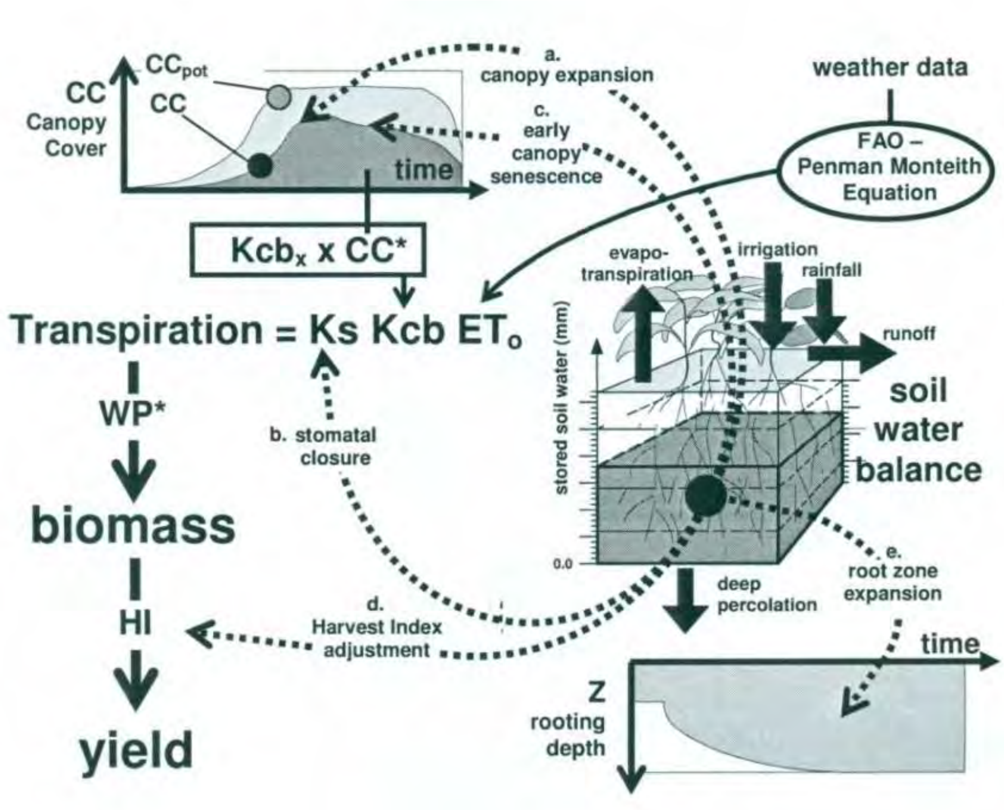

Figure 11.2: The chart showing the calculation scheme of AquaCrop (Raes *et al.*, 2009).

Temperature x varietal differences are also catered for in AquaCrop. The model provides the user with two simulation modes – thermal time (GDD) and calendar time. The model itself uses thermal time (Raes *et al*., 2009) based on Method 2 as described by McMaster and Wilhelm (1997). There is an important modification in AquaCrop in that there is no adjustment for T_n when and if it falls below base temperature (T_b). This allows for better and more realistic considerations of temperature fluctuations below T_b and allows for effective simulation of winter crops (Steduto *et al*., 2009; for algorithms see Raes *et al*., 2009). 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.

11.2 Conclusion

The review of modelling (Chapter 1) showed that there has been much progress in the development and understanding of crop models. However, a lot of this progress and most of the models currently developed are for the major crops. There have been very limited efforts to develop models for NUS. Perhaps, it is in this regard that AquaCrop leads. Although the model is still in its infancy, it has already been calibrated and validated for some NUS – quinoia (Geerts *et al*., 2009) and bambara groundnut (Karunaratne *et al*., 2011) (see also Steduto *et al*. 2011). These efforts form stepping stones to modelling of other NUS. A huge gap currently exists in this regard. As such, part of the focus of this study was to also contribute to international efforts on modelling yield response to water availability of NUS through calibrating and validation AquaCrop for four selected traditional crops – amaranth, bambara groundnut, pearl millet and taro.

Chapter 12

Calibration and validation of AquaCrop model for taro (*Colocasia esculenta* L. Schott) and bambara groundnut (*Vigna subterranea* L. Verdc) landraces

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12.1 Introduction

Taro (*Colocasia esculenta* L. Schott) and bambara groundnut (*Vigna subterranean* L. Verdc) fall within the category of underutilised indigenous and traditional crops in South Africa. Taro is a major root crop of the Araceae family with its centre of origin in the Indo-Malay regions (Kreike *et al*., 2004; Lebot *et al*., 2005). On the other hand, bambara groundnut, an indigenous African legume, originates between the Jos Plateau in Northern Nigeria and Garu in Cameroon (Pasquet *et al*., 1999). Although both crops have their origins outside of South Africa, they have become "indigenised" over many years (>100 years) of cultivation and natural and farmer selection within South Africa (Schippers, 2002, 2006). Such selection, often occurring under harsh conditions, may have led to these crops "acquiring" drought tolerance.

Lack of quantitative information describing their agronomy and water-use is a major hindrance to the promotion of both crops. With the threat of looming climate change and in the absence of extensive, and often costly, agronomic trials, the use of calibrated and validated crop models may prove useful to generate such information.

Crop models have proved to be useful tools for estimation of crop yields (Azam-Ali *et al*., 2001; Steduto *et al*., 2009; Singels *et al*., 2010) and for comprehensive synthesis of quantitative understanding of physiological processes as well as for evaluating crop management options. However, crop models have not been fully explored for underutilised crops. There have been previous attempts to model bambara groundnut using several other models like the Predicting

Arable Resource Capture in Hostile environment (PARCH – Bradley & Crout, 1993) model (Collinson *et al.,* 1996). This developed through to BAMnut (Bannayan, 2001; Azam-Ali *et al*., 2001), subsequently to BAMFOOD (Cornelissen, 2005), ultimately leading up to BAMGRO (Karunaratne, 2009; Karunaratne *et al*., 2010). Recently, Karunaratne *et al*. (2011) calibrated and validated AquaCrop for bambara groundnut.

AquaCrop (Raes *et al*., 2009; Steduto *et al*., 2009; Steduto *et al*., 2012) is a water-driven FAO crop model suitable for simulating yield responses to water stress. The model has been previously used for several underutilised crops such as quinoia (Geerts *et al*., 2009), bambara groundnut (Karunaratne *et al*., 2011), orange fleshed sweet potato (Beletse *et al*., 2011) and pearl millet (Bello *et al*., 2011). The aim of this study was to calibrate and validate the FAO's AquaCrop model for taro and bambara groundnut landraces from South Africa.

12.2 Material and Methods

12.2.1 Study site descriptions

Field and rainshelter experiments (Table 12.1) were conducted at the Agricultural Research Council – Roodeplaat, Pretoria (25º60´S; 28º35´E; 1168 masl) and Ukulinga, Pietermaritzburg (29°37'S; 30°16'E; 775 masl), during the 2010/11 and 2011/12 summer seasons. Soil in field and rainshelter trials at Roodeplaat was classified as sandy loam and sandy clay loam, respectively (USDA taxonomic system) (Table 12.2). The average, within season rainfall (November to April) of Roodeplaat is about 500 mm, and is highly variable with maximum precipitation in December and January. Daily maximum and minimum temperature averages are 34℃ and 8℃ in summer (November-April). Ukulinga represents a semi-arid environment and is characterised by clay-loam soils (USDA taxonomic system) (Table 12.2). The average, within season rainfall (November to April) of Ukulinga is 738 mm, with most of it being received in November, December and January.

Table 12.1: Summary of experiments used to develop model parameters for calibration and validation of AquaCrop.

Experiment	Location	Crop	Treatment	Season
Calibration				
Pot trials	CERU (KZN-PMB)	Taro and bambara groundnut	No stress, intermittent stress & terminal stress	2010
Field	Pretoria (ARC-VOPI)	Bambara groundnut	Irrigated & Rainfed	2010-11
Field	Ukulinga, (KZN-PMB)	Taro	Irrigated & Rainfed	2010-11
Rain shelter	Pretoria (ARC-VOPI)	Taro and bambara groundnut	100% Eta	2010-11
Validation				
Field	Ukulinga, (KZN-PMB)	Taro	Irrigated & Rainfed	2011-12
Rain shelter	Pretoria (ARC-VOPI)	Taro and bambara groundnut	30, 60 & 100% Eta	2011-12
*Field	Umbumbulu, KZN	Taro	Rainfed	2007-08

*Experiments were described by Mare & Modi (2009).

Table 12.2: Soil descriptions and properties of each experimental site and the inputs entered in AquaCrop to develop the soil file.

Location	Textural class	[v]PWP	[w]FC	[x]SAT	[y]TAW	[z]Ksat
		vol %			(mm m^{-1})	(mm day^{-1})
Ukulinga	Clay	28.3	40.6	48.1	123	25.0
Roodeplaat	Sandy loam	10.0	22.0	41.0	120	500.0
Rainshelter (Taro)	Sandy clay loam	16.1	24.1	42.1	80	324.2
Rainshelter (Bambara groundnut)	Sandy loam	12.6	19.9	42.8	73	663.6

[v]PWP – permanent wilting point; [w]FC – field capacity; [x]SAT – saturation; [y]TAW – total available water; [z]Ksat – saturated hydraulic conductivity.

12.2.2 Experiments

Controlled (pot), field and rainshelter experiments were conducted for taro and bambara groundnut landraces in order to develop crop specific parameters and to calibrate and validate the FAO AquaCrop model.

Plant materials. A taro landrace – Umbumbulu, was collected from Umbumbulu rural district in KwaZulu-Natal, South Africa. The Umbumbulu landrace is well-domesticated and widely cultivated upland. A bambara groundnut landrace was collected from Jozini, KwaZulu-Natal and characterised into three selections (Brown, Light-brown and Red) based on seed coat colour

Pot trials. The objective of the pot trials was to evaluate emergence, canopy expansion and stomatal closure and their sensitivity to water stress. These trials were conducted during 2010 under simulated drought conditions, for both taro and bambara groundnut, in tunnels at the University of KwaZulu-Natal, Pietermaritzburg. The experimental layout was a completely randomised design (CRD) with two factors: landrace type (3) and water stress (no stress, intermittent stress and terminal stress), replicated six times. Details of experimental designs, procedures and measurements taken are described in Mabhaudhi *et al*. (2011, 2012).

Rainshelters trials. The objective of the rainshelter experiments was to evaluate growth, yield and water-use of taro and bambara groundnut landraces in response to a range of water regimes. With regards to modelling, the experiments were designed to contribute in developing parameters for maximum canopy cover and effect of stress on canopy expansion as well as stomatal conductance. Details of experimental designs, procedures and measurements taken are described in Chapters 8 and 10.

Field trials. The objective of these trials was to determine the mechanisms involved in taro and bambara groundnut landraces' drought tolerance under field conditions. Data collected from these experiments contributed in developing parameters for time to emergence, initial cover, times to maximum canopy cover, senescence and maturity as well as harvest index. Details of experimental designs, procedures and measurements taken are described in Chapters 7 and 9.

12.2.3 Agronomic practices

For all trials, management was similar and kept at optimum during 2010/11 and 2011/12. Land preparation was done according to best agronomic practices. Fertiliser application was based on results of soil fertility analysis and applied using an organic fertiliser Gromor Accelerator (30 g N kg^{-1}, 15 g P kg^{-1} and 15 g K kg^{-1}). Weekly observations of pests and diseases were done to ensure effective control. Routine weeding and ridging were done to prevent weeds from competing with crops for water, nutrients and radiation.

12.2.4 Measurements

Experimental designs and data collection were specifically designed to collect empirical data that would be used for modelling both taro and bambara groundnut landraces. Soil physical characteristics (soil depth, soil texture, bulk density and gravimetric field capacity) were determined for each experimental site (field trials and rainshelters). The Soil Water Characteristics Hydraulic Properties Calculator (http://hydrolab.arsusda.gov/soilwater/Index.htm) was then used to calculate volumetric soil water content at field capacity (FC), permanent wilting point (PWP), saturation (SAT) and saturated hydraulic conductivity (Ksat) (Table 12.2). These were also used to develop the soil files for the respective sites in AquaCrop.

Daily weather parameters (maximum and minimum air temperature, relative humidity, solar radiation, wind speed, rainfall and ET_o) for the duration of the experiments were recorded and collected from automatic weather stations located within 100 m radii from each of the field and rainshelter experiments. These were used to create climate files for each experiment in AquaCrop for the respective sites. The climate file for the rainshelter experiments excluded rainfall.

Soil water content (SWC) in pot trials was monitored gravimetrically by periodic weighing of pots and electronically using an ML-2x Theta probe. In the rainshelters, SWC was monitored using ML-2x Theta Probes connected to a DL-2 data logger (Delta-T Devices, UK). In each plot, two probes were carefully inserted within the root zone at depths of 30 cm and 60 cm, respectively, and then buried with soil. The frequency of data collection for SWC using the Theta probes was every 4 hours. In the field trials, SWC was measured using gravimetric sampling and a PR2/6 profile probe connected to an HH-2 moisture meter (Delta-T Devices, UK) at depths of 10, 20, 30, 40, 60 and 100 cm.

Pot trials. Daily emergence was counted; up to 35 and 49 days after planting (DAP) for taro and bambara groundnut landraces, respectively. Weekly data were collected to determine leaf number, plant height, leaf area (Modi, 2007) and stomatal conductance. Measurements of seedling leaf area for taro's Umbumbulu landrace and the 'Red' bambara groundnut landrace selection were also used to develop the parameter for seedling leaf area in AquaCrop.

Field and rainshelter experiments. Time to emergence (DAP) was defined as the time taken to achieve 90% emergence as stated in AquaCrop (Raes *et al*., 2009) and was counted weekly for taro and bambara groundnut, respectively. Destructive sampling was done at full emergence to determine seedling leaf area (cm^2), root length and biomass. Measured seedling leaf area for taro's Umbumbulu landrace and the 'Red' bambara groundnut landrace selection were used to complement pot trial data and used to describe seedling leaf area in AquaCrop. Measurements of seedling root length taken at full emergence were used to determine the parameter for minimum rooting depth (Zr_{min}). Stomatal conductance was measured using a steady state leaf porometer (Model SC-1, Decagon Devices, USA) and used to describe crop sensitivity (stomata) to water stress in AquaCrop.

Leaf area index (LAI) index was measured using the LAI 2200 Canopy Analyser (Li-Cor, USA & Canada). However, measurements of LAI were not used to calculate canopy cover (CC) for AquaCrop. Instead, diffuse non-interceptance (DIFN), which is an output of the LAI 2200 canopy analyser, was used to determine CC. In essence, DIFN is calculated by integrating the gap fraction (GAPS) to obtain a value indicative of the fraction of the sky that is NOT obscured by the plant's canopy. The value of DIFN ranges from 0 (no sky visible to the sensor) to 1 (no canopy obscuring the sun) (LAI 2200 Manual, 2010). Thus, it may be argued that DIFN is more indicative of actual canopy cover than LAI; thence there is no need to convert LAI to CC (Abraham Singels, pers. comm., 2011). Therefore CC was obtained from DIFN as follows;

$$\mathbf{1 - DIFN = CC} \qquad \text{Equation 12.1}$$

Canopy cover values observed in field and rainshelter trials for taro's Umbumbulu landrace and the 'Red' bambara landrace selection were used to develop parameters for maximum canopy cover (CC_x) and time taken to achieve CC_x which were entered in AquaCrop. Observations of canopy cover under irrigated and rainfed conditions as well as using the 60% and 30% ETa treatments from rainshelter experiments were used to describe crop sensitivity to water stress in AquaCrop.

Measurements of biomass were routinely collected for evaluation of crop water productivity, development and dry matter partitioning. Final biomass, yield and harvest index (HI) were determined at harvest. The occurrence of major phenological stages, timing and duration of flowering, times to senescence and maturity, was recorded in days after planting (DAP). A phenological stage was deemed to have either occurred or been completed if and when it was observed in at least 50% of experimental plants. Data were later converted to thermal time according to the Method 2 as described by McMaster & Wilhelm (1997);

$$GDD = \left[\frac{(Tmax+Tmin)}{2}\right] - T_{base}$$ Equation 12.2

where GDD = growing degree days

T_{max} and T_{min} = maximum and minimum temperature, respectively, and

T_{base} = base temperature for the crop

Where if $T_{max} < T_{base}$, then $T_{max} = T_{base}$ and if $T_{min} < T_{base}$, then $T_{min} = T_{base}$

Thereafter, simulations for taro's Umbumbulu landrace and the 'Red' bambara groundnut landrace selection were performed in AquaCrop as described by Steduto *et al*. (2009) and Raes *et al*. (2009). Table 12.1 gives a detailed list of the experiments used to calibrate and validate AquaCrop for taro's Umbumbulu landrace and the 'Red' bambara groundnut landrace selection. For taro, independent results from experiments conducted by Mare and Modi (2009) were also used to test the model's accuracy under dryland conditions. Validation for Mare and Modi (2009) was for the *Dumbe dumbe* landrace which is the vernacular name for the Umbumbulu landrace used to calibrate taro in this study.

12.2.5 Model Evaluation

Goodness of fit of AquaCrop outputs against observed field measurements was evaluated using the coefficient of determination (R^2), root mean square error and its components (RMSE, RMSEs and RMSEu) and Willmott's coefficient of agreement (*d-index*). The coefficient of determination (R^2) is used for comparison of observed (O) and predicted (P) values. It shows goodness of fit between observed and predicted values. It is however, dependent on the number (n) of data sets used.

Willmott (1981) proposed the use of RMSE and its systematic (RMSEs) (biased or non-random) and unsystematic (RMSEu) (unbiased or random) components as alternative measures of model performance. For interpretation of results, RMSEs should approach zero, while the RMSEu should approach RMSE in order for a model's performance to be deemed as "good". The systematic (RMSEs) and unsystematic (RMSEu) components are computed as follows;

$$RMSE_s = \left[n^{-1} \sum_{i=1}^{n} \left(\hat{P}_i - O_i \right)^2 \right]^{0.5}$$ Equation 12.3

$$RMSE_u = \left[n^{-1} \sum_{i=1}^{n} \left(P_i - \hat{P}_i \right)^2 \right]^{0.5}$$

Equation 12.4

$$\boldsymbol{RMSE = (RMSE_S + RMSE_U)^{0.5}}$$

Equation 12.5

where, n = the number of observations, and $\hat{P}_i$ is derived from $\hat{P}_i = a + b.O_i$ whereby a and b are the intercept and slope, respectively, of a least regression between the predicted (dependent variable) and observed (independent variable) values.

In addition to computing RMSE and its systematic (RMSEs) and unsystematic components (RMSEu), Willmott (1981) further suggested an index of agreement (d) which reflects the degree to which the observed values are accurately estimated by the model. This is computed as follows;

$$d = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum \left[\left| P_i' \right| + \left| O_i' \right| \right]^2}, \quad 0 \le d \le 1$$

Equation 12.6

where, $P_i' = P_i - \bar{O}$ and $\bar{O}i = Oi - \bar{O}$ whereby $\bar{O}$ is the observed means.

Willmott's index of agreement (d) is a measure of the degree to which a model's predictions (P) are error free or the degree to which observed deviations about observed means (Ō) correspond, both in size and sign, to predicted deviations about Ō. Concurrently, the *d-index* is a standardised measure developed with the intention that (i) it may be easily interpreted, and (ii) cross-comparisons of its magnitudes for a variety of models, regardless of units, could be readily made. The *d-index* varies between 0.0 – indicating complete disagreement, and 1.0 – indicating complete agreement between observed and predicted values. According to Willmott (1981), the *d-index* often complements information contained in RMSE, RMSEs and RMSEu. Therefore, in addition to the use R^2, evaluation of crop models should also include RMSE, RMSEs, RMSEu and the *d-index*.

12.3 Calibration

Crop parameters used to calibrate AquaCrop for taro's Umbumbulu landrace and the 'Red' bambara groundnut landrace selection were derived from controlled, field and rainshelter experiments representing a wide range of water regimes and environmental conditions and soils (Tables 12.1 and 12.2). Selection of landraces was based on results from pot, field and rainshelter experiments which showed 'Umbumbulu' and the 'Red' landrace selection as the most stable, in terms of within landrace variability, and adapted (to water-limited conditions) landraces of taro and bambara groundnut, respectively.

Initial calibration involved matching observed CC to simulated CC. Subsequent to this; the model was calibrated by comparing observed and simulated biomass (B) and yield (Y). Calibration included adjusting selected parameters within a known range of fluctuation to represent within landrace variation. Data used for calibration were not used for validation. The reduced input requirements of the model, compared to others, enhanced the ease of calibration. Crop parameters used to calibrate taro and bambara groundnut landraces are summarised in Tables 12.3 and 12.5.

12.3.1 Calibrating bambara groundnut

Since AquaCrop was previously calibrated for bambara groundnut by Karunaratne *et al*. (2011), calibration started with fine-tuning their crop file to South African local conditions. Time to emergence was observed in pot, field and rainshelters as days after planting (DAP) as 35 DAP and converted to GDD in AquaCrop (Table 12.3).

In order to determine CC_o, destructive sampling was done when the crop had achieved 90% emergence in all trials (field, rainshelter, pot and seedling establishment trials). Measured values of seedling leaf area observed were entered in AquaCrop as 2.0 cm^2 (Table 12.3) compared to 5.0 cm^2 described by Karunaratne *et al*. (2011). This was acceptable since our experimental conditions and landraces were different to those used by Karunaratne *et al*. (2011). Thereafter, the model used initial seedling leaf area to compute CC_o. Observed values for maximum canopy cover (CC_x), times taken to achieve CC_x and leaf senescence were input in AquaCrop (Table 12.3). Thereafter, using these observed values, the model computed canopy growth and decline coefficients (CGC and CDC) (Table 12.3).

Minimum rooting depth (Zr_{min}) was entered in AquaCrop as 0.10 m. (Table 12.3). Destructive sampling in field and rainshelter trials showed maximum root length of about 0.30 m; however, for better simulation a value of 1.0 m described by Karunaratne *et al*. (2011) was entered in AquaCrop as Zr_{max} (Table 12.3). The time taken to achieve maximum rooting depth was also entered in AquaCrop. Based on these observed parameters, the model then derived root expansion rate as described in Raes *et al*. (2009). Karunaratne *et al*. (2011) reported that AquaCrop's default settings for describing a grain crop were reasonably good for simulating bambara groundnut under both irrigated and rainfed conditions – our own calibration concurred with their assertion. A WP value of 11 was used and harvest index was calculated as 20% and entered in AquaCrop. This provided good simulation for final biomass and yield.

Table 12.3: Preliminary input parameters for the 'Red' bambara groundnut landrace selection in AquaCrop.

Parameter	Description	Model Input
T_{base}	Base temperature (°C)	9*
T_{upper}	Cut-off temperature (°C)	30*
Emergence	Time to 90% emergence	299
CC_x	Maximum canopy cover (%)	85
Time to CC_x (GDD)		1155
Zr_{max}	Maximum rooting depth (m)	1.0
Zr_{min}	Minimum rooting depth (m)	0.10
Canopy senescence	Time to canopy senescence	1814
Start of yield formation		1047
Duration of flowering		629
Length of HI build up		1024
Maturity		2227
Soil water depletion factor canopy expansion (p-leaf) Upper Limit		0.50*
Soil water depletion factor canopy expansion (p-leaf) Lower Limit		0.80*
Shape factor for water stress coefficient leaf expansion		1.00*
Soil water depletion for stomatal control (p-stomatal)		0.80*
Shape factor for water stress coefficient stomatal control		2.00*
Soil water depletion for canopy senescence (p-senescence)		0.90*
Shape factor for water stress canopy senescence		3.00*
Root expansion rate (cm/day)		1.2
Shape factor for root expansion		2.00*
Canopy cover per seedling (cm^2)		2.00
Canopy growth coefficient p(CGC): increase in CC/ degree day		0.942
Canopy declining coefficient (CDC) per degree day		0.600
K_{cb}		1.15
Normalised water productivity (WP) g m^{-2}		11^x
Harvest index (percentage)		20^y
Positive effect of HI as result of limited growth in vegetative period		Moderate
Positive effect of HI as result of water stress affecting leaf expansion		Moderate
Water stress during flowering (p-upper)		0.90*
Negative effect on HI as a result of water stress inducing stomatal closure		Strong
Aeration stress		Sensitive

*Parameters described by Karunaratne *et al.* (2011); ^{x}WP differed for the rainshelter experiments and was set at 10; ^{y}HI for the rainshelter experiments was 15%.

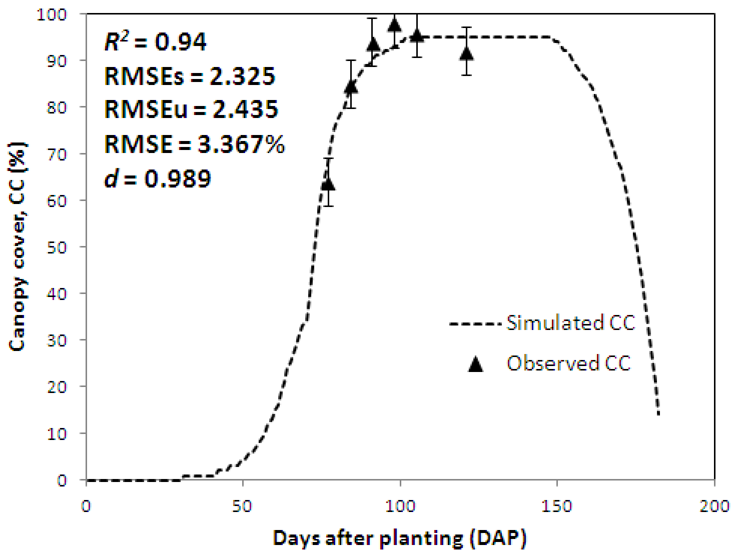

Figure 12.1: Calibration results of bambara groundnut canopy cover (CC %) under irrigated conditions (field trials) during 2010/11 growing season at Roodeplaat, Pretoria. Vertical bars indicate +/- standard error of means.

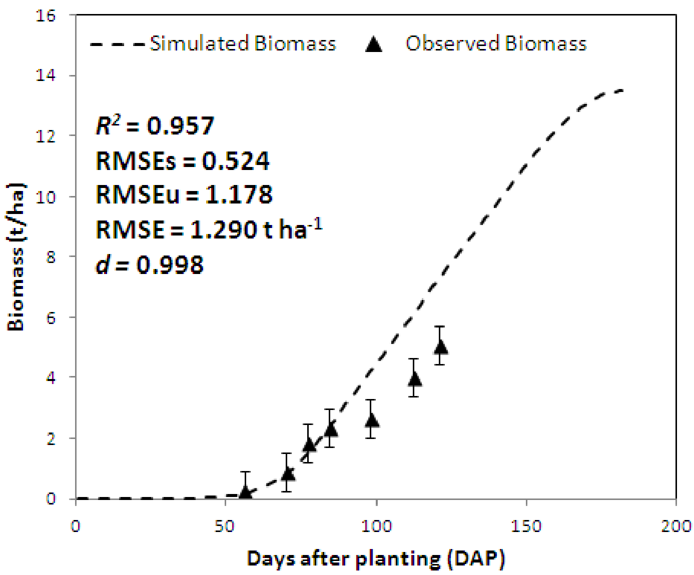

Figure 12.2: Calibration results of bambara groundnut biomass accumulation (t ha^{-1}) under irrigated conditions (field trials) during 2010/11 growing season at Roodeplaat, Pretoria. Vertical bars indicate +/- standard error of means.

Results for calibration showed a reasonably good goodness of fit for both canopy cover and biomass (Figures 12.1 and 12.2). The coefficient of determination (R^2) for CC was 0.94 and for biomass R^2 was 0.957. Therefore, the model was able to predict CC and biomass reasonably well. The RMSE for CC was 3.37% which was very good compared to a RMSE of 14.79% reported by Karunaratne *et al*. (2011) for their calibration of four bambara groundnut landraces. They concluded that RMSE of 14.79% was very acceptable given the huge amount of variation that exists between and within bambara groundnut landraces. They further stated that high RMSE observed for biomass was due to a carry-over effect from the error from CC.

Results of final biomass and yield showed good comparison between predicted and observed biomass and yield (Table 12.4). The model over-estimated final biomass by 14% and yield by about 8.79% compared to observed biomass and yield; this may be regarded as acceptable. The margin of error for predicted biomass and yield is still within acceptable margins and may be due to the carry-over error from simulation of CC and cumulative B.

Table 12.4: Calibration results of final biomass and yield (simulated vs. observed) for irrigated (FI) field trials of taro's Umbumbulu landrace and 'Red' bambara groundnut landrace selection conducted during 2010/11.

	Bambara groundnut		**Taro**	
	Biomass (t ha^{-1})	**Yield (t ha^{-1})**	**Biomass (t ha^{-1})**	**Yield (t ha^{-1})**
Observed	11.80	3.341	20.7	17.1
Simulated	13.495	3.635	22.05	18.305
RMSE	1.695	0.294	1.350	1.205

12.3.2 Calibrating taro

Taro was calibrated in AquaCrop using measurements from the optimum irrigated (FI) field trials conducted at Ukulinga during 2010/11. The optimum treatment (100% ETa) from the rainshelter trials conducted at Roodeplaat during 2010/11 was also used to develop as well as to confirm some parameters (Table 12.5). Rainfed trials were also used to fine-tune the calibrations.

Time to emergence for taro's Umbumbulu landrace was observed as 49 DAP; this was converted to GDD and entered in AquaCrop (Table 12.5). Observed seedling leaf area (25 cm^2) (Mabhaudhi *et al*., 2012) was used to define seedling cover in AquaCrop. Together with plant density, AquaCrop then computed initial canopy cover (CC_o) (Table 12.5). Observed CC_x and time taken to achieve CC_x were input in AquaCrop (Table 12.5). Using these, the model then derived the CGC (Table 12.5).

Observed times to senescence and maturity were input in AquaCrop; canopy decline coefficient (CDC) was then derived from these. However, contrary to observations of taro growth, the model derived value for CDC simulated canopy cover to reach zero about a month before harvest. Under actual conditions, unless frost occurs and kills off the foliage, taro's canopy can continue through winter as a perennial crop. Therefore, CDC was adjusted accordingly in order to obtain a better simulation of canopy decline (Table 12.5).

AquaCrop describes effects of water stress based canopy growth and senescence, crop transpiration and HI. Each of these stress response factors, excluding HI, has its own stress coefficient *Ks*, which acts as an indicator of the stress' intensity. Canopy growth, senescence and stomatal closure for taro's Umbumbulu landrace were entered in AquaCrop as sensitive to water stress. This was because results from field and rainshelter trials had shown that this landrace avoided drought by stomatal regulation (closure) and having a small canopy size. Thereafter, AquaCrop calculated p-values (Table 12.5) corresponding to these descriptions (Raes *et al*., 2009). Since taro is naturally a wetland crop (Lebot, 2009), the crop was described in AquaCrop as tolerant to water logging (Table 12.5).

Table 12.5: Preliminary input parameters for taro's Umbumbulu landrace in AquaCrop.

Parameter	Description	Model input
T_{base}	Base temperature (°C)	10
T_{upper}	Cut-off temperature (°C)	35
Emergence	Time to 90% emergence	460
CC_x	Maximum canopy cover (%)	85
Time to CC_x (GDD)		1557
Zr_{max}	Maximum rooting depth (m)	0.8
Zr_{min}	Minimum rooting depth (m)	0.1
Canopy senescence	Time to canopy senescence	2115
Start of yield formation		1512
Length of build-up of HI		861
Maturity		2406
Soil water depletion factor canopy expansion (p-leaf) Upper Limit		0.10
Soil water depletion factor canopy expansion (p-leaf) Lower Limit		0.45
Shape factor for water stress coefficient leaf expansion		3.0
Soil water depletion for stomatal control (p-stomatal)		0.45
Shape factor for water stress coefficient stomatal control		3.0
Soil water depletion for canopy senescence (p-senescence)		0.45
Shape factor for water stress canopy senescence		3.0
Root expansion rate (cm/day)		0.6
Shape factor for root expansion		1.5
Canopy cover per seedling (cm^2)		25
Canopy growth coefficient p(CGC): increase in CC/ degree day		0.698
Canopy declining coefficient (CDC) per degree day		0.577
K_{cb}		1.10
Normalised water productivity (WP) g m^{-2}		15^x
Harvest index (percentage)		80^y
Positive effect of HI as result of limited growth in vegetative period		Moderate
Positive effect of HI as result of water stress affecting leaf expansion		Small
Negative effect on HI as a result of water stress inducing stomatal closure		Very strong
Aeration stress		Not stressed

^{x}WP differed for the rainshelter experiments and was set at 22; ^{y}HI for the rainshelter experiments was 70%.

Our observations showed Zr_{max} to range between 0.30-0.45 m. However, AquaCrop was unable to simulate for rainfed conditions using this value. This may be a result of our sampling procedure used to determine root depth as well as other soil factors. As such, following a series of simulations, a value of 0.8 m was used in AquaCrop for Zr_{max} (Table 12.5) since it gave good results under both irrigated and rainfed conditions. This value corresponded to the model's description of a shallow-medium rooted crop; this concurs with the description of taro rooting depth suggested by Lebot (2009).

The model was able to simulate canopy cover (CC) (Figure 12.3) reasonably well (R^2 = 0.789). Willmott's coefficient of agreement (*d-index*) showed very good agreement (*d* = 0.9196) between predicted and observed CC for taro under irrigated (FI) conditions. Simulated final biomass (B) and yield (Y) also showed a very good fit with the observed data (RMSE = 1.350 and 1.205 t ha^{-1}) (Table 12.4). Simulated B and Y were respectively, 6 and 7% greater than observed B and Y. This can be considered to be very good given that the model was simulating a landrace.

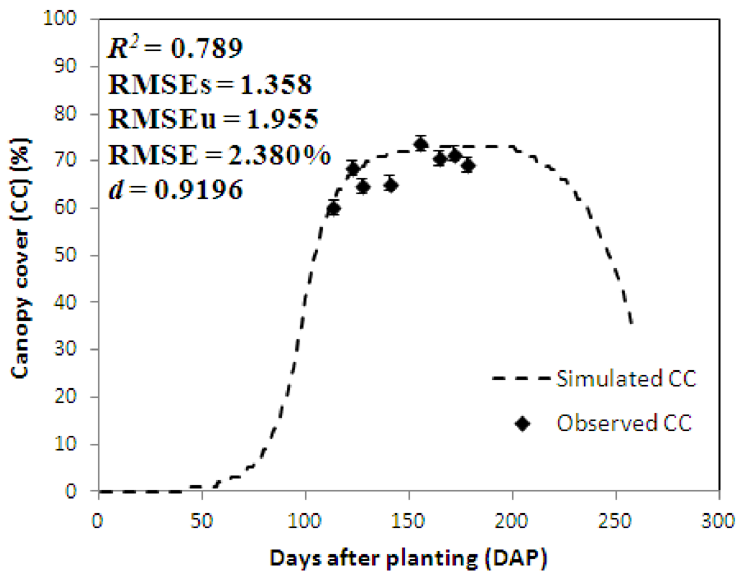

Figure 12.3: Calibration results of taro canopy cover (CC %) under irrigated conditions (field trials) during 2010/11 growing season at Ukulinga, Pietermaritzburg. Vertical bars indicate +/- standard error of means.

12.4 Validation

Subsequent to AquaCrop's calibration using data from optimum experiments conducted during 2010/11 season with no fertility or temperature stress, the model was validated for both bambara groundnut and taro using observed measurements from experiments [field (RF and FI) and rainshelter (100, 60 and 30% ETa)] conducted during 2011/12. In the case of taro, AquaCrop was also tested against independent data from previous experiments conducted by Mare and Modi, 2009 (Table 12.1).

12.4.1 Validating bambara groundnut

Results of validation for the field trials showed a good fit between simulated and observed CC under irrigated (R^2 = 0.858) (Figure 12.4A) and rainfed conditions (R^2 = 0.951) (Figure 12.4B). Results also showed good agreement (*d-index*) between observed and simulated CC for irrigated (d = 0.9558) (Figure 12.4A) and rainfed (d = 0.9746) conditions (Figure 12.4B). The RMSE obtained from statistical analysis of simulated and observed values for rainfed and irrigated conditions was relatively low and similar to that obtained during calibration; this indicated model consistency and robustness. In addition, RMSEs was relatively low and close to zero, while RMSEu was shown to approach RMSE, thus indicating good model performance (Figure 12.4A and B). Therefore, the model showed very good simulation for rainfed production. This concurs with statements by Raes *et al*. (2009) and Steduto *et al*. (2009) that the model was especially useful for predicting yield under water-limited conditions.

Validation of the model using measurements from rainshelter experiments showed relatively good fit between observed and simulated CC under varying water regimes. Simulation of CC under optimum conditions (100% ETa) showed the best fit (R^2 = 0.951) (Figure 12.5A) relative to 60% (R^2 = 0.901) (Figure 12.5B) and 30% ETa (R^2 = 0.813) (Figure 12.5C). The model managed to simulate well actual experimental observations that showed little difference in CC between the 100% and 60% ETa treatments (Figure 12.5A and B). In all three cases, the model was shown to under-estimate CC in the early and later parts of the season. This was also evidenced by the relatively lower agreement at 60% (d = 0.951) (Figure 12.5 B) and 30% (d = 0.950) (Figure 12.5C) compared with the 100% ETa treatment (d = 0.972) (Figure 12.5A). This may account for the relatively high RMSE obtained from statistical evaluation of model outputs (Figure 12.5A, B and C). The RMSE for CC simulated for the 100% ETa treatment was 14.06% (Figure 12.5A), which was similar to that reported by Karunaratne *et al*. (2011) for their calibration and validation of bambara groundnut. The RMSE, as well as its components (RMSEs and RMSEu), were shown to increase for the 60% and 30% ETa treatments (Figure 12.5B and C).

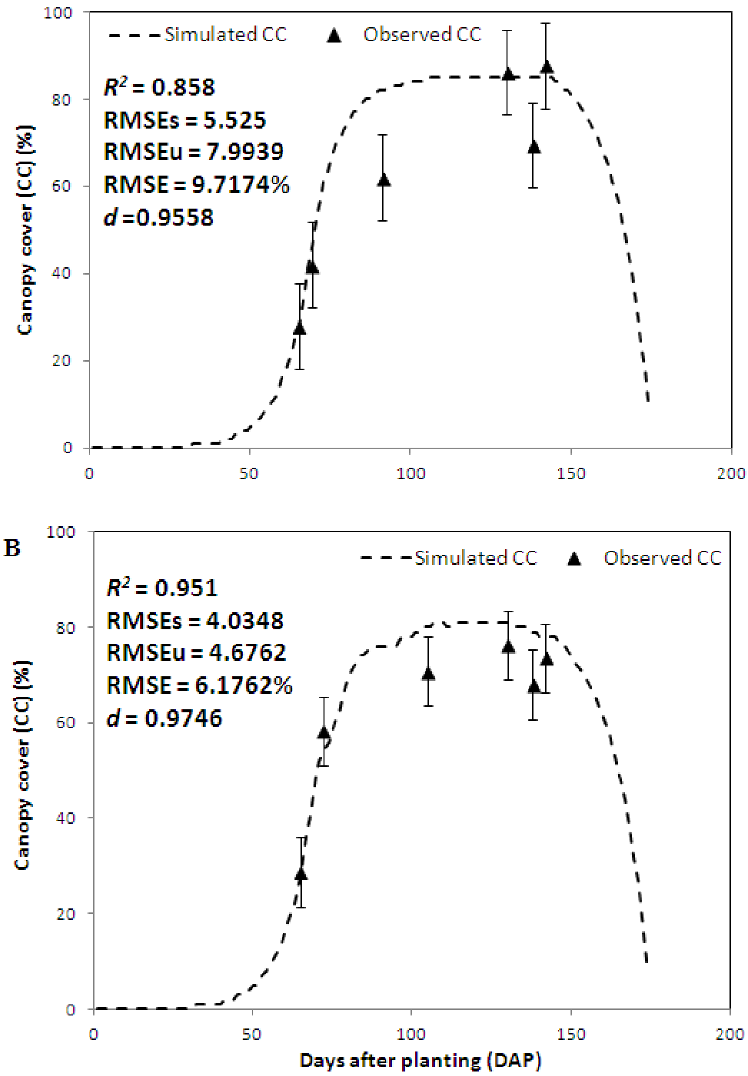

Figure 12.4: Validation of canopy cover (CC %) for bambara groundnut grown under A. Irrigated and B. Rainfed field conditions during 2011/12 growing season at Roodeplaat, Pretoria. Vertical bars indicate +/- standard error of means.

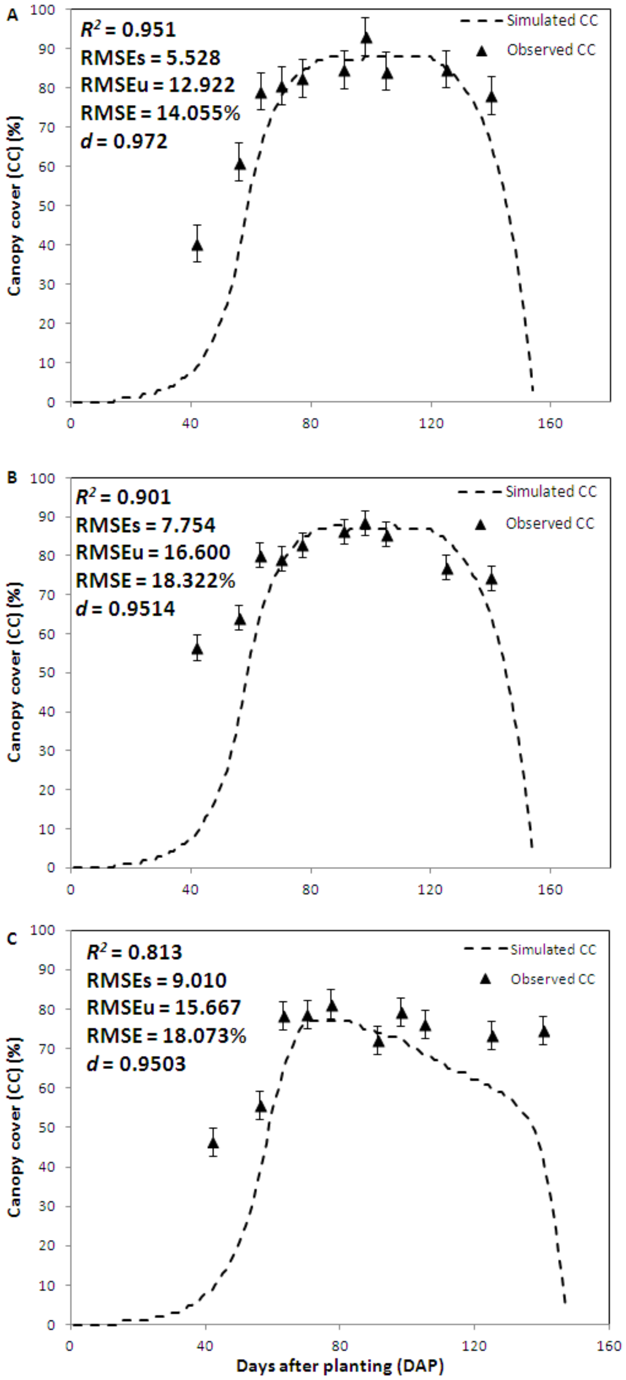

Figure 12.5: Validation of canopy cover (CC %) for bambara groundnut grown under A. 100% ETa, B. 60% ETa and C. 30% ETa in rainshelters during 2011/12 growing season at Roodeplaat, Pretoria. Vertical bars indicate +/- standard error of means.

The model predicted final biomass and yield very well for bambara groundnut grown under irrigated (FI) and rainfed (RF) field conditions (Table 12.6). The margin for error (RMSE) under field conditions (RF and FI) was relatively low, showing good model performance. However, the model did not show good prediction for biomass and yield for the three rainshelter irrigation treatments (100, 60 and 30% ETa) (Table 12.6). While Karunaratne *et al*. (2011) reported under-estimation of some landraces, in this study; the model was shown to over-estimate both biomass and yield in the rainshelter irrigation treatments (Table 12.6). The over-estimation of biomass and yield in the rainshelter may be due to carry-over error from simulation of CC. It is possible that model performance in the rainshelter may have been affected by periodic closing and opening of the shelter during rainfall events – this could have altered the microclimate in the rainshelter – a phenomenon which the model could not account for.

Over-all, despite the model's performance with regards to the rainshelter irrigation treatments, the model was shown to predict well biomass under yield under field conditions (RF and FI). This further strengthens the model's suitability for simulating yield response to water availability.

Table 12.6: Validation results of the 'Red' bambara groundnut landrace for final biomass (B) and yield (Y) [simulated (S) vs. Observed (O)] for field trials (FI and RF) and rainshelter experiments (30, 60, 100% ETa) conducted during 2011/12.

	Yield (t ha^{-1})									
	IRR		RF		30% ^{w}ETa		60% Eta		100% ETa	
	B	Y	B	Y	B	Y	B	Y	B	Y
O	12.14	2.84	8.75	1.84	7.41	0.35	8.61	0.32	8.11	0.52
S	11.84	2.37	8.81	1.80	4.56	0.52	7.84	0.91	9.51	1.14
^{x}RMSE	0.30	0.47	0.06	0.04	2.85	0.17	0.77	0.59	1.40	0.62

^{W}ETa – crop water requirement; ^{x}RMSE – root mean square error.

12.4.2 Validating taro

Rainfed and irrigated treatments affected taro growth, biomass and yield significantly. The model was able to simulate CC under irrigated conditions very well (R^2 = 0.844) (Figure 12.6A), although the model was not as accurate (R^2 = 0.018) under rainfed conditions (Figure 12.6B). The model showed low RMSE, RMSEs and RMSEu for the full irrigation treatment under field conditions (Figure 12.6A), indicating good model performance. Consistent with the low R^2 observed for rainfed conditions, model evaluation showed comparatively large RMSE, RMSEs and RMSEu under rainfed conditions, indicating poor model performance (Figure 12.6B). This may be due to the fact that the model was unable to simulate the sharp decline in CC that occurred in taro in response to stress. It must also be noted that unlike bambara groundnut, AquaCrop's default file for root and tuber crops may not be particularly suited to the unique growth pattern and behaviour of taro, an aroid. Parameters such as suckers/stolons and leaf appearance rate catered for in the simulating of underground bulking storage organs (SUBSTOR) aroid model (Singh *et al*., 1998) as well as the crop's distinctive growth stages (Lebot, 2009) may need to be factored in the model for improved simulation of taro's canopy.

However, despite this setback, the model showed good prediction for biomass and yield under varying conditions. Figure 12.7 shows results of observed vs. simulated biomass and yield from field (RF and FI) and rainshelter (100, 60 and 30% ETa) experiments. The model was shown to simulate both biomass (R^2 = 0.898) and yield (R^2 = 0.964) relatively well with acceptably low values of RMSE, RMSEs and RMSEu. The agreement between simulated and observed biomass (d = 0.875) and yield (d = 0.987) was very good, which showed good agreement between predicted and observed values of biomass and yield (Figure 12.7). According to Jaleel *et al*. (2009), yield attainment is the most important attribute in crop production. As such, with regard to simulating yield response to water availability, the model's performance was good.

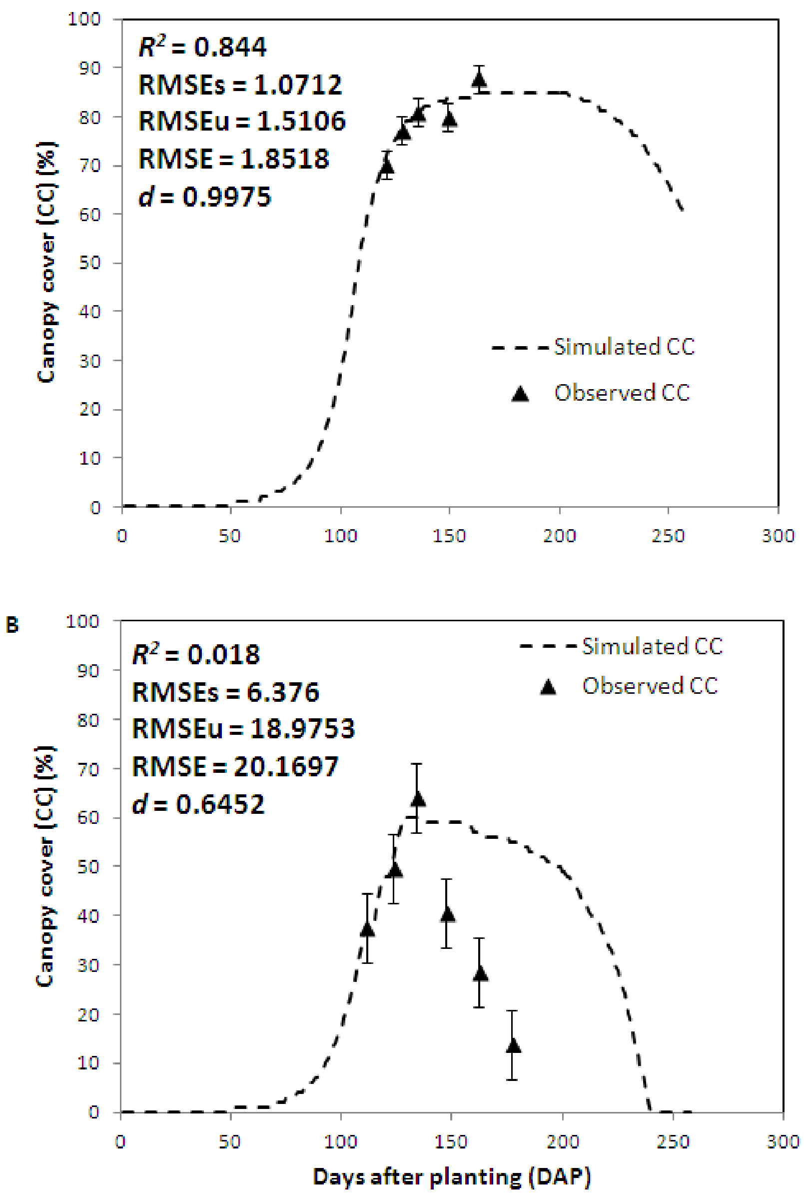

Figure 12.6: Validation of canopy cover (CC %) for taro grown under A. Irrigated and B. Rainfed field conditions during 2011/12 growing season at Ukulinga, Pietermaritzburg. Vertical bars indicate +/- standard error of means.

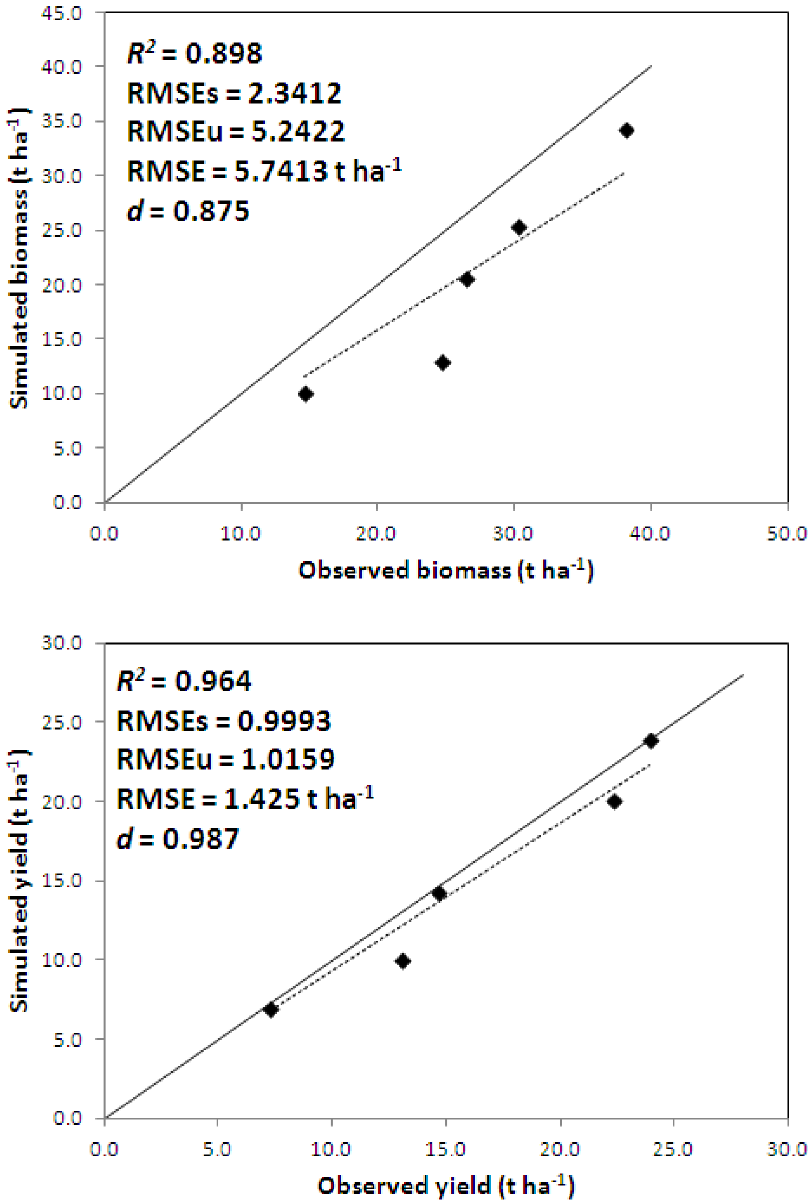

Figure 12.7: Validation results of taro final biomass and yield (t ha^{-1}). Measured data are means from irrigated and rainfed field trials and rainshelter experiments (30, 60 and 100% ETa) grown during 2011/12 growing season at Ukulinga, Pietermaritzburg and Roodeplaat, Pretoria, respectively.

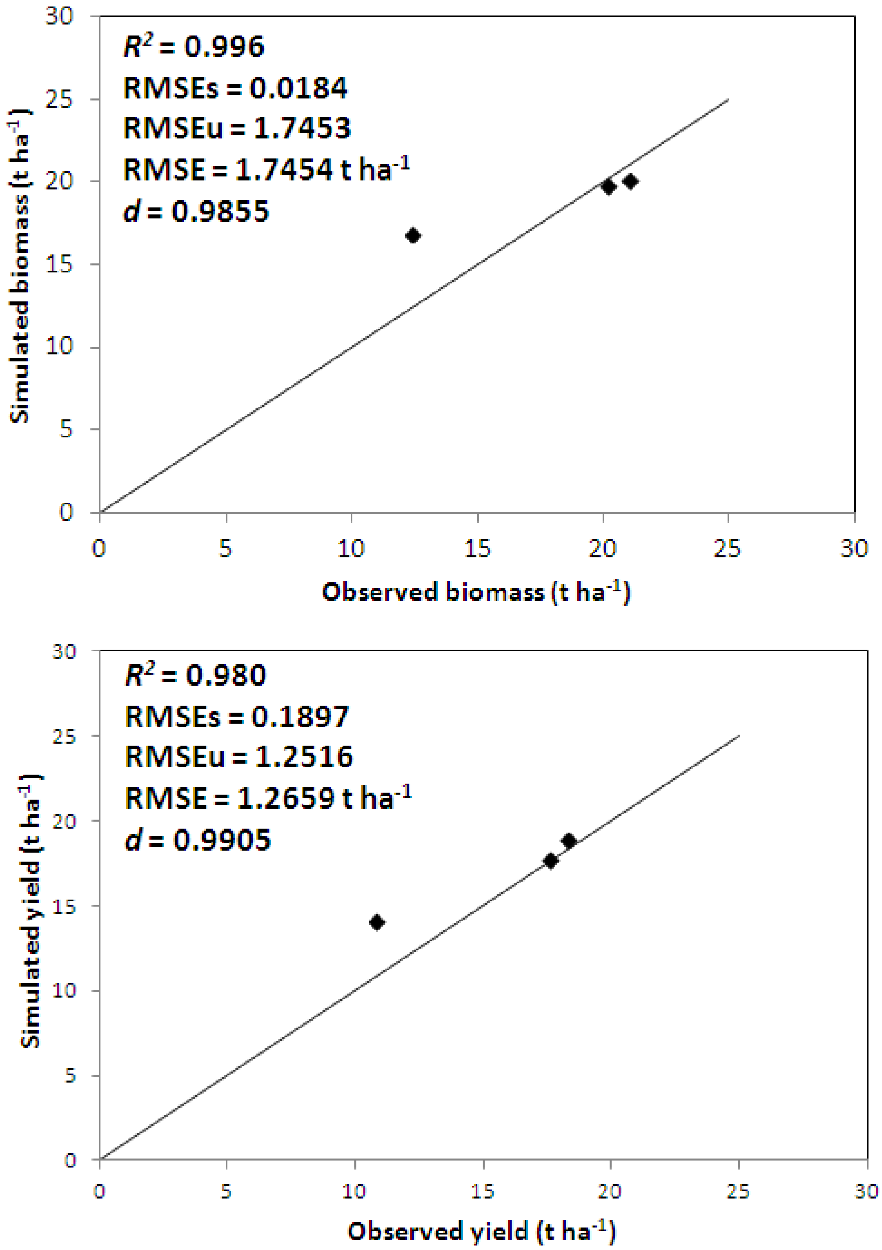

Figure 12.8: Validation results of taro biomass and yield (t ha^{-1}) using independent data set for taro (Mare & Modi, 2009).

Validation of the model using results from independent experiments gave a very good fit for both biomass (R^2 = 0.996) and yield (R^2 = 0.980) (Figure 12.8). For interpretation of these results, R^2 is dependent on the number of data points, were few data were used ($5 \leq n \geq 3$), R^2 has to be very high (R^2 = 0.99) to show significance. Therefore, R^2 of 0.99 and 0.98 for biomass and yield, respectively, for the 3 planting dates implies a significant regression. The agreement (*d-index*) between simulated and observed values of biomass and yield was respectively, 0.9855 and 0.9905 (Figure 12.8), showing very good agreement between predicted and observed values. In addition, RMSE was shown to be very low. The RMSEs was shown to approach zero for simulations of biomass and yield (Figure 12.8). This shows very good model performance and prediction given that this was an independent data set under dryland (rainfed) conditions. This further strengthens the model's applicability to simulating rainfed or water-limited production.

12.5 Conclusion

While bambara groundnut has recently been calibrated in AquaCrop, the calibration and validation of taro was a first. The calibration and validation of AquaCrop for bambara groundnut gave good results, especially under field conditions. Final simulation of biomass and yield under field conditions (RF and FI) was satisfactory. However, due to great variability within landraces, more research needs to be done to further test the model for bambara groundnut landraces from other locations. This may also aid in selection and screening for drought tolerance in bambara groundnut. With regards to taro, the model simulations for biomass and yield were very satisfactory. Despite the model's obvious challenges in simulating canopy cover under rainfed conditions, the model was able to simulate final biomass and yield reasonably well. Given the unique nature of taro growth, more research needs to be done, together with possible improvements to the model, to better simulate taro growth. To fine-tune the model for taro, improvements should consider the crop's distinctive growth stages, pattern of yield formation as well sensitivities to frost which typically kills off the crop which would otherwise be a perennial. The model's minimal requirements for site specific information and crop input parameters for AquaCrop added to the ease of calibration and validation of the model – this is particularly beneficial within the greater and broader context of encouraging the adoption of models as decision making support tools in places were access to extensive data sets may be limited. Over-all, the model showed that the taro Umbumbulu landrace and 'Red' bambara groundnut landrace selection are possible drought tolerant crops. This was evidenced by the model's ability to simulate both crops under water-limited conditions (30% ETa) and the crops' ability to achieve reasonable yields under such conditions. The continuing efforts to model bambara groundnut and this first attempt to model taro should be used as a stepping stone for modelling other neglected underutilised crops.

Chapter 13

Calibration and validation of AquaCrop for amaranth and pearl millet

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13.1 Introduction

Water, as an important crop production determining factor is becoming scarcer. In agriculture, water supplies are through rainfall and irrigation. Rainfall provides 65% of water needed for global food production, compared to 35% from irrigation (Smith, 2000). However, in semi-arid areas, rainfall is erratic and unevenly distributed (Botha *et al.,* 2003). Rainfall in semi-arid areas is unreliable due to dry spells and droughts that severely impact water resources and threaten sustainable agriculture (Ferres & Connor, 2004). Low water availability in semi-arid areas calls for alternative management practices which can be in the form of choice of crops, irrigation management and cropping systems. Due to erratic rainfall, crop production in semi-arid areas depends mostly on irrigation; 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 (Evett *et al*., 2003). However, as crop production becomes increasingly dependent on irrigation, irrigation is expected to consume a large portion of global fresh water resources. It was reported that irrigated agriculture consumes about 72% of available fresh water resources on a global scale (Geerts & Raes, 2009). Irrigated agriculture is expected to reduce water usage and produce sufficient food and fiber for increasing world population (Garcia-Villa *et al*., 2009). In South Africa, it has been observed that the water resources available for irrigation are all currently being utilized (Backeberg *et al*., 1996), thus there is little scope for new development. This is forcing managers and irrigators to re-evaluate their strategies for growth in the agricultural sector (Haka, 2010).

Accurate quantification of crop water use is part of effective water management. Effective water use both in irrigated and rainfed crop production is a main requirement to design strategies to manage available water resources (Smith, 2000). Importance of water for crop growth and development of major crops has been proven many times but little information on this has been documented for underutilized crops (Karunaratne *et al*., 2011) such as amaranthus and pearl millet. Strategies of optimizing crop production per unit of water include identification of means to improve water use efficiency of rainfed and irrigated crop production. Computerized procedures, crop modelling, can also help to form strategies for crop production optimization. Crop modelling is an agricultural tool used to predict water use and yield of many of the main staple crops. However, few of the crop models have been calibrated for minor or underutilized crops (Walker *et al*., 2012).

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

Some crop models perform better to achieve specific goals. 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 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 (Akponikpe *et al*., 2010). 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 the farm managers with the formulation of guidelines to increase crop water productivity for both rainfed and irrigated production 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 study were to calibrate and validate AquaCrop crop model for two underutilized crops, amaranthus and pearl millet, under irrigated and rainfed conditions.

13.2 Materials and Methods

13.2.1 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 lysimeter on pearl millet during the 2010/11 season, while field trials were during the 2008/09 and 2009/10 seasons for both amaranthus and pearl millet. These sets of experiments were for calibration and validation of the AquaCrop crop growth model. Details of the pot, lysimeter and field trials layouts, experimental design and agronomic practices employed in the studies are found in Chapter 6. The pot and lysimeter datasets were used for parameterization and calibration of the model while the 2008/09 and 2009/10 seasons field experiments were also for calibration and validation of the model (Table 13.1).

13.2.2 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 irrigation and rainfed treatments. Phenological development of the two crops was monitored with the observations from the field trials during the 2008/09 and 2009/10 seasons. For the pot trial, transpiration rate was measured every other day. Soil water content was monitored twice a week on lysimeter trial while it was done weekly in field trials during the two seasons for the two crops. Harvested yield was calculated at the end of second season for pearl millet (Chapter 6).

Table 13.1: Summary of source of datasets for calibration and validation of AquaCrop model.

Experiment	Purpose for datasets	Crop	Season	Soil water regime	Sowing date
Glasshouse	Calibration	Amaranthus	2010/11	Irrigation	27/12/2010
Lysimeter	Calibration	Pearl millet (GCI 17 & Monyaloti)	2010/11	Irrigation	16/12/2010
Field trial	Validation	Amaranthus	2008/09	Irrigation & rainfed	30/12/2008
Field trial	Calibration	Pearl millet (GCI 17 & Monyaloti)	2008/09	Irrigation & rainfed	28/11/2008
Field trial	Calibration	Amaranthus	2009/10	Irrigation &rainfed	11/11/2009
Field trial	Validation	Pearl millet (GCI 17 & Monyaloti)	2009/10	Irrigation & rainfed	16/12/2009

13.2.3 Model parameters and input data

13.2.3.1 Climatic data

In order to create a climate file, 10 years of daily weather data from the AWS at the study site 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 ET_o calculator was used to calculate ET_o as recommended in AquaCrop model. The minimum and maximum air temperatures, and ET_o were then a measure of atmospheric evaporative demand. AquaCrop requires the temperatures in order to calculate growing degree day (GDD) which influence crop growth and phenology development (Raes *et al.,* 2009).

13.2.3.2 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 was converted to CC using Equation 13.1 (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.

$$CC = \frac{(1 - e^{-\mathrm{LAI}/1.3})}{(1 + e^{-\mathrm{LAI}/1.3})} \qquad \text{Equation 13.1}$$

13.2.3.3 Soil data

Information from previous studies (Chimungu, 2009; Haka, 2010) describing soil characteristics was used for creating the soil profile characteristics file. The information included soil type for the whole profile and physical characteristics such as soil water content at saturation, field capacity (DUL) and permanent wilting point (LL), and saturated hydraulic conductivity (K_{sat}) and. 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.

13.2.3.4 Field management

The actual amount of irrigation water applied and dates of irrigation were used to create irrigation files. The field management was described as optimum characterised by non-limiting soil fertility, without surface mulches and no temperature stress. Datasets from the pots and lysimeter trials under water stress as well as rainfed treatments for the two crops were used for calibrating the model for water stress conditions.

13.2.4 Model calibration and validation

Calibration is adjusting certain model parameters to make the model match the measured values at the given 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 of the field. The conservative parameters were selected as a default which should be generally applicable or maybe for a given species or cultivar specific. Default values were selected for some parameters that were not measured during the studies. Examples of these parameters are initial CC cover per seedling, water extraction pattern and average root zone expansion. The observations from the pots, lysimeter and field trials were used to parameterize the model. Calibration was performed using data from field studies for the two crops under well-watered and rainfed conditions. Data for the 2009/10 season were used for the calibration of the model for amaranth because leaf area was not measured during the 2008/2009 season. The 2008/09 season datasets were used to validate the model for the crop.

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 from the field studies while parameters such as canopy growth and canopy decline coefficients were generated by the model from the observed values (Tables 13.2 and 13.4). Calibration of the model for the two crops started with the green crop canopy (CC) development. During the calibration process, the importance of the coefficient of transpiration (K_{ctr}) was observed as it is proportional to CC (Karunaratne *et al.*, 2011). The canopy covers of the well-watered treatments were the first to be calibrated before the rainfed which was assumed to represent water stress conditions. Simulations were run and the K_{ctr} were reduced until a better fit was achieved for the CC of the two crops under well-watered and rainfed conditions. Thereafter, biomass production was the next parameter to be calibrated. Values for the WP parameter, 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 biomass production. The reference harvest index (HI_o) for leafy vegetables was set at default for amaranth while the HI_o of pearl millet as a grain crop was set at 52%. This was to determine yield, product of HI_o and B, for the two crops. Fine-tuning and adjustments of parameters were done until good matches between simulated and measured were obtained. Responses due to salinity, fertility and temperature were not considered during the calibration and validation of the model for the two crops. Parameters evaluated for goodness of fit of the model were CC, biomass, SWC and ET.

13.2.5 Statistics

Goodness of fit for the calibration and validation of the model was carried out using three statistical methods. They are R^2, which is the coefficient of determination; root mean square error (RMSE) calculated using Equation 13.2 and index of agreement (d) (Willmot, 1982) derived with Equation 13.3 as follows:

$$RMSE = [n^{-1} \sum_{i=1}^{n} (S_i - O_i)^2]^{0.5} \quad \text{Equation 13.2}$$

$$d = 1 - \frac{\sum_{i=1}^{n} (S_i - O_i)^2}{\sum_{i=1}^{n} (|S_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad \text{Equation 13.3}$$

where n is the number of observations, S_i and O_i are the simulated and observed values for the corresponding parameter, respectively, and $\bar{O}$ is the mean of the observed variable. The RMSE assumes the same unit as the parameter under observation. The model's goodness of fit increases as the value of RMSE approaches zero. The values of the index of agreement (*d*) range from 0 to 1. The closer the *d* value is to 1 the better the agreement between the simulated and observed values.

13.3 Results and Discussion

13.3.1 Amaranth

13.3.1.1 Calibration for amaranth

Table 13.2 shows the crop parameters and values resulting from the calibration of the model for amaranth using data from the 2009/10 season. Crop parameters that depend on management include plant density (33 333 plants ha^{-1}), time to recover (4 days) and maximum CC (95%) while conservative parameters include water productivity normalized for ET_o and CO_2, WP*, (28 tons ha^{-1}) and the crop transpiration coefficient (K_{ctr}) (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 amaranth. The calibration showed a good fit between observed and simulated values for CC for the well-watered treatment (W5) as well as the rest of irrigation treatments (Figure 13.1). However, the model under-estimated CC under rainfed conditions (W1)by. This may be due to the small value of the initial cover size of transplanted seedling (CC_o = 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 for all treatments but showed a good fit by the end of the season for all the irrigated treatments. Overall, there was a moderately good agreement between simulated and observed CC with R^2 of 0.577 and *d* of 0.746 (Table 13.3).

Biomass production of amaranth was well-simulated by AquaCrop for most of the treatments with the better fits found in the W2 and W1 treatments (Figure 13.2). There was over-estimation of biomass production in the W5 treatment which was thought to may have been due to nutrient leaching causing nutrient stress which was not considered during model calibration. The RMSE (1.866 t ha^{-1}), R^2 (0.900) and *d* (0.957) also supported the good overall performance of AquaCrop in simulating biomass production of amaranth (Table 13.3). The simulated and observed soil water content had the best fit for the W3 and W2 treatments (Figure 13.3). Although the initial soil water content was well-simulated for all the treatments, there was over-estimation in well-watered treatment (W5) and under-estimation in the rainfed (W1) treatment. The discrepancies between simulated and observed values may be due to the fact that information from the literature was used to calibrate the model for effective rooting depth because there was no available data from the field studies to develop this parameter for amaranth. The values of RMSE, R^2 and *d* index of agreement for model performance during calibration for soil water content were 50.466 mm, 0.454 and 0.802, respectively (Table 13.3). Good simulation of cumulative ET for all the treatments is illustrated in Figure 13.4. This was contrary to the model's 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 cumulative ET for amaranth.

13.3.1.2 Validation for amaranth

For validation, only biomass, soil water content and cumulative ET parameters were used to evaluate performance of the model since CC was not measured during the 2008/09 season. AquaCrop was able to simulate accurately biomass production for the well-watered (W5) and rainfed (W1) treatments (Figure 13.5). There was under-estimation 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 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. The simulated initial soil water contents for all the treatments were accurate compare to the observed (Figure 13.6). AquaCrop over-estimated soil water content around 40 days after transplanting until the end of the season in all the treatments; however, the trends of observed and simulated values were similar. Model performance was very good in simulating cumulative ET (Figure 13.7). The model slightly over-predicted at the earliest stage and under-predicted cumulative ET during the later stages of crop growth. Out of all the treatments, the best agreement between simulated and observed cumulative ET was found in the rainfed treatment (W1). Differences between simulated and observed cumulative ET may be due to possible error in calculating observed daily ET. AquaCrop performed consistently well in simulating cumulative ET with RMSE of 75.635 mm, R^2 of 0.912 and *d* index of agreement of 0.908.

Generally, calibration and validation of AquaCrop for amaranth was satisfactory, although the R^2 of simulated versus observed SWC for the calibration and validation were low with moderate *d* index of agreement. The tendency by the model to over-predict SWC as was found during the validation process for the crop was also 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. 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 quinoia, a similar crop to amaranth, with good agreements between 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 8 quinoia 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 amaranth for this study.

Table 13.2: Selected crop parameters and values for calibration and validation of AquaCrop for amaranth.

Crop parameters	Descriptions	Input
Type of Crop		leafy vegetable
Carbon cycle		C4
T base	Base temperature (°C)	7
Tupper	Upper temperature (°C)	30
Method of planting	Sowing / Transplanting	Transplanting
Initial cover	Cover size transplanted seedling ($cm^2 plant^{-1}$)	20
CCo	Initial canopy cover (%)	0.67
Plant density	Plants ha^{-1}	33 333
Time to CCx	planting to CCx (day)	55
CCx	Maximum canopy cover (%)	95
CGC	Canopy growth coefficient ($\%day^{-1}$)	14.7
CDC	Canopy decline coefficient ($\%day^{-1}$)	8.0
Time for decline	Canopy decline (day)	37
Time to recover	transplants recovery (day)	4
Time to Zr(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
Zr (max)	Max effective rooting depth (m)	1.75
Zr (min)	Min. rooting depth (m)	0.3
Expansion	Avg. root zone expansion (cm day^{-1})	2.7
Kc_{tr}	Coefficient for transpiration	0.8
Aging	Reduction with age (% day^{-1})	0.15
Green canopy cover	Effect of canopy in late season (%)	60
WP*	Water productivity (ton ha^{-1})	28
HIo	Reference harvest index (%)	85
Canopy expansion		Moderately tolerant to water stress
	Ks p(upper)	0.25
	Ks p(lower)	0.6
	shape factor	6
Stomatal closure		Moderately tolerant to water stress
	Ks p(upper)	0.65
	shape factor	6
Early canopy Senescence		Moderately tolerant to water stress
	Ks p(upper)	0.65
	shape factor	5
Aeration stress		Very sensitive to water logging

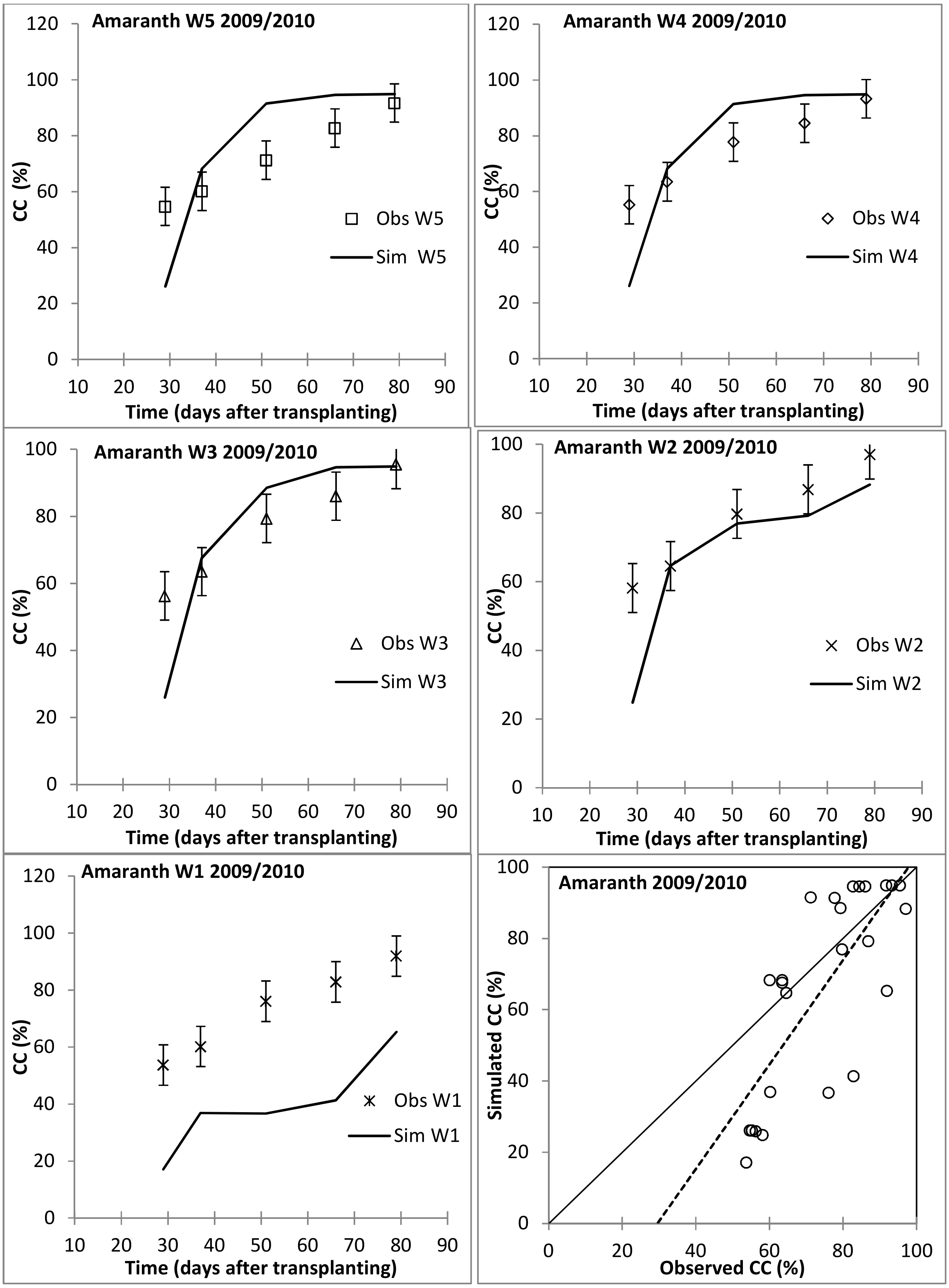

Figure 13.1: Simulated versus observed canopy cover (CC) under irrigation and rainfed treatments during the 2009/10 season used for calibration of the AquaCrop model for amaranth.

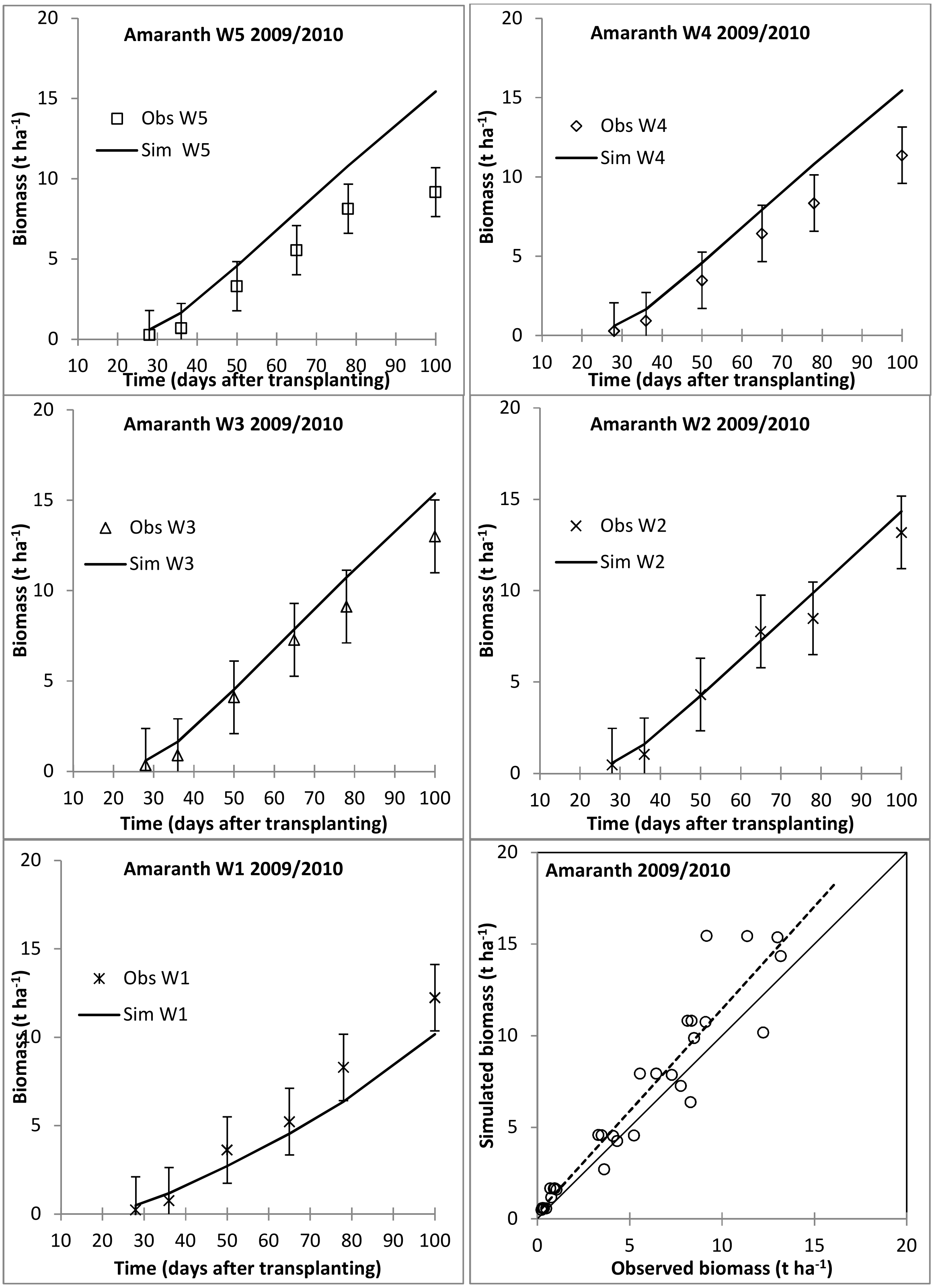

Figure 13.2: Simulated versus observed biomass under irrigation and rainfed treatments during the 2009/2010 season used for calibration of the AquaCrop model for amaranth.

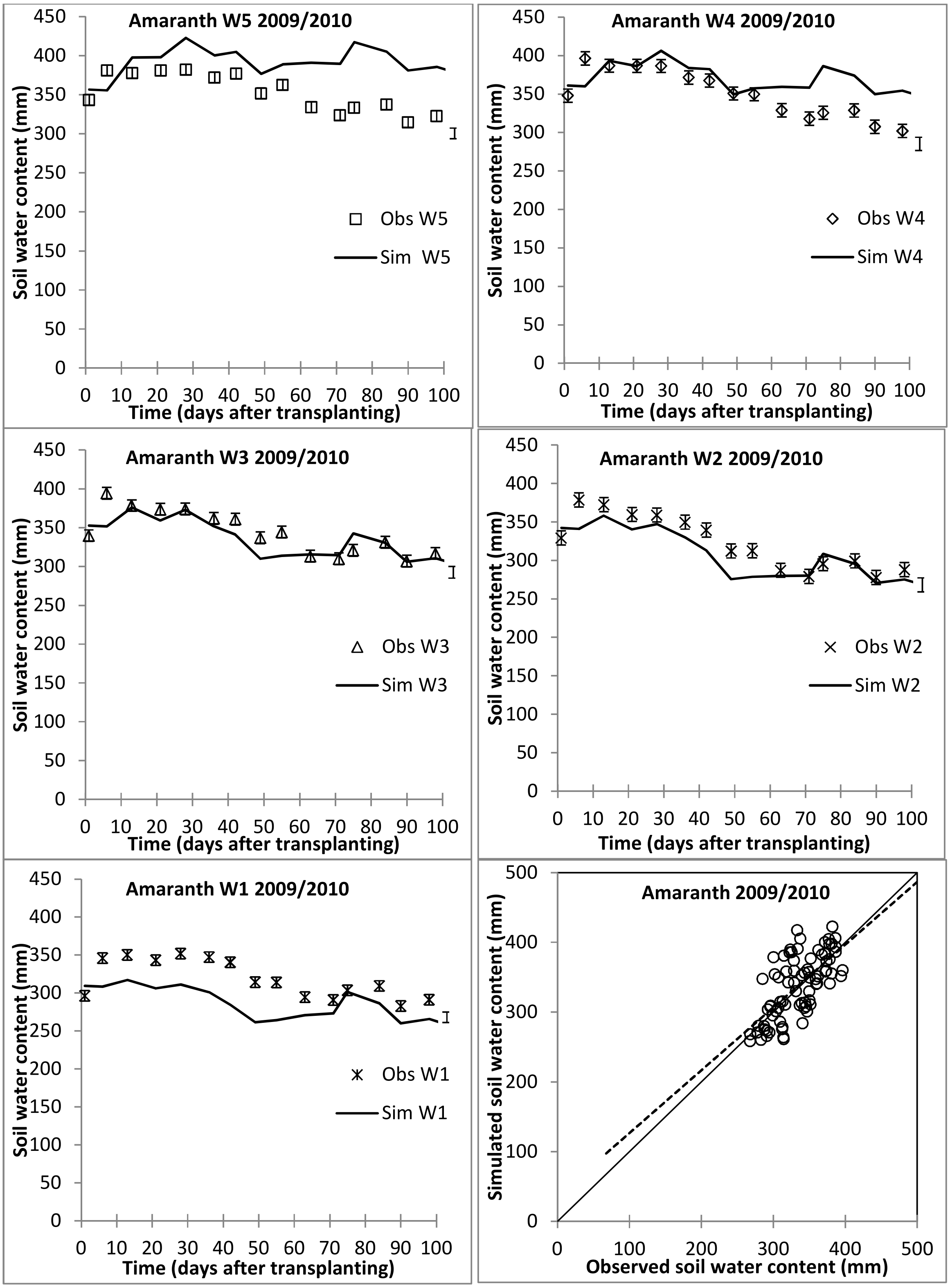

Figure 13.3: Simulated versus observed soil water content (SWC) under irrigation and rainfed treatments during the 2009/10 season used for calibration of the AquaCrop model for amaranth.

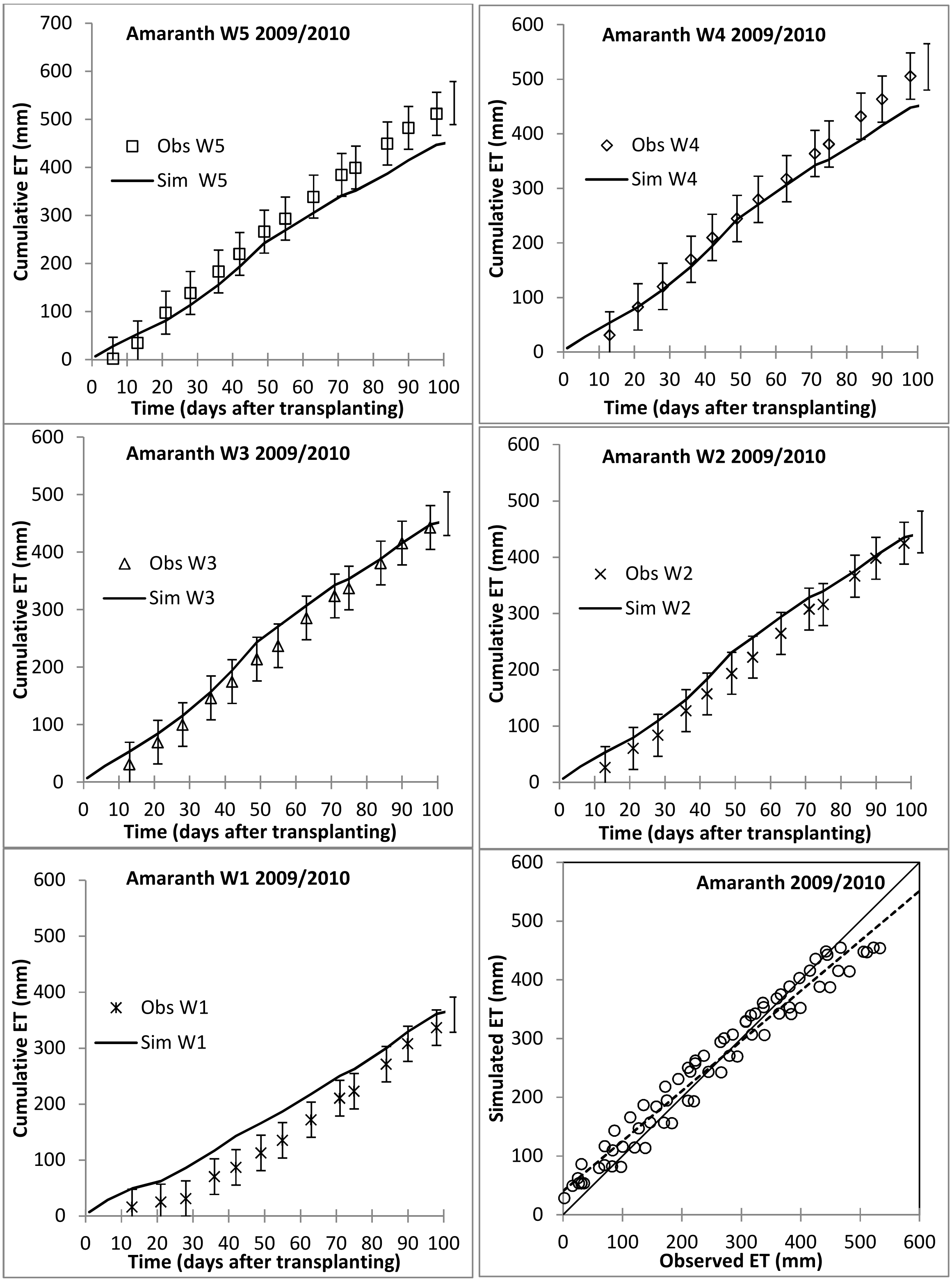

Figure 13.4: Simulated versus observed cumulative evapotranspiration (ET) under irrigation and rainfed treatments during the 2009/10 season used for calibration of the AquaCrop model for amaranth.

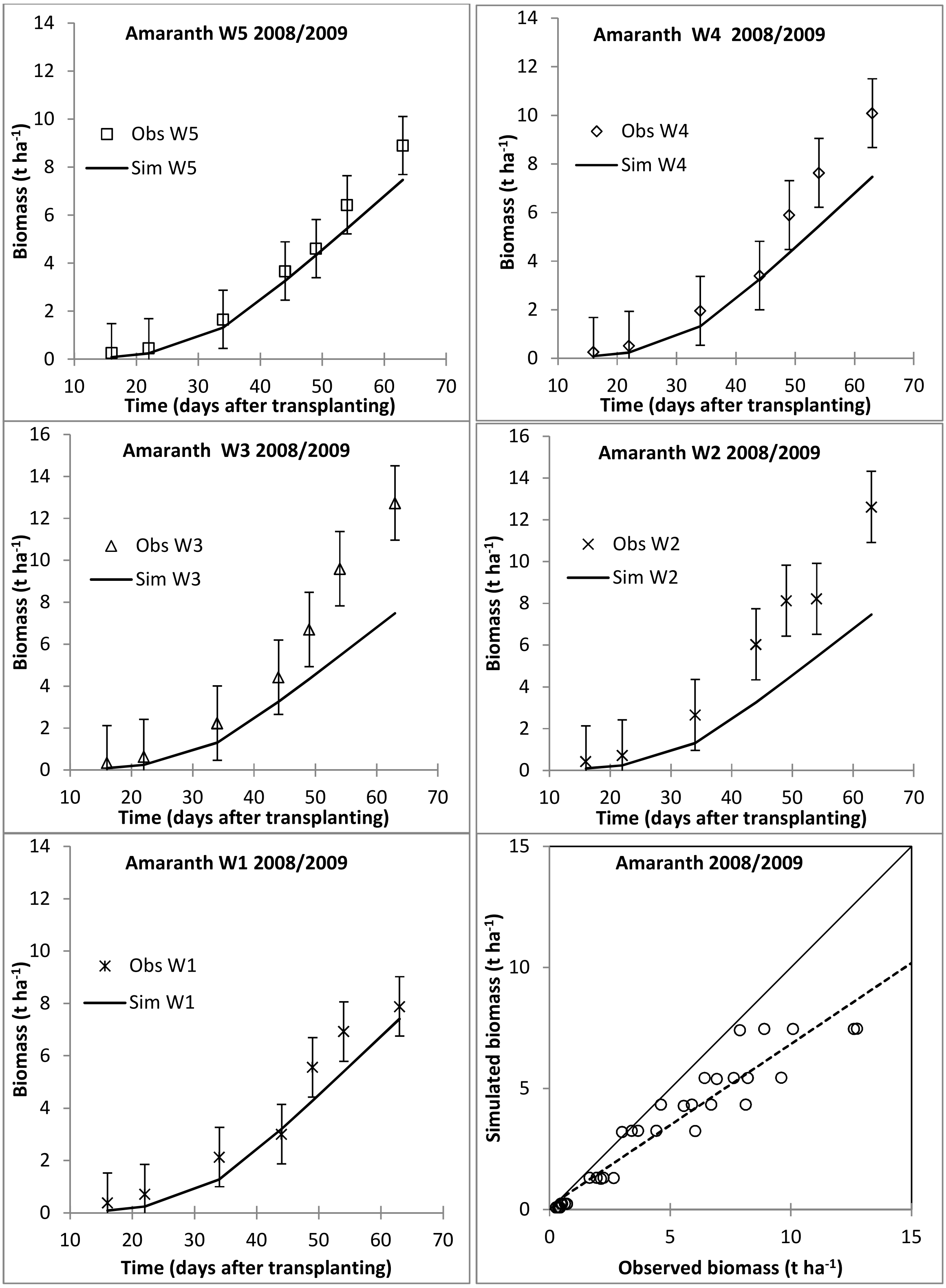

Figure 13.5: Simulated versus observed biomass under irrigation and rainfed treatments during the 2008/2009 season used for validation of the AquaCrop model for amaranth.

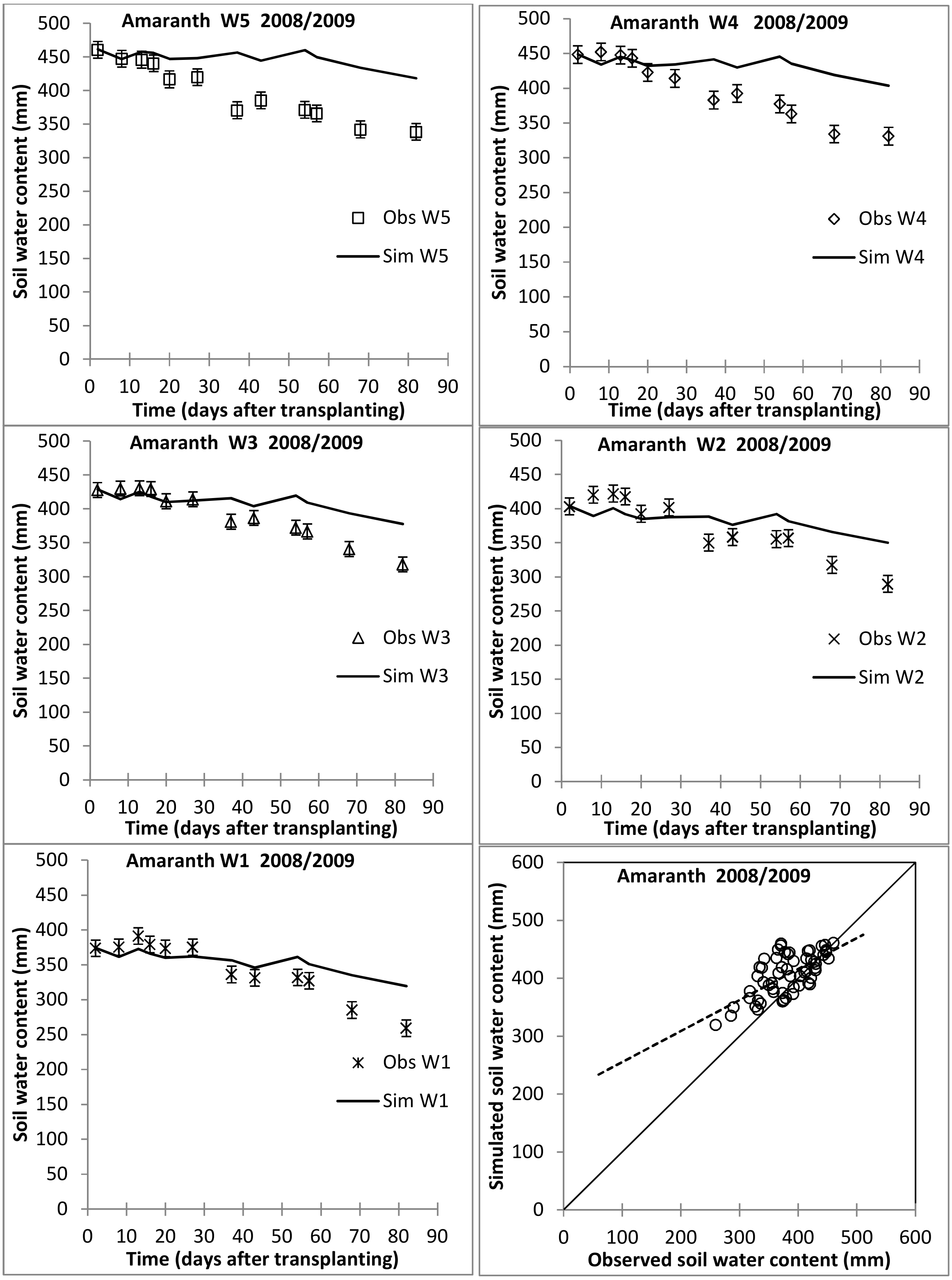

Figure 13.6: Simulated versus observed soil water content (SWC) under irrigation and rainfed treatments of the 2008/2009 season used for validation of the AquaCrop model for amaranth.

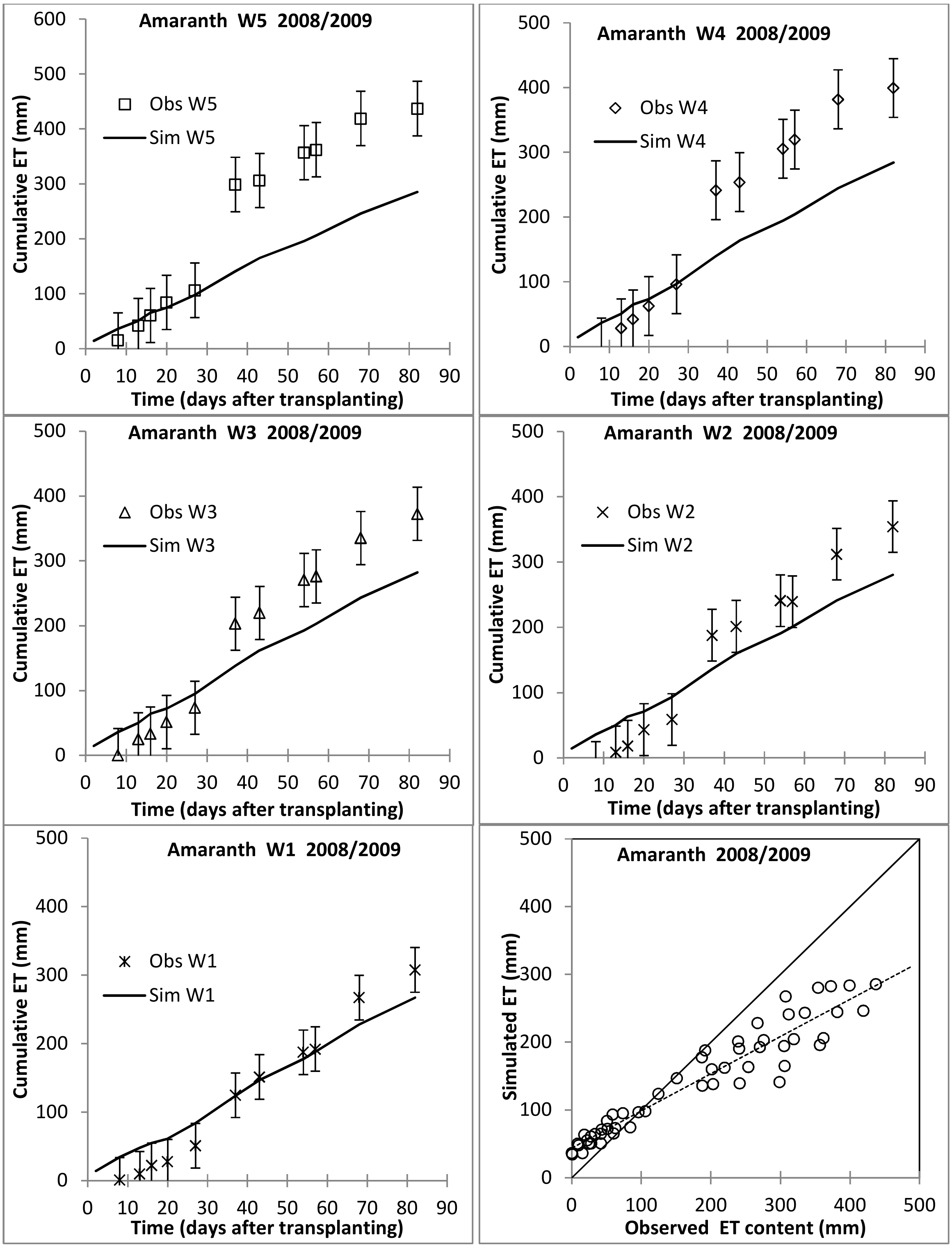

Figure 13.7: Simulated versus observed cumulative evapotranspiration (ET) under irrigation and rainfed treatments of the 2008/09 season used for validation of the AquaCrop model for amaranth.

Table 13.3: Root mean square (RMSE), coefficient of determination (R^2) and index of agreement (*d*) for canopy cover (CC), biomass production, soil water content (SWC) and cumulative evapotranspiration (ET) for calibration and validation of AquaCrop for amaranth.

Calibration 2009/10			
Parameters	*RMSE*	R^2	*d*
Canopy cover CC	20.817	0.577	0.746
Biomass	1.866	0.900	0.957
SWC	50.466	0.454	0.802
ET	34.1128	0.963	0.989
Validation 2008/09			
Biomass	1.964	0.916	0.905
SWC	50.616	0.302	0.666
ET	75.635	0.912	0.908

13.3.2 Pearl millet

13.3.2.1 Calibration for pearl millet

Calibration for pearl millet was performed using data from the 2008/09 planting season field trials under irrigated and rainfed conditions. Non-conservative parameters for the two lines of pearl millet included plant population (55 556 plants ha^{-1}), planting method (sowing), time to 90% emergence (4 days) and maximum canopy cover (95 and 98%) (Table 13.4). The two lines had different times to maturity; GCI 17 (improved line) and monyaloti (local variety) matured in 105 and 120 days after sowing, respectively. Calibration was done under conditions of no fertility stress while the effects of soil water stress on canopy expansion, stomatal closure and early senescence were set at extremely tolerant to water stress for the two lines of pearl millet.

Response of the two pearl millet lines to environment showed good simulation for CC under irrigation (Figure 13.8). There was under-estimation of CC earlier in the season but the model was able to simulate CC accurately from 39 DAS for all irrigation treatments and for both pearl millet lines. Under rainfed conditions (W1), the model under-estimated CC of both pearl millet lines. However, there was a strong overall R^2 of 0.898 for CC for both pearl millet lines. The model simulated CC accurately for GCI 17 and monyaloti with R^2 of 0.906 and 0.914 and also *d* index of 0.837 and 0.783, respectively (Table 13.5). During model calibration, biomass was accurately simulated for all conditions (Figure 13.9). Biomass was slightly under-predicted for GCI 17 and monyaloti at the end of the season for all conditions. The highest deviation between simulated and observed biomass was found in the W5 and W4 treatments of monyaloti. The deviation could be due to the tillering ability of the crop. Overall, the simulation was good with

R^2 of 0.961, RMSE of 2.931 t ha^{-1} and *d* index of 0.974. There was good agreement between simulated and measured biomass of GCI 17 and monyaloti (R^2 = 0.963, RMSE = 1.519 t $ha^{-1}$and *d* = 0.983 for GCI 17; R^2 = 0.967, RMSE = 2.625 t ha^{-1} and *d* = 0.968 for monyaloti) (Table 13.5).

For all conditions, initial SWC was well-simulated for both pearl millet lines. Initial soil water content is an important parameter of the model in simulating measured values of different crop parameters. Though, the observed SWC for both pearl millet lines followed the same trend, 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 DAS for monyaloti for all conditions. Figure 13.10 shows that the model simulated SWC fairly well (*d* = 0.556 and low R^2 = 0.127). The RMSE, R^2 and *d* index for SWC for each line of pearl millet were as low as when all results were combined for the two lines of pearl millet (Table 13.5). Irrespective of the performance of the model in simulating SWC, cumulative ET was predicted accurately for both pearl millet lines with high values of R^2 and *d* index (Figure 13.11). Observed cumulative ET was well simulated at the beginning of the season for both pearl millet lines. However, as the crop approached maturity the model under-estimated cumulative ET for both pearl millet lines under well-watered conditions (W5). Cumulative ET was better simulated for GCI 17 for the W3, W2 and W1 treatments while there was under-estimation of ET for monyaloti from 80 DAS for all conditions. Table 13.5 shows the statistical evaluation for simulations of cumulative ET. Overall, the agreement between simulated and observed cumulative ET was very good with R^2 = 0.876 and *d* index = 0.937.

Results of simulations of CC for both pearl millet lines under rainfed condition exhibited the same trend of simulations reported by Heng *et al.* (2009) but with good overall performance of the model. During validation of AquaCrop for maize by Heng *et al*. (2009), the CC of non-irrigated short-season treatment was not well simulated with CC declining faster 70 days after sowing. The under-estimation of final biomass of the two lines of pearl millet may be due to the fact that the rate of 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, reaching a maximum before slowing down as leaves senesce

Table 13.4: Selected crop parameters and values for calibration and validation of AquaCrop for pearl millet.

PARAMETER	DESCRIPTION	GCI	MONYALOT
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^2)	5	5
Plant density	Plants/ha	55 556	55 556
CC0	CCo	0.28	0.28
Emergence	Days to 90% emergence (calendar)	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 entirely	Almost entirely
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 (max)	Max effective rooting depth (m)	1.75	1.75
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	medium-deep	medium-deep
Rooting depth	Time from sowing to maximum rooting	45	45
Expansion	Average root zone expansion (cm day^{-1})	3.6	3.6
Kctr	Coefficient for transpiration	0.7	0.6
	Green canopy cover (%)	60	60
	Reduction with age (% day^{-1})	0.15	0.15
Water extraction pattern	Maximum root water extraction (mm	56	56
$S_{x, top}$ top quarter of root	Maximum root water extraction (m^3	0.051	0.051
$S_{x, bot}$ bottom quarter of	Maximum root water extraction (m^3	0.013	0.013
WP	Water productivity (g m^{-2})	35	40
HI0	Reference harvest index	52	52
Canopy expansion		Extremely tolerant to water stress	
	Ks p(upper)	0.35	0.35
	Ks p(lower)	0.7	0.7
	shape factor	3	3.5
Stomatal closure		Extremely tolerant to water stress	
	Ks p(upper)	0.75	0.75
	shape factor	3	3.5
Early canopy		Extremely tolerant to water stress	
	Ks p(upper)	0.8	0.8
	shape factor	3	3.5
Aeration stress	Aeration stress	Sensitive to water logging	
	Ks_{aer} (vol %)	15	15

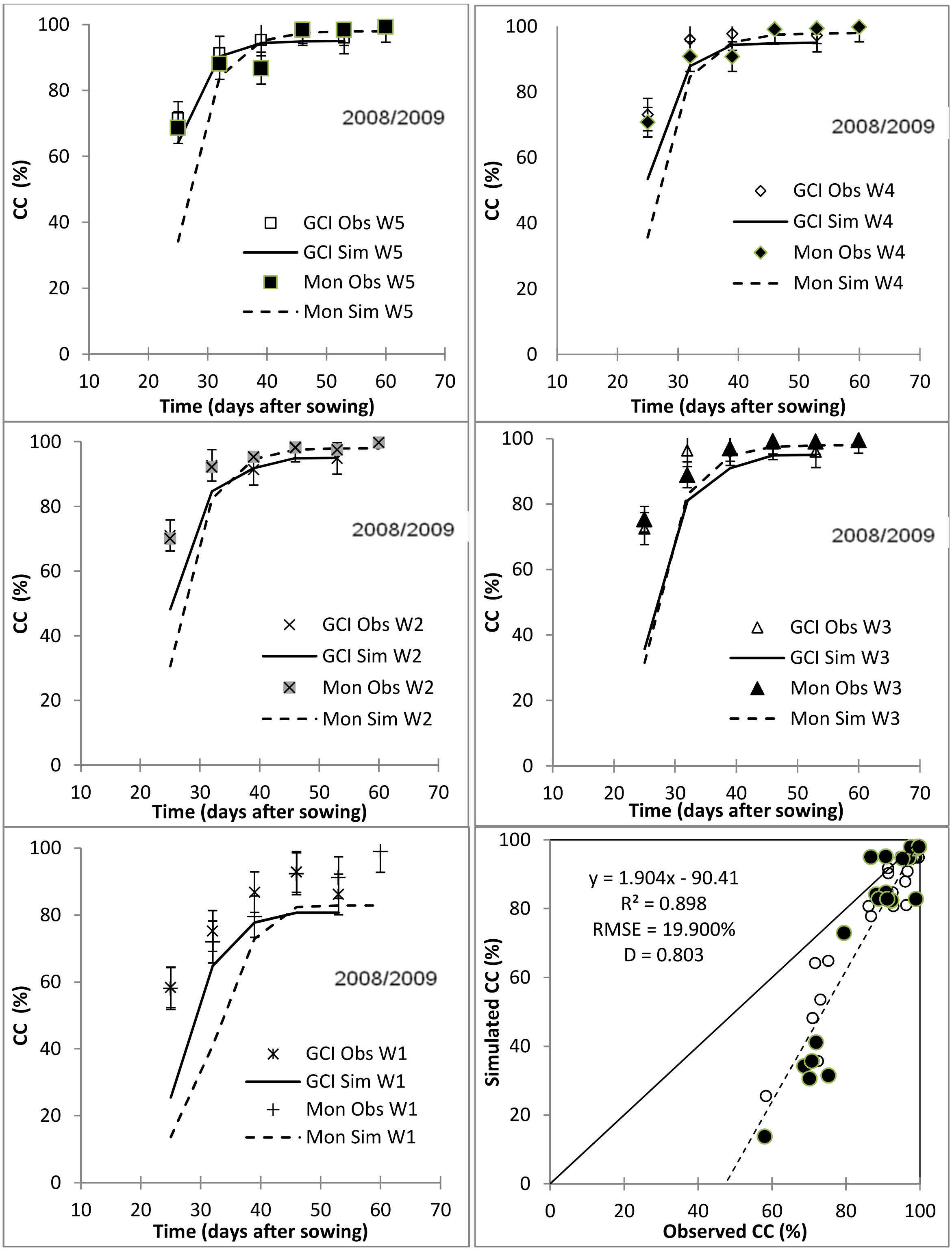

Figure 13.8: Simulated versus observed canopy cover (CC) under irrigation and rainfed treatments during the 2008/09 season used for calibration of the AquaCrop model for pearl millet.

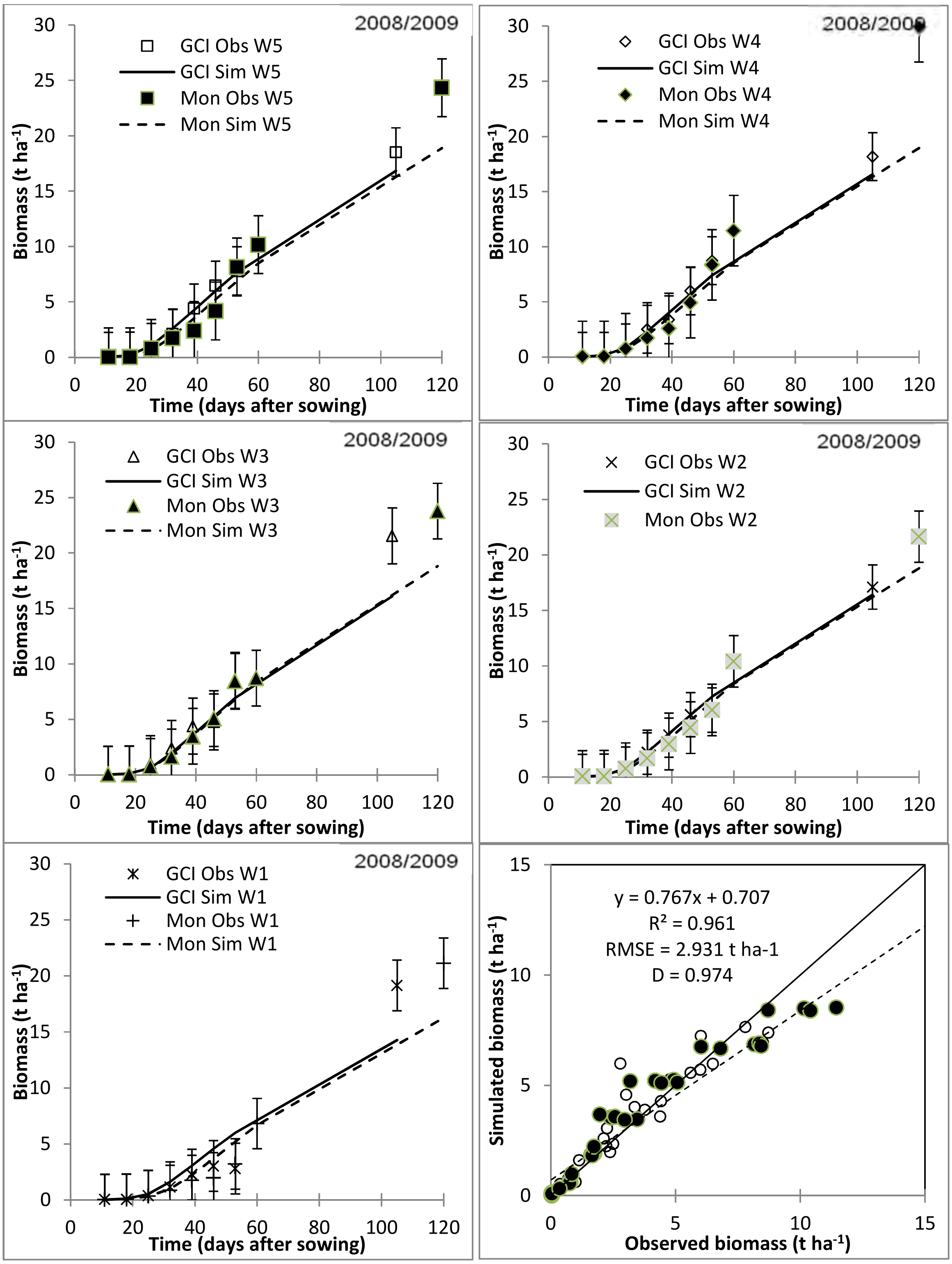

Figure 13.9: Simulated versus observed biomass produced under irrigation and rainfed treatments during the 2008/09 season used for calibration of the AquaCrop model for pearl millet.

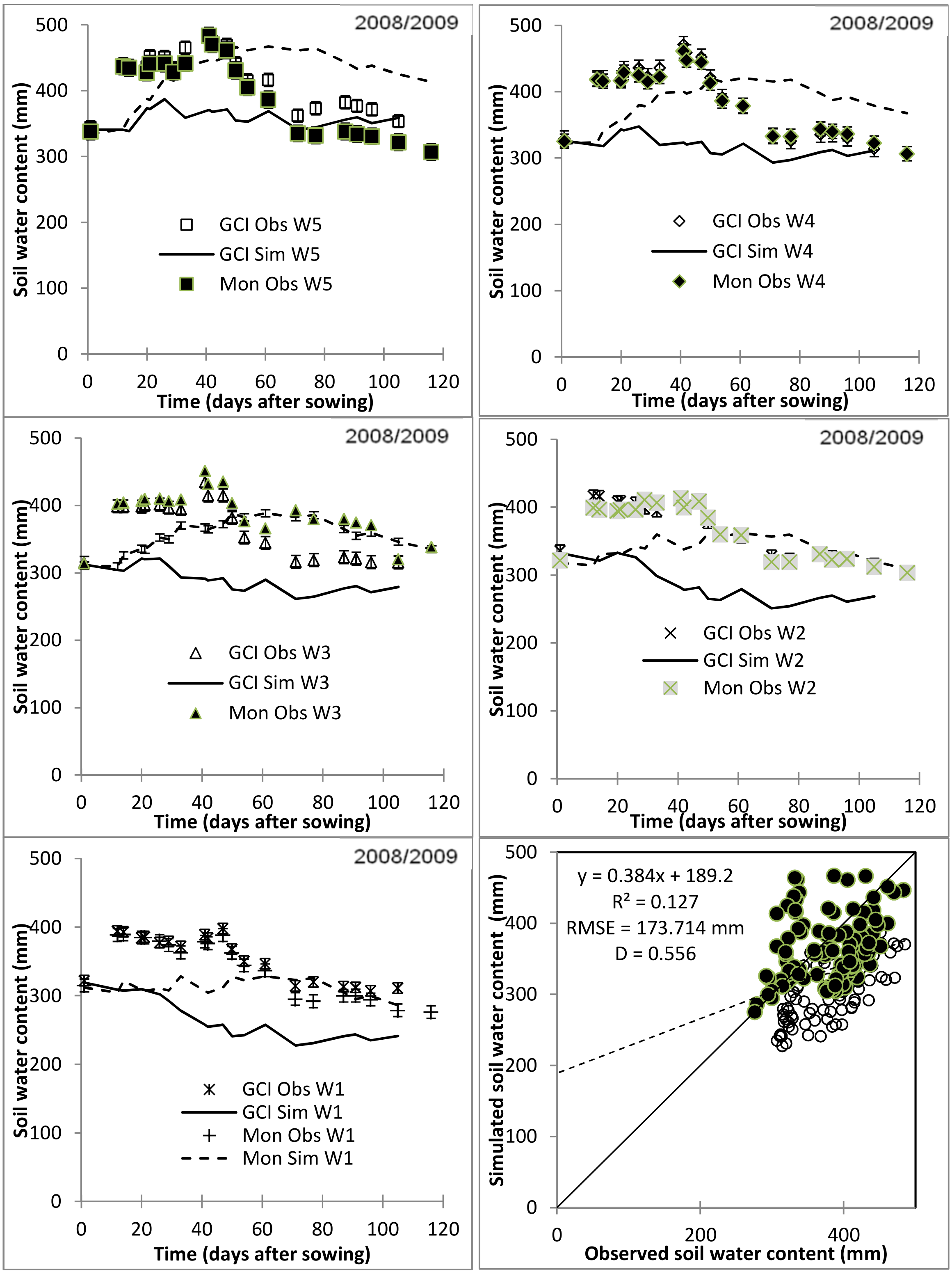

Figure 13.10: Simulated versus observed soil water content (SWC) under irrigation and rainfed treatments during the 2008/09 season used for calibration of the AquaCrop model for pearl millet.

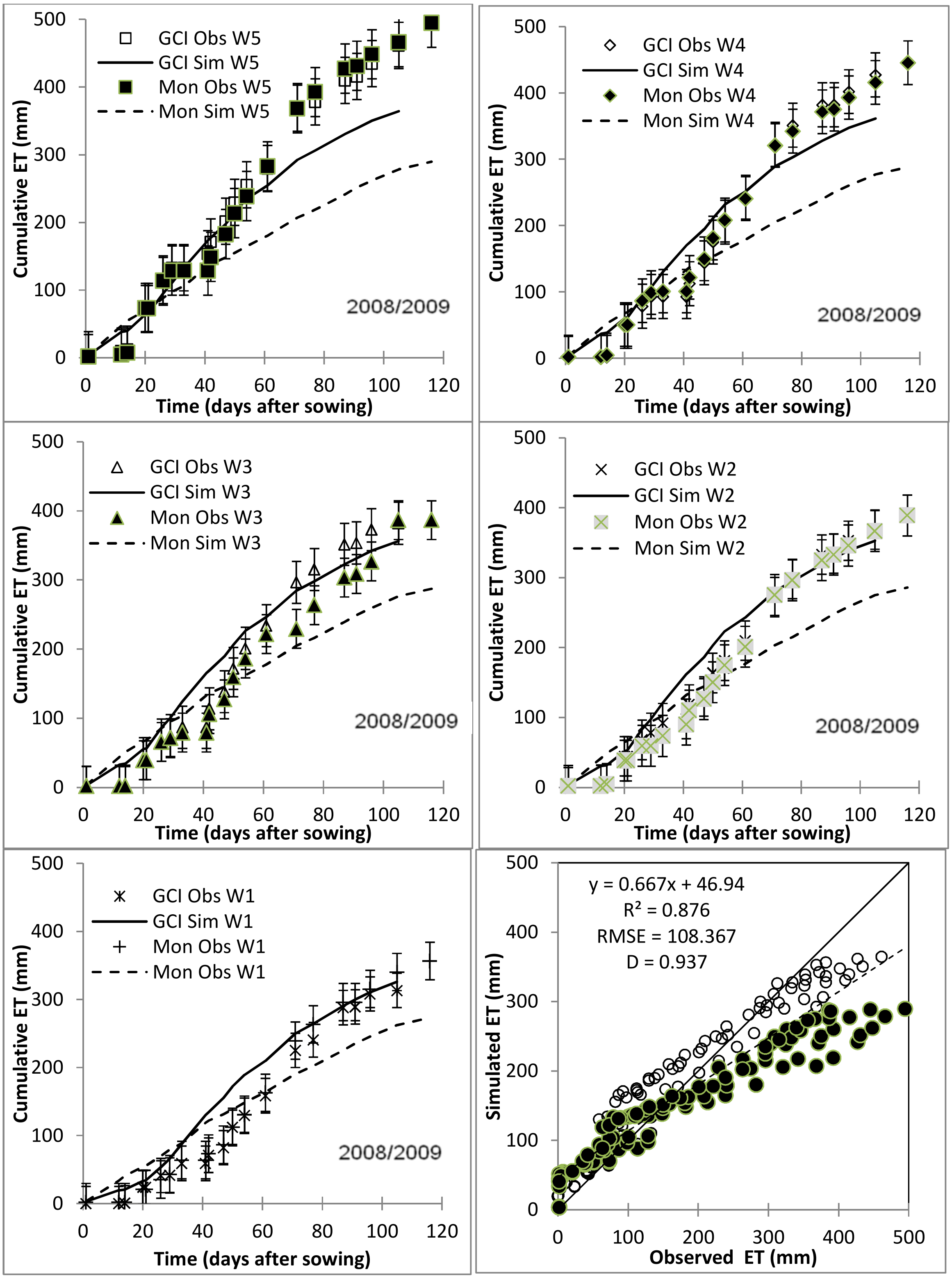

Figure 13.11: Simulated versus observed cumulative evapotranspiration (ET) under irrigation and rainfed treatments during the 2008/09 season used for calibration of the AquaCrop model for pearl millet.

Rahman *et al*. (2010), Farahani *et al.* (2009) and Hussein *et al.* (2011) reported the tendency of AquaCrop to over-estimate SWC when calibrating the model for potato and cotton. The SWC was over-predicted for these experiments but the patterns of 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, simulating cumulative ET of cotton using AquaCrop. These are not farfetched from the values achieved when simulated and observed cumulative ET were compared for the two lines of pearl millet.

13.3.2.2 Validation for pearl millet

Simulations of CC for the two pearl millet lines are illustrated in Figure 13.12. The predictions of CC for the two lines of pearl millet were accurate under all conditions (R^2 = 0.782; RMSE = 16.053%; *d* = 0.920). However, simulation of monyaloti CC was slow to reach senescence in all the treatments unlike the observed that started senescing 80 days after sowing. A possible reason for this could be due to the fact that the year was considered to be a good year in terms of high rainfall occurrence.

Predictions of biomass for the two lines of pearl millet were in agreement with the observed biomass at the first half of the season in all the irrigated treatments (Figure 13.13). Biomass was under-estimated for monyaloti from 80 DAS under irrigated conditions. This could be due to the same reason mentioned during model calibration. However, throughout the season, simulation of biomass production under rainfed conditions (W1) was accurate for GCI 17 line. On average, the model simulated biomass accurately under all conditions and both lines of pearl millet (R^2 = 0.891, RMSE = 6.889 t ha^{-1} and *d* index = 0.924). Considering the calibration simulations, the model consistently reproduced, moderately, the trend of SWC both lines of pearl millet (Figure 13.14). For all conditions, there was over-prediction of SWC after 100 DAS. The good fit of the simulations were demonstrated by *d* index of 0.659, combining results of all the treatments. The statistical interpretations of the goodness of fit for each line of pearl millet are presented Table 13.5. The model's performance was consistent for the two lines of pearl millet. There were good simulations of cumulative ET for the two lines of pearl millet for all conditions (Figure 13.15). However, cumulative ET was slightly over-estimated for GCI 17 for all irrigation treatments. Generally, simulated versus observed cumulative ET showed good fit (R^2 = 0.967, RMSE = 57.329 mm and *d* index = 0.981).

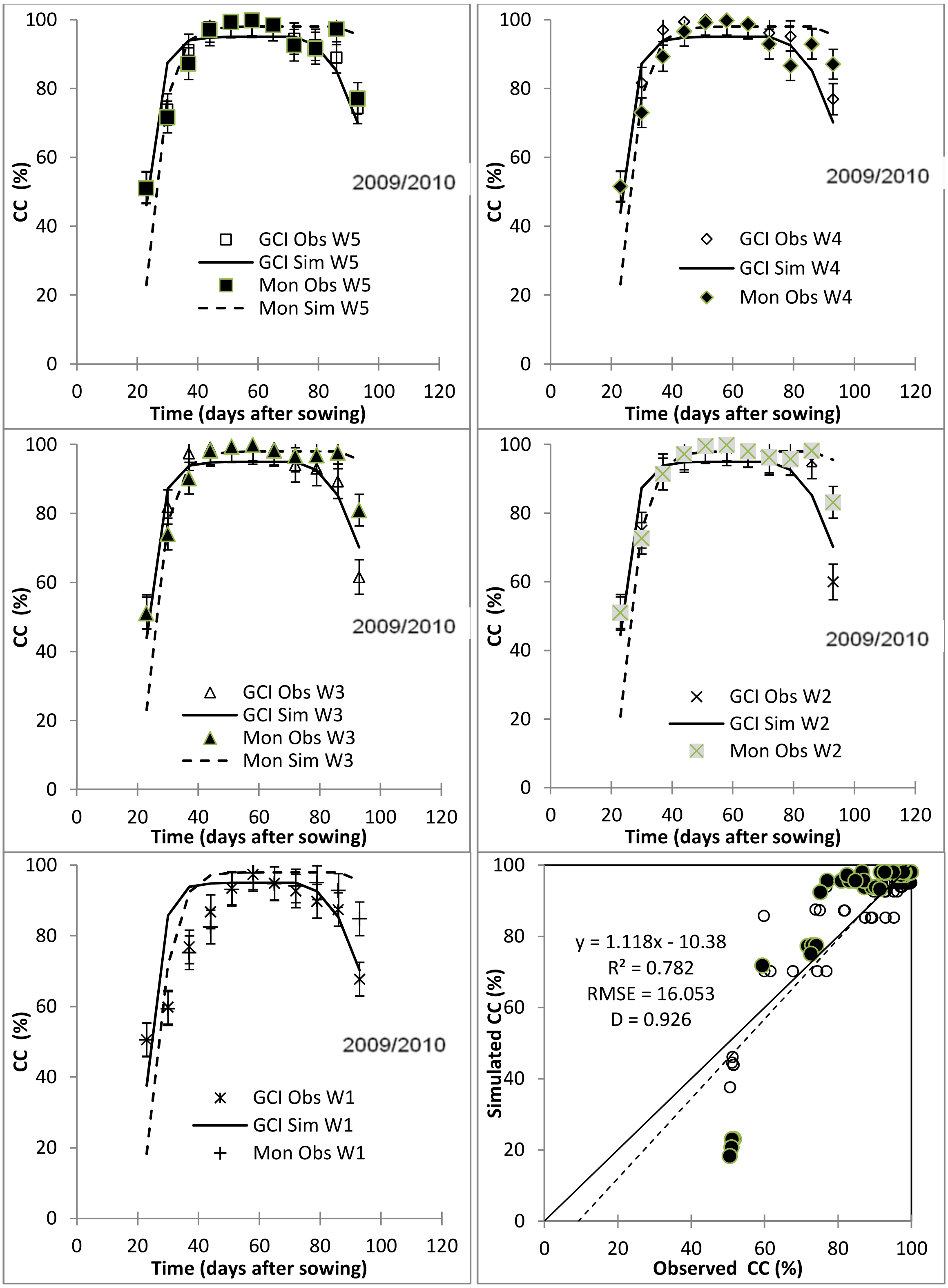

Figure 13.12: Simulated versus observed canopy cover (CC) under irrigation and rainfed treatments of the 2009/10 season datasets used for validation of the AquaCrop model for pearl millet.

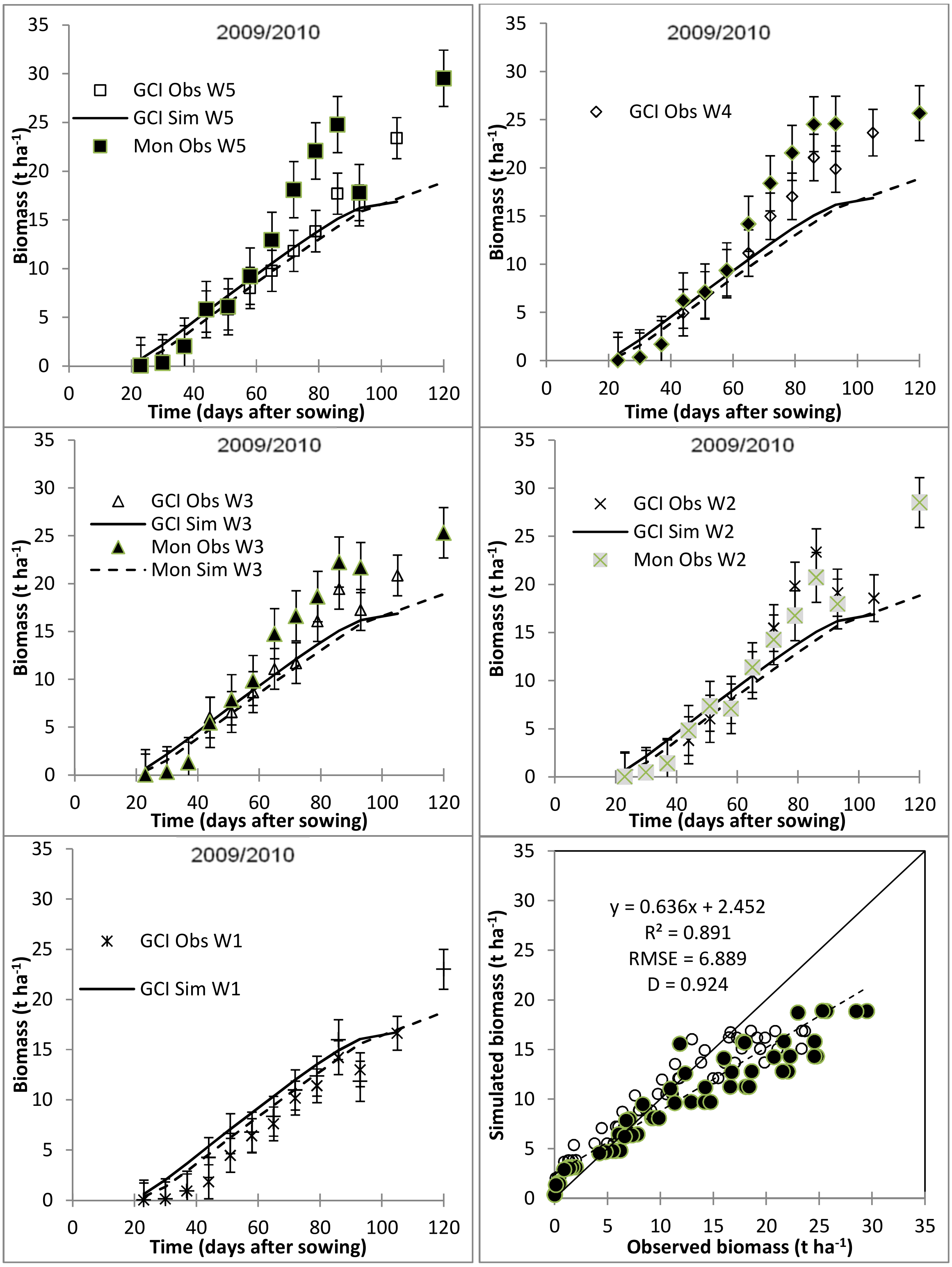

Figure 13.13: Simulated versus observed biomass produced under irrigation and rainfed treatments of the 2009/10 season datasets used for validation of the AquaCrop model for pearl millet.

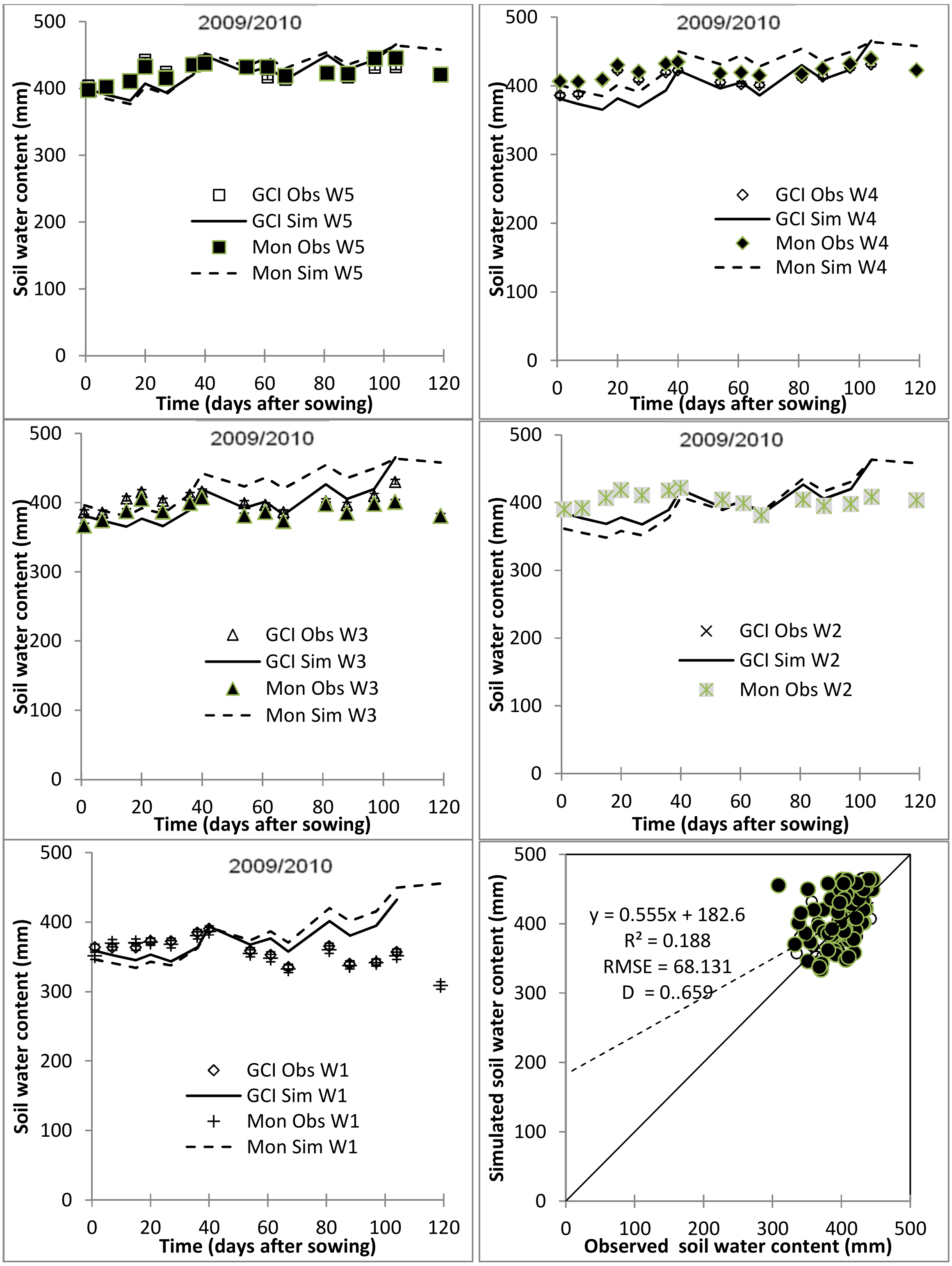

Figure 13.14: Simulated versus observed soil water content (SWC) under irrigation and rainfed treatments of the 2009/10 season datasets used for validation of the AquaCrop model for pearl millet.

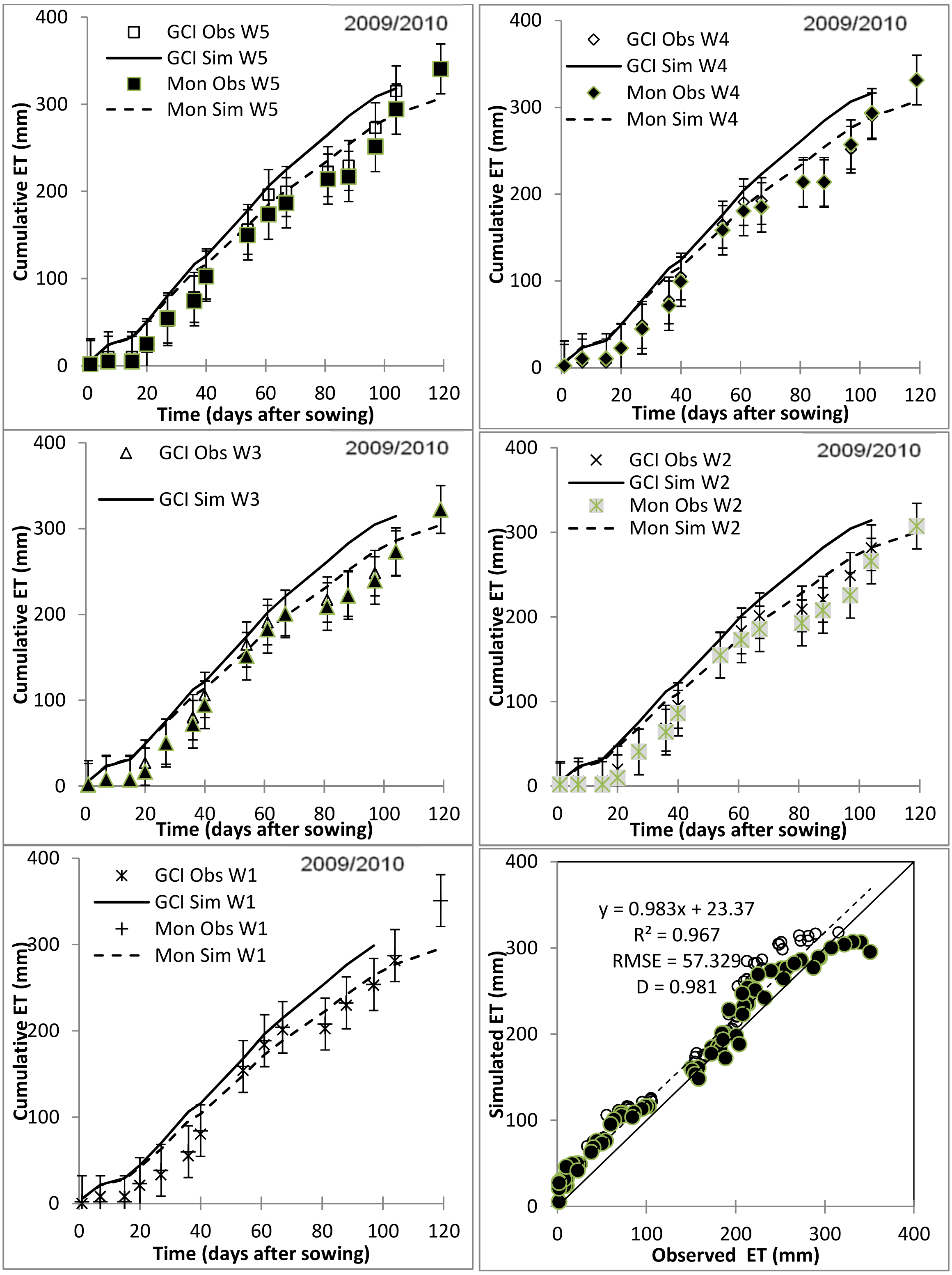

Figure 13.15: Simulated versus observed cumulative evapotranspiration (ET) under irrigation and rainfed treatments of the 2009/10 season datasets used for validation of the AquaCrop model for pearl millet.

Table 13.5: 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.

GCI 17	***Calibration 2008/2009***			***Validation 2009/2010***		
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	1.519	0.963	0.983	3.566	0.917	0.953
SWC	142.98	0.431	0.54	23.48	0.327	0.747
ET	64.786	0.944	0.976	46.255	0.981	0.975
Monyaloti						
Canopy cover CC	17.897	0.914	0.783	13.564	0.817	0.91
Biomass	2.625	0.967	0.968	5.901	0.914	0.904
SWC	98.657	0.107	0.614	57.63	0.134	0.607
ET	126.876	0.928	0.892	33.868	0.974	0.987

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 the two lines of pearl millet. The soil water content was moderately simulated for the two lines of pearl millet but needs more improvement. 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 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 means of determining irrigation scenarios that can lead to 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 crops even if available input data were limited.

13.4 Conclusion

The AquaCrop model was able to simulate canopy cover (CC), biomass production and cumulative evapotranspiration (ET) for the amaranth and pearl millet 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 14

Conclusions and Recommendations

AT MODI

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South Africa faces a challenge of climate change and poor access to germplasm by the producers. Food insecurity is not declining. These two challenges can be obviated somewhat by taking advantage of natural biodiversity that includes a wild range of edible plants. Some of these plants have already been domesticated, but they are underutilised or neglected by the modern system of agriculture. Others are potential domesticants that need basic agronomy to explain their responses to the key challenges of crop growth and development. This study identified traditional maize landraces, wild watermelon, wild mustard, cowpeas, amaranth, pearl millet, bambara groundnut, and taro as underutilised indigenous and traditional (maize) crops of South Africa that require in-depth agronomic research. The aim was to explain their potential response to drought at different sites mainly in KwaZulu-Natal and to a measurable extent in the Free State and to a less extent in Gauteng. The study made an important contribution to the existing body of literature on neglected underutilised species or food crops both locally and internationally. The key outcomes of novelty in this study are the following:

(a) Seed coat colour as an important morphological characteristic

Landraces and indigenous crops are identified by morphological characteristics, which could be linked to crop performance. In this study, seed colour was used to separate the different landraces and varieties as a major factor in addition to water stress and location. The hypothesis that seed colour was associated with drought tolerance was of interest, especially in the context of it having not been tested before in grain cereals and legumes as well as vegetable crops. The study confirmed that seed colour had an effect on early crop establishment. The dark coloured seeds showed better emergence than light coloured seeds. This trend often extrapolated well under field conditions, especially in the case of bambara groundnut, wild watermelon, maize landraces, cowpeas and wild mustard. This suggests that seed colour can be a criterion for initial selection of drought tolerance.

(b) Potential drought tolerance in maize landraces exists

Although maize landraces did not perform as well as hybrids, this study showed that they are drought tolerant, especially at the establishment stage. As such, maize landraces may be suitable for dryland cultivation in low input agricultural systems. The favourable response of landraces to water stress was associated with emergence. Emergence of hybrids was 6% and 18% lower than landraces in the optimum and late planting, respectively. This allowed landraces to maintain a better yield potential than hybrids as the planting dates were becoming less favourable by being late in the year. For example, for both Landrace A and Landrace B, grain yield increased with successive plantings, with highest grain yield being achieved in the late planting (Table 2.2). However, it is important to note that SR52 and SC701 are green mealies hybrids and there is no evidence that they were bred for drought tolerance. Hence, future studies should compare landraces with hybrids selected specifically for drought tolerance.

(c) Wild watermelon is a potential drought tolerant crop

Wild watermelon is an underutilised domesticated crop mainly because there are crop varieties that play a similar role to it in areas of South Africa that are not strictly semi-arid. In this study, the major focus was to determine whether seed colour was linked to drought tolerance. Results showed that seed coat colour as linked to both seed quality in terms of germination and drought tolerance in favour of darker seeds. In addition, the use of planting dates as a management tool for managing water stress under dryland conditions was confirmed as an important management approach. There were significant differences ($P < 0.05$) between planting dates with respect to average fruit mass. Based on mean values for all seed colour selections, early planting had the highest fruit mass (Figures 3.17 & 3.18). Overall, for all planting dates, the red seed colour selection had the highest fruit mass although there were no significant differences between seed colour selections (Figure 3.18).

(d) Wild mustard tolerance to drought is moderate

Wild mustard showed moderate drought tolerance and performed well in spring compared to winter planting. The crop showed resilience to drought by growing under SWC of less than 40%. There is a need to explore this crop further as a leafy vegetable in marginal areas of production. The wild mustard study also introduced the use of proline as a possible drought tolerance index. Although there is still much debate on the roles of proline under stress, all parties concerned acknowledge the fact that it accumulates under stress. In this case, its accumulation was negatively correlated with drought tolerance. This also necessitates further studies in the future.

(e) Cowpea drought tolerance is associated with seed coat colour

Cowpea is already widely reported to be drought tolerant. Results of this study confirmed this widely held view. As with wild mustard, wild watermelon and maize landraces, seed colour was also used to evaluate drought tolerance in cowpea. The trend confirmed that dark coloured seeds generally exhibited greater drought tolerance compared to light-coloured seeds. The study also explored the possibility of utilising cowpea as a dual purpose crop – as a leafy vegetable and as a grain crop. One variety showed potential for this use, moreso under rainfed conditions typical of drought. This shows potential to use the crop as a food gap-filling crop in areas that are prone to drought.

(f) Bambara groundnut drought tolerance is associated with seed coat colour

Seed colour in bambara groundnut had an effect on crop establishment. The red landrace selections showed better emergence than light-coloured selections. The red landrace selection also showed greater stomatal regulation suggesting an association between seed colour and drought avoidance. The red bambara landrace selection also showed lower chlorophyll content under water-limited conditions. The red landrace selection also showed reduced canopy size under water stress conditions. Bambara groundnuts also exhibited drought escape by flowering and maturing earlier as well as shortening the duration of flowering. This drought escape mechanism was related to lower leaf number and reduced canopy duration.

(g) Taro is an important dryland crop of the subtropics

Taro is perhaps one of the few recent successes in the group of underutilised crops that has been successfully commercialised. However, the crop is dogged by the perception that it is water-loving, and therefore not suitable for water-limited agriculture. This study showed that one variety of taro from Umbumbulu, an upland variety, was suitable for production in water-limited areas. The study also showed that water use efficiency (WUE) and yield of taro was greatly improved by drip irrigation compared with sprinkler irrigation or rainfed irrigation. This means that taro production can be promoted in areas that have access to irrigation such as smallholder irrigation schemes. Drought tolerance in the taro Umbumbulu landrace was crop responses such as leaf rolling, leaf heliotropism, partial senescence of leaves, lower stomatal conductance, lower chlorophyll content and hastened maturity under water-limited conditions. These responses are associated with drought avoidance and escape mechanisms.

(h) Pearl millet and amaranth studies explained the concepts of water productivity and water use efficiency of underutilised crops

Studies from the Free State showed that amaranth and pearl millet were both very drought tolerant crops and very efficient at utilising water. These studies explored the use of water productivity (WP) and water use efficiency (WUE) as indices for drought tolerance, especially in the context of rainfed and irrigated agriculture. They also highlighted the difference between WP and WUE, two terms that are often confused to mean the same thing. The study showed that both WP and WUE are useful indicators of drought tolerance and that amaranth and pearl millet are drought tolerant crops.

(i) AquaCrop is suitable for modelling production of selected underutilised indigenous crops

One major objective of this study was to model at least four of the crops studied in the project. The crops selected for this were bambara, taro, amaranth and pearl millet. Together these crops were representative of legume, tuber, leafy vegetable and a cereal crop. The crops were selected on the basis of results that indicated that they were drought tolerant and had potential for further agronomic studies. The FAO's AquaCrop was selected for the modelling exercises. Model selection was based on suitability – simulating yield response to water. The FAO's AquaCrop model was particularly designed with this task in mind. In addition, the model's simplicity compared to other established models makes it suitable in that it will be easier to transfer to target groups. The AquaCrop model showed good prediction for biomass and yield of taro under field and rain shelter conditions but was not as accurate under rainfed conditions. The model also predicted biomass and yield very well for bambara groundnut under varying water regimes. Model simulations for amaranth and pearl millet were very good under all conditions. The model tended to under-estimate and/or over-estimate SWC but it was accurate for predicting ET. The model also showed that all the crops studied were suitable for water-limited cultivation. The calibration and validation of four underutilised crops in this project indicates a major contribution in the modelling of neglected and underutilised crops both locally and internationally.

REFERENCES

ACEVEDO E, HSIAO TC and HENDERSON DW (1971) Immediate and subsequent growth responses of maize leaves to changes in water stress. *Plant Physiol*. 48, 631-636.

AGERGAARD J and BIRCH-THOMSEN T (2006) Transitional rural landscapes: The role of small-scale commercial farming in former homelands of post-apartheid KwaZulu-Natal. *Dan. J. Geo.* 106: 87-102.

AKPAROBI SO (2009) Effect of farmyard manures on the growth and yield of *Amaranthus cruentus*. *Agricultural tropica et subtropica* 42, 1-4.

AKPONIKPE PBI, GERARD B, MICHELS K and BIELDERS C (2010) Use of the APSIM model in long term simulation to support decision making regarding nitrogen management for pearl millet in the Sahel. *Europ. J. Agron.* 32, 144-154.

ALDRICH SR, SCOTT WO and HOEFT RG (1986) Modern corn production. 2nd edn. A&L Publications, Champaign, III.

ALLEMAN J, VAN DEN HEEVER E and VILJOEN J (1996) Evaluation of Amaranthus as a possible vegetable crop. *App. Plant Sci.* 10, 1-4.

ALLEN RG, PEREIRA LS, RAES D, SMITH M (1998) FAO Irrigation and Drainage Paper No. 56, Crop Evapotranspiration (guidelines for computing crop water requirements). FAO, Rome, Italy.

ANJUM F, YASEEN M, RASUL E, WAHID A, ANJUM, S (2003) Water stress in barley (*Hordeum vulgare* L.). II. Effect on chemical compositions and chlorophyll contents. *Pak. J. Agric. Sci. 40, 45-49.*

ANJUM SA, XIE X, WANG L, SALEEM MF, MAN C, LEI W (2011) Morphological, physiological and biochemical responses of plants to drought stress. *Afri. J. Agric. Res.* 6, 2026-2032.

ANNANDALE JG, BENADÉ N, JOVANOVIC NZ, STEYN JM and DU SAUTOY N (1999) Facilitating irrigation scheduling by means of the Soil Water Balance model. WRC report No 753/1/99, Water Research Commission, Pretoria, South Africa.

ANURADHA R, BALAMURUGAN P, SRIMATHI P, SUMATHI S (2009) Influence of seed coat colour variations on seed quality in Bengalgram CV.CO4 (*Cicer arietinum* L.). *Legume Res. 32, 136-138*.

ARAUS JL, SLAFER GA, REYNOLDS MP and ROYO C (2002) Plant breeding and drought in C3 cereals: what should we breed for? *Ann. Bot.* 89, 925-940.

ARAYA A, HABTU S, HADGU KM, KEBEDE, A and DEJENE T (2010) Test of AquaCrop model in simulating biomass and yield of water deficient and irrigated barley (*Hordeum vulgare*). *Agric. Water Manage.* 97, 1838-1846.

ARNON I (1972) Crop production in dry regions, Volume II: Systematic Treatment of the Principal Crops. Leonard Hill, London. pp 146-184.

ASADA K (1999) The water-water cycle in chloroplast: scavenging of active oxygen and dissipation of excess photons. *Ann. Rev. Pl. Physiol. Plant Mol. Bio.* 50, 601-639.

ASHRAF MY, AZMI, AR, KHAN, AH and ALA SA (1994). Effect of water stress on total phenols, peroxidase activity and chlorophyll content in wheat *(Triticum aestivum* L.*)* genotypes under soil water deficits. *Acta Physiol. Plant* 16, 185-191.

AYKROYD WR and DOUGHTY J (1982) Legumes in Human Nutrition: *FAO Food and Nutrition Paper 20*, FAO, Rome.

AYODELE VI (2002) Influence of nitrogen fertilization on yield of *Amaranthus* species. Proc. Workshop Eco. Fertilization Veg. *Acta Hort*, 571, 89-94.

AZAM-ALI SN (2010) Fitting underutilized crops within research-poor environments: Lessons and approaches. *S. Afr. J. Plant & Soil* 27, 293-298.

AZAM-ALI SN, KHONGA E, WENZEL G, FLESSNER K and SESAY A (2004) Increasing the productivity of bambara groundnut (*Vigna subterranea* (L.) Verdc.) for sustainable food production in semi-arid Africa. BAMFOOD Project Final Report. (Available on http://ebookbrowse.com/bamfood-final-report-pdf-d38034097)

AZAM-ALI SN, CROUT NMJ and BRADLEY R.G (1994) Perspectives in modelling resource capture by crops. pp. 125-148. *In* Monteith J.L. *et al*. (Eds.) Resource capture by crops. Proc. of the 52nd Univ. of Nottingham Eastern School on Resource Capture by Crops. Nottingham Univ. Press, UK.

AZAM-ALI SN, SESAY A, KARIKARI S, MASSAWE FJ, AGUILAR-MANJARREZ J, BANNAYAN M and HAMPSON KJ (2001) Assessing the potential of an underutilized crop – a case study using bambara groundnut. *Expl. Agric.* 37, 433-472.

BABIKER AMA (1989) Growth, dry matter and yield of bambara groundnut (*Vigna subterranea*) and groundnut (*Arachis hypogaea*) under irrigated and droughted conditions. MSc Thesis, University of Nottingham, UK.

BACKEBERG GR, BEMBRIDGET.J, BENNIE ATP, GROENEWALD JA, HAMMES PS, PULLEN RA and THOMPSON, H (1996) Policy proposal for irrigated agriculture in South Africa. Water Research Commission, Report No. KV 96/96, Pretoria.

BADR MA, EL-TOHAMY WA AND ZAGHLOUL AM (2012) Yield and water use efficiency of potato grown under different irrigation and nitrogen levels in an arid region *Agric Water Manage* 110, 9-15.

BANNAYAN M (2001) BAMNut: a crop simulation model for bambara groundnut *Agric Sci Technol* 15, 101-110.

BARRETT RP, SIMON JE and JANICK J (1997) Legume species as leaf vegetables Advances in New Crops Timber Press Portland.

BARRETT RP (1990) Legume species as leaf vegetables *In* Janick J, Simon JE (eds), *Advances in new crops* Portland: OR, Timber Press pp 391-396.

BAYE T, KEBEDE H and BELETE K (2001) Agronomic evaluation of *Vernonia galamensis* germplasm collected from Eastern Ethiopia *Industrial Crops and Products* 14, 179-190.

BELAYGUE C, WERY J, COWAN AA and TARDIEU F (1996) Contribution of leaf expansion, rate of leaf appearance, and stolon branching to growth of plant leaf area under water deficit in white clover *Crop Sci* 36, 1240-1246.

BELETSE YG, LAURIE R, DU PLOOY CP, VAN DEN BERG A and LAURIE S, (2011) Calibration and validation of AquaCrop model for orange fleshed sweet potatoes In *Capacity development for farm management strategies to improve Crop Water Productivity using AquaCrop: lessons learned*, (Eds Ardakanian, R and Walter, T) UNW-DPC Publication Series, Knowledge No7, Bonn, Germany.

BELLO ZA, WALKER S and TFWALA CM (2011) Predicting Pearl millet response to water under South African climatic conditions In *Capacity development for farm management strategies to improve Crop Water Productivity using AquaCrop: lessons learned*, (Eds ARDAKANIAN, R and WALTER, T) UNW-DPC Publication Series, Knowledge No7, Bonn, Germany.

BENHIL, J (2002) Climate, water and agriculture: Impacts on and adaptation of agro-ecological systems in South Africa A case study of the Republic of South Africa, University of Pretoria, SA.

BENNIE, ATP and HENSLEY M (2001) Maximizing precipitation utilization in dryland agriculture in South Africa – a review. *J Hydrol* 241, 124-139.

BENNIE ATP, COETZEE MJ, VAN ANTWERPEN R, VAN RENSBURG LD and BURGER R, DU T (1988) 'n Waterbalans-model vir besproeiing gebaseer op profielwatervoorsienings-tempo en gewaswaterbehoeftes (Afrikaans) WRC Report No 144/1/88, Water Research Commission, Pretoria, South Africa.

BENNIE, ATP, STRYDOM, MG and VREY, HS (1998) Gebruik van rekenaarmodelle vir landboukundige waterbestuur op edotoopvlak (Afrikaans with English summary) WRC Report No 102/98, Water Research Commission, Pretoria, South Africa.

BENNIE ATP, VAN RENSBURG LD, STRYDOM MG and CC (1997) Reaksie van gewasse op voorafgeprogrammeerde tekortbesproeiing (Afrikaans with English summary) WRC Report No 423/1/97, Water Research Commission, Pretoria, South Africa.

BERCHIE JN, OPOKU M, ADU-DAPAAH H, AGYEMANG A, SARKODIE-ADDO J, ASARE E, ADDO J and AKUFFO H (2012) Evaluation of five bambara groundnut (*Vigna subterranea* L Verdc) landraces to heat and drought stress at Tono Navrongo, Upper East Region of Ghana *Afri J Agric Res 7, 250-256.*

BERCHIE JN, SARKODIE-ADDO J, ADU-DAPAAH H, AGYEMANG A, ADDY S, ASARE E and DONKOR J (2010) Yield evaluation of three early maturing bambara groundnut (*Vigna subterranea* L Verdc) landraces at the CSIR-Crops Research Institute, Fumesua-Kumasi, Ghana *J Agron* 9, 175-179.

BHATT, RM AND RAO SRINIVASA, NK (2005) Influence of pod load response of okra to water stress *Indian J Plant Physiol* 10, 54-59.

BITTENBENDER HC (1992) Handling storage of cowpea *Vigna unguiculata* (L) Walp as a leaf vegetable *Trop Agric* 69, 197-199.

BLUM A (2004) Sorghum physiology *In* Nguyen, HT and Blum, A (Eds) Physiology and biotechnology integration for plant breeding Marcell Dekker, New York pp 141-223.

BLUM A (2005) Drought resistance, water-use efficiency, and yield potential – are they compatible, dissonant, or mutually exclusive? *Austr J Agric Res* 56, 1159-1168.

BLUM A (2009) Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress *Field Crops Res* 112, 119-123.

BOOGAARD HL, VAN DIEPEN CA, ROTTER RP, CABRERA JMCA and VAN LAAR HH (1998) User's guide for the WOFOST 71 crop growth simulation model and WOFOST Control Center 15 Tech Doc 52 DLOWinand Staring Centre, Wageningen, The Netherlands.

BOOTE KJ, JONES JW and PICKERING NB (1996) Potential use and limitations of crop models *Agron J* 88, 704-716.

BOOTE KJ, JONES JW, and HOOGENBOOM G (1998) Simulation of crop growth: CROPGRO model *In* Peart, RM and Curry, RB (Eds) Agricultural systems modelling and simulation Marcel Dekker, New York pp 651-692.

BOOTE, KJ MINGUEZ, MI and SAU F (2002) Adapting the CROPGRO legume model to simulate growth of faba bean *Agron J* 94, 743-756.

BOTHA JJ, VAN RENSBURG LD, ANDERSON JJ, HENSLEY M, MACHELI MS, VAN STADEN PP, KUNDHLANDE G, GROENEWALD DG and BAIPHETHI MN (2003) Water conservation techniques on small plots in semi-arid areas to enhance rainfall use efficiency, food security, and sustainable crop production Water Research Commission Report 1176/1/03, Pretoria, South Africa.

BOUMAN BAM, VAN KEULEN H, VAN LAAR HH and RABBINGE R (1996) The "school of de Wit" crop growth simulation models: A pedigree and historical overview *Agric Syst* 52, 171-198.

BOWN D (2000) Aroids Plants of the Arum family 2nd edn Timber Press Portland, Oregon, USA

BRADLEY RJ and CROUT NMJ (1993) The PARCH model University of Nottingham, Nottingham, UK.

BRESSANI R (1985) Nutritive value of cowpea *In* Singh, SR and Rachie, KO (eds), *Cowpea Research Production and Utilization* London: John Wiley and Sons, Chichester pp 353-356.

BRISSON N, GARY C, JUSTES E, ROCHE R, MARY B, RIPOCHE D, ZIMMER D, SIERRA J, BERTUZZI P, BURGER P, BUSSIERE F, CABIDOCHE YM, CELLIER P, DEBAEKE P, GAUDILLERE JP, HENAULT C, MARAUX F, SEGUIN B and SINOQUET H (2003) An overview of the crop model STICS *Eur J Agron* 18, 309-332.

BUBENHEIM DL, MITCHELL CA and NELSON, SS (1990) Utility of Cowpea foliage in a crop production system for space *In* Janick, J and Simon, JE (eds), *Advances in new crops*, Portland: OR, Timber Press pp 535-538.

CABLE, WJ (1984) The spread of taro (*Colocasia sp*) in the Pacific *In* Chandra, S (Ed) Edible Aroids Clarendon Press, Oxford, UK pp 28-33.

CAMPBELL, GS and MULLA, DJ (1990) Measurement of soil water content and potential *In* Stewart, BA and Nielsen, DR (Eds) Irrigation of Agricultural Crops *Agronomy* 30, 127-142.

CARBERRY, PS, MUCHOW, RC and HAMMER, GL (1993) Modelling genotypic and environmental control of leaf area dynamics in grain sorghum II Individual leaf level *Field Crops Res* 33, 311-328.

CHAVES, MM, MAROCO JP and PEREIRA, JS, 2003 Understanding plant responses to drought from genes to the whole plant *Funct Plant Bio* 30, 239-264.

CHAVES, MM and OLIVEIRA, MM, 2004 Mechanisms underlying plant resilience to water deficits: prospects for water saving agriculture *J Expt Bot* 55, 2365-2384.

CHAVES, MM, PEREIRA, JS, MAROCO, J, RODRIGUES, ML, RICARDO, CPP, OSORI, ML, CARVALHO, I, FARIA, T and PINHEIRO, C (2002) How plants cope with water stress in the field Photosynthesis and growth *Ann Bot* 89, 907-916.

CHEEROO-NAYAMUTH, BF (1999) Crop modelling/simulation: An overview AMAS Food and Agricultural Research Council, Reduit, Mauritius.

CHEN, L, HUANG, JF, WANG, FM and TANG, YL (2007) Comparison between back propagation neural network and regression models for the estimation of pigment content in rice leaves and panicles using hyperspectral data *Int J Remote Sens* 28, 3457-3478.

CLAUSSEN, W (2005) Proline as a measure of stress in tomato plants *Plant Sci* 168, 241-248.

COFFMAN, C (1998) Critical growth stages of corn Texas Agricultural Extension Service, Texas.

COLLINS, WW and HAWTIN, GC (1999) Conserving and using crop plant biodiversity in agroecosystems. *In* Collins, WW and Qualset, CO (Eds) Biodiversity in agroecosytems CRC Press, Boca Raton, Washington pp 267-281.

COLLINSON, ST, AZAM-ALI, SN, CHAVULA, KM and HODSON, DA (1996) Growth development and yield of bambara groundnut (*Vigna subterranea*) in response to soil moisture *J Agric Sci* 126, 307-318.

COLLINSON, ST, BERCHIE, J and AZAM-ALI, SN (1999) The effect of soil moisture on light interception and the conversion coefficient for three landraces of bambara groundnut (*Vigna subterranea*) *J Agric Sci* 133, 151-157.

COLLINSON, ST, CLAWSON, EJ, AZAM-ALI, SN and BLACK, CR (1997) Effects of soil moisture deficits on the water relations of bambara groundnut (*Vigna subterranea* L Verdc) *J Expt Bot* 48, 877-884.

CORNELISSEN, RLE (2005) Modelling variation in the physiology of bambara groundnut (*Vigna subterranea* L Verdc) PhD thesis, University of Nottingham, UK.

CORNIC, G and MASSACCI, A (1996) Leaf photosynthesis under drought stress *In* Baker, NR (Ed) Photosynthesis and the environment The Netherlands, Kluwer Academic Publishers.

CORREIRA, MJ, PEREIRA, JS, CHAVES, MM, RODRIGUES, ML and PACHECO, CA (1995) ABA xylem concentrations determine maximum daily leaf conductance of field-grown *Vitis vinifera* L plants *Plant Cell Env* 18, 511-521.

CROSBY, CT and CROSBY CP (1999) A computer programme for establishing irrigation requirements and scheduling strategies in Southern Africa WRC Report No 624/1/99, Water Research Commission, Pretoria, South Africa.

CRUZ DE CARVALHO, MH (2000) Etude physiologique, biochimique et moléculaire de la réponse à la sécheressechez *Phaseolus vulgaris* L et *Vigna unguiculata* L Walp Implication de l'aspartique protéinase Mise au point del'étape préalable à la transgenèse : régénération in vitro des plantes Thèse doct physiol cellulaire et moléculaire des plantes Paris, univ VI, France: Paris.

DARNTON-HILL I, WEBB P, HARVEY PWJ, HUNT JM, DALMIYA N, CHOPRA M, BALL MJ, BLOEM MW and DE BENOIST B (2005) Micronutrient deficiencies and gender: social and economic costs. American Journal of Clinical Nutrition 81, 1198S-1205S.

DAVIES, WJ and ZHANG J, (1991) Root signals and the regulation of growth and development of plants in drying soil *Ann Rev Plant Physiol Plant Mol Biol* 42, 55-76.

DE JAGER, JM (1974) "PUTU", a dynamic seasonal maize crop growth model Canadian IBP Res Report 306-320.

DE KLERK M, DRIMIE S, ALIBER M, MINI S, MOKEONA R, RANDELA R, MODISELLE SC, DE SWART, C and KIRSTEN J (2004) Food security in South Africa: key policy issues for the medium term Human Sciences Research Council, Pretoria pp82.

DE WIT CT (1958) Transpiration and crop yields Agric Res Rep 64(6) Pudoc, Wageningen, The Netherlands.

DE WIT CT (1965) Photosynthesis of leaf canopies pp 57 *In* Agricultural Research Report 663, PUDOC, Wageningen, the Netherlands.

DE WIT CT (1982) Simulation of living systems *In* Penning de Vries, FWT and Laar van, HH (Eds) Simulation of Plant Growth and Crop Production Wageningen, Pudoc, The Netherlands.

DE WIT CT, BROUWER R and PENNING DE VRIES FWT (1970) The simulation of photosynthetic systems *In* Setlik, I (Ed) Prediction and management of photosynthetic productivity, Proc of the Int Biological Program/Plant Production Technical Meeting Trebon PUDOC, Wageningen, the Netherlands pp 47-70.

DE WIT MJ and STANKIEWICZ J (2006) Potential changes in drainage systems with predicted precipitation changes across Africa 3rd General Assembly European Geosciences Union (EGU), Vienna, Austria, 2006 *Geophysical Research Abstracts* 8.

DEBLONDE PMK and LEDENT JF (2001) Effects of moderate drought conditions on green leaf number stem height, leaf length and tuber yield of potato cultivars *Euro J Agron* 14, 31-41

DEMBINSKA H (1970) Influence of water deficiency in autumn and spring on development and structure of winter rape yield *Rocz Nauk Roln A* 96, 73-94.

DEMMIG-ADAMS B and ADAMS WW III (1996) The role of xanthophylls cycle carotenoids in the protection of photosynthesis *Trends in Plant Science* 1, 21-26.

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAFF) (2011) Pearl millet-Production guideline. pp. 1-10.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (DWAF) (2002) 1st Edn National water resource strategy: report Pretoria, South Africa.

DE-RONDE JA, MESCHT VD AND STEYN HSF (2000) Proline Accumulation In Response To Drought And Heat Stress In Cotton *African Crop Sci J* 8, 85-91.

DJIBRIL S, MOHAMED OK, DIAGA D, DIÉGANE D, ABAYE BF, MAURICE S and ALAIN B (2005) Growth and development of date palm (*Phoenix dactylifera* L) seedlings under drought and salinity stresses *African J Biotechnol* 4, 968-972.

DOORENBOS J and KASSAM AH (1979) Yield response to water Irrigation and Drainage Paper 33 FAO, Rome, Italy, 193 pp.

EHLERS L, BENNIE ATP and DU PREEZ CC (2003) The contribution of root accessible water tables towards the irrigation requirements of crops Water Research Commission, Report 1089/1/03, Pretoria, South Africa.

ESTILL K, DELANEY RH, SMITH WK and DITTERLINE RL (1991) Water relations and productivity of alfalfa leaf chlorophyll variants *Crop Sci* 31, 1229-1233.

EVETT SR, CARMAN D and BUCKS DA (2003) Expansion of irrigation in mid-south United States: Water allocation and research issues *In* Proc 2nd International Conference on Irrigation and Drainage Water for a sustainable World limited supplies and expanding demand 12-15 May 2003, Phoenix, AZ US Committee on Irrigation and Drainage Denver, Denber, CO pp 247-260.

EZUMAH HC (1972) The growth and development of taro (*Colocasia esculenta* (L) Schott) in relation to selected cultural management practices PhD Thesis University of Hawaii.

FABER M and WENHOLD F (2007) Nutrition in contemporary South Africa. Water SA 37, 393-400.

FAFUNSO, M and BASSIR O (1976) The comparative assessment of the problem quality of some Nigerian edible leaves with that of soybean *Plant Food Man* 2, 35-40.

FAO (2001) A global mapping system for bambara groundnut production FAO, Rome, Italy

FAOSTAT (2012) FAO Statistical Database http://faostatfaoorg (accessed 28/01/2012).

FARAHANI HJ, IZZI G and OWEIS TY (2009) Parameterization and evaluation of the AquaCrop model for full and deficit irrigated cotton *Agron J* 101, 469-476.

FARE A (2008) Water management software to estimate crop irrigation requirements for consumptive use permitting in Hawaii Final Report, University of Hawai'i at Mānoa http://hawaiigov/dlnr/cwrm/publishedreports/PR200808pdf (accessed 01/06/2010).

FAROOQ M, WAHID A, KOBAYASHI N, FUJITA D and BASRA SMA (2009) Plant drought stress: effects, mechanisms and management *Agron Sustainable Dev* 29, 185-212.

FARRE I, VAN OIJEN M, LEFFELAAR PA and FACI JM (2000) Analysis of maize growth for different irrigation strategies in north-eastern Spain *Euro J Agron* 12, 225-238.

FERRES E and CONNOR D (2004) Sustainable water management in agriculture *In* Cabrera, E and Cobacho, R (ed) Challenges of the new water policies for the XXI century Swets and Zeitlinger, Lisse, the Netherlands pp 157-170.

FISCHER G, SHAH M, VAN VELTHUIZEN H and NACHTERGAELE FO (2000) Global agro-ecological assessment for agriculture in the 21st century *In* Proc of the IIASA, Vienna Int Inst for Applied Systems Analysis, IIASA, Laxenburg, Austria pp 44.

FISCHER RA and TURNER NC (1978) Plant productivity in Arid and Semiarid Zones *Ann Rev Plant Physiol*29, 277-317.

FREDERICK JR, CAMP CR and BAUER PJ (2001) Drought-stress effects on branch and main stem seed yield and yield components of determinate soybean *Crop Sci* 41, 759-763.

FRENCH RJ and SCHULTZ JE (1984) Water use efficiency of wheat in a Mediterranean-type environment I The relation between water use and climate *Aust J Agric Res* 35, 743-764.

GANGOPADHYAY G, BASU S and GUPTA S (1997) In vitro selection and physiological characterization of NaCl- and mannitol-adapted callus lines in *Brassica juncea Plant Cell Tiss Org Cult* 50, 161-169.

GARCIA AL, TORRECILLAS A, LEON A and RUIZ SANCHEZ MC (1987) Biochemical indicators of water stress in maize seedlings *Biol Plant* 29, 45-51.

GARCIA-VILA M, FERRES E, MATOES L, ORGAZ F and STEDUTO P (2009) Deficit irrigation optimization of cotton with AquaCrop *Agron J* 101, 477-487 .

GARDNER FP, PEARCE RB and MITCHELL RL (1990) Physiology of crop plants Iowa State University Press Iowa, USA.

GARN SM and LEORNARD WR (1989) What did our ancestors eat? *Nutr Rev* 47, 337-345.

GEERTS S and RAES D (2009) Deficit irrigation as on-farm strategy to maximise crop water productivity in dry areas *Agric Water Manage* 96, 1275-1284.

GEERTS S, RAES D, GARCIA M, MIRANDA R, CUSICANQUI JA, TABOADA C, MENDOZA J, HUANCA R, MAMANI A, CONDORI O, MAMANI J, MORALES B, OSCO V and STEDUTO P (2009) Simulating Yield Response to Water of Quinoa (*Chenopodium quinoa* Willd) with FAO-AquaCrop *Agron J* 101, 499-508.

GEISSLER PW, HARRIS SA, PRINCE RJ, OLSLEN A, ODHIAMBO RA, OKETCH-RABAH H, MADIAGA PA, ANDERSON A and MOLGAARD P (2002) Medicinal plants used by Luo mothers and children in Bondo district Kenya *J Ethnopharmacol* 83, 39-54.

GOWING DJG, DAVIES WJ and JONES HG (1990) A positive root-source signal as an indicator of soil drying in apple, *Malus domestica J Expl Bot* 41, 1535-1540.

GREEN TS, ENDER M and MOCK JJ (1985) Effect of sowing dates on maize yields *Agric Sci* 20, 843-850.

GUNESEKERA CP, MARTIN LD, SIDDIQUE KHM and WALTON GH (2005) Genotype by environment interactions of Indian mustard (*Brassica juncea* L) and canola (*B napus* L) in Mediterranean-type environments, 1 Crop growth and seed yield *Europ J Agron* 25, 1-12.

GUPTA NK, GUPTA S and KUMAR A (2001) Effect of water stress on physiological attributes and their relationship with growth and yield of wheat cultivars at different stages J *Agron Crop Sci* 186, 55-62.

HAKA IBU (2010) Quantifying evaporation and transpiration in field lysimeters using the soil water balance PhD thesis, University of the Free State, Bloemfontein, South Africa

HALL AE, THIAW S, ISMAIL AM and EHLERS JD (1997) Water use efficiency and drought adaptation of cowpea *In* Singh BB, Mohan RDR, Dashiell KE, Jackai LEN (eds), *Advances in Cowpea Research, IITA and JIRCAS*, pp 87-98.

HAMIDOU F, ZOMBRE G and BRACONNIER S (2007) Physiological and biochemical response of cowpea genotypes to water stress under glasshouse and field condition *J Agron Crop Sci* 193, 229-239.

HAMMER GL, KROPFF MJ, SINCLAIR TR and PORTER JR (2002) Future contributions of crop modelling – from heuristics and supporting decision making to understanding genetic regulation and aiding crop improvement *Eur J Agron* 18, 15-31.

HANKS JR (1983) Yield and water-use relationships: An overview *In* Taylor, HM *et al* (Eds) Limitations to efficient water use in crop production ASA, Madison, WI pp 393-411.

HARE PD, CRESS WA and STADEN JV (1998) Proline synthesis and degradation, a model for elucidating stress related signal transduction *J Exp Bot* 50, 413-434.

HARE PD, CRESS WA and VAN STADEN J (1999) Proline synthesis and degradation: A model system for elucidating stress-related signal transduction *J Exp Bot* 50, 413-434.

HARRIS D and AZAM-ALI SN (1993) Implication of daylength sensitivity in bambara groundnut (*Vigna subterranea*) production in Botswana *J Agric Sci*120, 75-78.

HARRIS D, TRIPATHI RS and JOSHI A (2002) On-farm seed priming to improve crop establishment and yield in dry direct-seeded rice *In* Pandley S, Mortimer M, Wade L, Tuong TP, Lopes K and Hardy, B (Eds) Direct seeding: research strategies and opportunities International Research Institute, Manilla, Philippines pp 231-240.

HARRIS RE, MOLL RH and STUBER CW (1984) Control and inheritance of prolificacy in maize *Crop Sci* 16, 543-850.

HASSAN R **(**2006) Climate Change and African Agriculture *Policy No28* Based on Durand (2006), "Assessing the impact of climate change on crop water use in South Africa", *CEEPA Discussion Paper No28,* CEEPA, University of Pretoria.

HATFIELD JL, SAUER TJ and PRUEGER JH (2001) Managing soils to achieve greater water use efficiency: A review *Agron J* 93, 271-280.

HAUDRICOURT AG and HÉDIN L (1987) *L'homme el les plantes cultiveés* Métailié, AM (Ed), Paris

HAVAUX M and TARDY F (1999) Loss of chlorophyll with limited reduction of photosynthesis as an adaptive response of Syrian barley landraces to high light and heat stress *Australian Journal of Plant Physiology* 26, 569-578.

HEINIGRE, RW (2000) Irrigation and drought management Crop Science Department

HENG LK, HSIAO T, EVETT S, HOWELL T and STEDUTO P (2009) Validating the FAO AquaCrop model for irrigated and water deficient field maize *Agron J* 101, 488-498.

HEUER B and NADLER A (1995) Growth, development and yield of potatoes under salinity and water deficit *Australian J Agric Res* 46, 1477-1486.

HILLEL D (1977) Computer simulation of soil water dynamics: a compendium of recent work Ottawa, Ontario: International Development Research Centre, pp 214.

HOSSAIN MI, KHATUN A, TALUKDER MSA, DEWAN MMR and UDDIN MS (2010) Effect of drought on physiology and yield contributing characters of sunflower *Bangladesh J Agric Res* 35, 113-124.

HSIAO TC and BRADFORD KJ (1983) Physiological consequences of cellular water deficits *In* Taylor, HM *et al* (Eds) Limitations to efficient water use in crop production ASA, Madison, WI pp 227-265.

HSIAO TC, STEDUTO P and FERERES E (2007) A systematic and quantitative approach to improve water use efficiency in agriculture *Irrigation Sci* 25, 209-231.

HSU SY, HSU YT and KAO CH (2003) The effect of polyethylene glycol on proline accumulation in rice leaves *Biol Plant* 46, 73-78.

HUMPHREY M, CLEGG MS, KEEN CL and GRIVETTI LE (1983) Food Chemistry and drought survival: The Hausa example *Int J Food Sci & Nutri* 44, 1-16.

HUSSAIN M, MALIK MA, FAROOQ M, ASHRAF MY, CHEEMA MA (2008) Improving drought tolerance by exogenous application of glyceinbetaine and salicylic acid in sunflower *J Agron Crop Sci* 194, 193-199.

HUSSEIN F, JANAT M and YAKOUB A (2011) Simulating cotton yield response to deficit irrigation with the FAO AquaCrop model *Spanish J Agric Res* 1319-1330.

IBRAHIM UB, AUWALU M and UDOM GN (2010) Effect of stage and intensity of defoliation on the performance of vegetable cowpea (*Vigna unguiculata* (L) Walp) *Afri J Agr Res* 5, 2446-2451.

IDOWU OO (2009) Contribution of neglected and underutilized crops to household food security and health among rural dwellers in Oyo State, Nigeria Proc IS on Underutilised Plants (Eds: Janicke *et al*) *Acta Hort* 806, 49-56.

INMAM-BAMBER NG and KIKER G (1997) CANEGRO 310 DSSAT version 31 1998 Distribution Software, IBSNAT, University of Hawaii, Honolulu, Hawaii, USA.

INMAM-BAMBER NG (1995) Strategies for crop modelling research at SASEX *Proc S Afr Sug Tecnol Ass* 69, 212-214.

INTERNATIONAL BENCHMARK SITES NETWORK FOR AGROTECHNOLOGY TRANSFER (1993) The IBSNAT Decade Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, Hawaii, USA.

INTERNATIONAL WATER MANAGEMENT INSTITUTE (IWMI) (1996) World water demand and supply, 1990 to 2025: Scenarios and Issues, Research Report 19.

IVANCIC A, QUERO-GARCIA J and LEBOT V (2003) Development of visual tools for selecting qualitative corm characteristics of taro (*Colocasia esculenta* (L) Schott) *Australian J Agric* 54, 581-587.

JALEEL CA, MANIVANNAN P, WAHID A, FAROOQ M, AL-JABURI HJ, SOMASUNDARAM R and PANNEERSELVAM R (2009) Drought Stress In Plants: A review on morphological characteristics and pigments composition *Int J Agric & Biol* 11, 100-105.

JAME YW and CUTFORTH HW (1996) Crop growth models for decision support systems *Can J Plant Sci* 76, 9-19.

JONES CA and KINIRY JR (1986) CERES-Maize: A simulation model of maize growth and development Texas A&M Univ Press, College Station, TX.

JONES CA, DYKE PT, WILLIAMS JR, KINIRY,JR, BENSON CA and GRIGGS RH (1991) EPIC: An operational model for evaluation of agricultural sustainability *Agric Syst* 37, 341-350.

JONES JW and RITCHIE JT (1990) Crop growth models *In* Hoffman, GJ, Howell, TA and Solomon, KH (Eds) Management of farm irrigation systems ASAE An ASAE monograph, St Joseph pp 63-89.

JONES JW, HOOGENBOOM G, PORTER CH, BOOTE KJ, BATCHELOR WD, HUNT LA, WILKENS PW, SINGH U, GIJSMAN AJ and RITCHIE JT (2003) The DSSAT cropping system model *Eur J Agron* 18, 235-265.

JONES JW, TSUJI GY, HOOGENBOOM G, HUNT LA, THORNTON PK, WILKENS PW, IMAMURA DT, BOWEN WT and SINGH U (1998) Decision support system for agrotechnology transfer; DSSAT v3 *In* Tsuji, GY, Hoogenboom, G and Thornton, PK (Eds)

Understanding options for agricultural production Kluwer Academic Publishers, Dordrecht, the Netherlands pp 157-177.

JØRGENSEN ST, LIU F, OUÉDRAOGO M, NTUNDU WH, SARRAZIN J and CHRISTIANSEN JL (2010) Drought responses of two bambara groundnut (*Vigna subterranea* L Verdc) landraces collected from a dry and a humid area of Africa *J Agron & Crop Sci* 196, 412-422.

JØRGENSEN ST, NTUNDU WH, OUÉDRAOGO M, CHRISTIANSEN JL and LIU F (2011) Effect of short and severe intermittent drought on transpiration, seed yield, yield components, and harvest index in four landraces of bambara groundnut *Int J Plant Prod* 5, 25-36.

KAISER, HW and DE JAGER JM (1974) Effect of plant population density on maize crop photosynthesis and production *Crop Prod* 3, 107-110.

KARUNARATNE, AS (2009) Modelling the response of Bambara Groundnut (*Vigna subterranean* (L) Verdc) for abiotic stress PhD Thesis University of Nottingham.

KARUNARATNE AS, AZAM-ALI SN, AL-SHAREEF I, SESAY A, JORGENSEN ST and CROUT NMJ (2010) Modelling the canopy development of bambara groundnut *Agric & Forest Meteor* 150, 1007-1015.

KARUNARATNE AS, AZAM-ALI SN, IZZI G and STEDUTO P (2011) Calibration and validation of FAO-AquaCrop model for irrigated and water deficient bambara groundnut *Expl Agric* 47, 509-527.

KAVAR T, MARAS M, KIDRIC M, SUSTAR-VOZLIC J and MEGLIC V (2007) Identification of genes involved in the response of leaves of Phaseolus vulgaris to drought stress *Mol Breed* 21, 81-87.

KAYA MD, OKCUB G, ATAKA M, CIKILIC Y and KOLSARICIA O (2006) Seed treatments to overcome salt and drought stress during germination in sunflower (*Helianthus annus* L) *Eur J Agron* 24, 291-295.

KESARI AN, GUPTA RK and WATAl G (2005) Hypoglycaemic effects of Murraya koenigli on normal and alloxan-diabetic rabbits *J Ethnophamacol* 51, 2603-2607.

KHAN MB, HUSSAIN N and IQBAL M (2001) Effect of water stress on growth and yield components of maize variety YHS202 *J Res (Science)* 12, 15-18.

KHANA AK, RIZVI F and CHANDER R (2002) Lipid lowering activity of Phylloanthus niruri in hyperlipemic rats *J Ethnopharmacol* 82, 19-22.

KIANI SP, MAURY P, SARRAFI A, GRIEU P (2008) QTL analysis of chlorophyll fluorescence parameters in sunflower (*Helianthus annus* L) under well-watered and water-stressed conditions *Plant Sci* 175, 565-573.

KNIPP G and HONERMEIER B (2006) Effect of water stress on proline accumulation of genetically modified potatoes (*Solanum tuberosum* L) generating fructans *J Plant Physiol* 163, 392-397

KREIKE C M, VAN ECK H J and LEBOT V (2004) Genetic diversity of taro, *Colocasia esculenta* (L) Schott, in Southeast Asia and the Pacific *Theory of Applied Genetics* 109, 761-768.

KUBO I, FIJITA K, KUBO A, NECHEI K and GURA T (2004) Antibacterial activity of coriander volatile compounds against *Salmonella choleraesuis J Agric & Food Chem* 52, 3329-3332

LAI-2200 (2010) Instruction manualLi-Cor Biosciences Publication No 984-10633

LAKER MC (2007) Introduction to the special edition of Water SA on indigenous crops, water and human nutrition *Water SA* 33, 311-315.

LAUER J (2003) What happens within the corn plant when drought occurs? University of Wisconsin Extension http://wwwuwexedu/ces/ag/issues/drought2003/cornseffecthtml

LAUER JG, CARTER PR, WOOD TM, DIESEL G, WIERSMA DW, RAND RE and MLYNAREK MJ (1999) Corn hybrid response to planting date in the Northern Corn Belt *Agron J* 91, 834-839.

LAWSON T, OXBOROUGH K, MORISON JIL and BAKER NR (2003) The responses of guard and mesophyll cell photosynthesis to CO2, O2, light and water stress in a range of species are similar *J Expl Bot* 54, 1743-1752.

LEBOT V and ARADHYA KM (1991) Isozyme variation in taro (*Colocasia esculenta* (L) Schott) from Asia and Oceania *Euphytica* 56, 55-66.

LEBOT V (1999) Biomelecular evidence of plant domestication in Sahul *Genet Resour Crop Evol* 46, 619-628.

LEBOT V (2009) Tropical root and tuber crops: Cassava, sweet potato, yams and aroids CABI, Cambridge, UK pp 279-349.

LEBOT V, IVANCIC A and ABRAHAM K (2005) The geographical distribution of allelic diversity, a practical means of preserving and using minor root crop genetic resources *Expl Agric* 41, 475-489.

LEISINGER KM, SCHMITT K and INTERNATIONAL SERVICE FOR NATURAL AGRICULTURE (1995) Survival in the Sahel An ecological and developmental challenge (Ed) The Hague pp 123- 130.

LÉON J (1977) Origin, evolution and early dispersal of root and tuber crops Proceedings of the 4th Symposium of the International Society of Tropical Root Crops, Colombia, 1976, CRDI, Ottawa pp 20-36.

LEVITT J (1972) 'Responses of plants to environmental stresses' Academic Press, New York

LEVITT J (1979) Responses of plants to environmental stresses Academic Press, New York

LINNEMANN AR and AZAM-ALI SN (1993) Bambara groundnut (*Vigna subterranea* L Verdc) *In* WILLIAMS, JT (Ed) Underutilised crops series II Vegetable and pulses Chapman and Hall, London, UK pp 13-58.

LIU F and STUTZEL H (2002) Leaf water relations of vegetable amaranth (*Amaranthus spp*) in response to soil drying *Eur J Agron,* 16, 137-150.

LUDLOW MM (1989) Strategies of response to water stress *In* Kreeb, KH, Richter, H and Hinckley, TM (eds), Structural and functional responses to environmental stresses SPB Academic, The Hague pp 269-281.

LUDLOW MM and MUCHOW RC (1990) A critical evaluation of traits for improving crop yields in water-limited environments *Adv Agron* 43, 107-153.

MABHAUDHI T and MODI AT (2010) Early establishment performance of local and hybrid maize under two water stress regimes *S Afr J Plant & Soil* 27, 299-304.

MABHAUDHI T and MODI AT (2011) Can hydro-priming improve germination vigour, speed and emergence of maize landraces under water stress? *J Agric Sci Technol B* 1, 20-28.

MABHAUDHI T (2009) Responses of maize (*Zea mays* L) landraces to water stress compared with commercial hybrids MSc Thesis University of KwaZulu-Natal, Pietermaritzburg, South Africa.

MABHAUDHI, T, MODI AT and BELETSE YG (2011) Growth response of a bambara groundnut (*Vigna subterranea*) landrace to water stress *African Crop Science Conference Proceedings* 10, 99-103.

MABHAUDHI T, MODI AT and BELETSE YG (2012) Growth response of selected taro (*Colocasia esculenta*) landraces to water stress 2nd International Symposium of Underutilised Food Plants – Crops for the Future, University of Nottingham, Malaysian Campus, Kuala Lumpur, Malaysia, 25 June – 1 July, 2011 *Acta Horticulturae, In Press.*

MAKUS DJ and DAVIS DR (1984) A mid-summer crop for fresh greens or canning: vegetable amaranth *Arkansas Farm Res* 33, 10.

MAMMAN N, LYON DJ, MASON SC, GALUSHA TD and HIGGINS R (2003) Pearl millet and grain sorghum yield response to water supply in Nebraska *Agron J* 96, 1618-1624.

MANIVANNAN P, JALEEL CA, KISHOREKUMAR A, SANKAR B, SOMASUNDARAM R, SRIDHARAN R and PANNEERSELVAN R (2007a) Changes in antioxidant metabolism of *Vigna unguiculata* (L) Walp by proiconazole under water deficit stress *Colloids, Surf B: Biointerfaces* 57, 69-74.

MANIVANNAN P, JALEEL CA, KISHOREKUMAR A, SANKAR B, SOMASUNDARAM R, SRIDHARAN R and PANNEERSELVAN R (2007b) Growth, biochemical modifications and proline metabolism in *Helianthus annus* L as induced by drought stress *Colloids, Surf B: Biointerfaces* 59, 141-149.

MANSFIELD TJ and ATKINSON CJ (1990) Stomatal behavior in water stressed plants *In* Alscher, RG and Cumming, JR (Eds) Stress responses in Plants: Adaptation and acclimation mechanism Wiley-Liss, New York pp 241-264.

MARCELIS LFM, HEUVELINK E and GOUDRIAAN J (1998) Modelling biomass production and yield of horticultural crops: A review *Scientia Horticulturae* 74, 83-111.

MARE RM and MODI AT (2012) Taro corm quality in response to planting date and post-harvest storage: I Starch content and reducing sugars *Afri J Agri Res* 7, 3014-3021.

MARE R and MODI AT (2009) Influence of planting date and organic fertilisation on growth and yield of taro landraces *African Crop Science Conference Proceedings* 9, 179-189.

MARE RM (2006) Phytotron and field performance of taro (*Colocasia esculenta* (L) Schott) landraces from Umbumbulu MSc Thesis University of KwaZulu-Natal, South Africa.

MARE RM (2010) Taro (*Colocasia esculenta* (L) Schott) yield and quality in response to planting date and organic fertilisation PhD Thesis University of KwaZulu-Natal, South Africa.

MAROCO JP, KU MSB, FURBANK RT, LEA PJ, LEEGOOD RC and EDWARDS GE (1998) CO_2 and O_2 dependence of PSII activity in C4 plants having genetically produced deficiencies in C_3 or C_4 cycle *Photosynthesis Research* 58, 91-101.

MASINDE PW, STÜTZEL H, HGONG SG and FRICKLE A (2005) Plant growth, water relations and transpiration of spider plant (*Gynadropsis gynandra* LBriq) under water limited condition *J Amer Soc Hort Sci* 130, 469-477.

MASSACCI A, NABIEV SM, PIETROSANTI L, NEMATOV SK, CHERNIKOVA TN, THOR K and LEIPNER J (2008) Response of the photosynthetic apparatus of cotton (*Gossypium hirsutum*) to the onset of drought stress under field conditions studied by gas-exchange analysis and chlorophyll fluorescence imaging *Plant Physiol Biochem* 46, 189-195.

MATIKITI A, CHIKWAMBI Z, NYAKANDA C and MASHINGAIDZE AB (2009) Trade offs in grain and leaf yield of cowpea based on timing of leaf harvest *African J Plant Sci* 3, 85-92.

MATTHEWS PJ (1990) The origins, dispersal and domestication of taro PhD thesis Australian National University, Canberra.

MAYO S, BOGNER J and BOYCE PC (1997) The genera Araceae Royal Botanical Gardens, Kew, UK.

MBATHA TP and MODI AT (2010) Response of local mustard germplasm to water stress *S Afri J Plant & Soil* 27, 328-330.

McEWAN R (2008) Anti-nutritional constituent of *Colocasia esculenta* (Amadumbe) a traditional crop in KwaZulu-Natal PhD Thesis University of Zululand, South Africa.

McMASTER GS and WILHELM WW (1997) Growing degree-days: one equation, two interpretations *Agric Forest Meteorol* 87, 291-300.

MENSHA JK, OBADONI BO, EROUTOR PG and ONOME IF (2006) Simulated flooding and drought effects on germination, growth and yield parameters of Sesame (*Sesamum indicum* L) *African J Biotech* 5, 1249-1253.

MITCHELL JH, SIAMHAN D, WAMALA MH, RISIMERI JB, CHINYAMAKOBVU E, HENDERSON SA and FUKAI S (1998) The use of seedling leaf death score for evaluation of drought resistance of rice *Field Crops Res* 55, 129-139.

MODI AT (2003) What do subsistence farmers know about indigenous crops and organic farming? Preliminary case in KwaZulu-Natal *Development Southern Africa* 20, 673-682.

MODI AT (2004) Short-term preservation of maize landrace seed and taro propagules using indigenous storage methods *S Afr J Bot* 70, 16-23.

MODI AT (2007) Effect of indigenous storage method on performance of taro (*Colocasia esculenta* (L) Schott) under field conditions in a warm sub-tropical area *S Afr J Plant & Soil* 24, 214-219.

MODI M, MODI AT and HENDRIKS SH (2006) Potential role for wild vegetables in food security: a preliminary case study in KwaZulu-Natal, South Africa AJFAND 6.

MOHAMMADKHANI N and HEIDARI R (2008) Water stress induced by polyethylene glycol 6000 and sodium chloride in two maize cultivars *Pak J Biol Sci* 11, 92-97.

MONDEL MH, BRUN WA and BRENNER MI (1978) Effect of sink removal on photosynthesis and senescence in leaves of soybeans plants *Plant Physiol* 61, 394-397.

MONTEITH JL (1977) Climate and the efficiency of crop production in Britain Philos *Proc R Soc London, Ser B* 281, 277-294.

MONTEITH JL (1996) The quest for balance in crop modelling *Agron J* 88, 695-697.

MUKURUMBIRA LW (1985) Effects of the rate of fertiliser nitrogen and the previous grain legume on maize yields *Zimbabwe Agric J* 82, 177-179.

MUNNÉ-BOSCH S and PENNUELAS J (2003) Photo and antioxidative protection, and a role of salicylic acid during drought and recovery in field grown *Phillyrea angustifolia* plants *Planta* 217, 758-766.

MURTHY VRK (2003) Crop growth modeling and its applications in agricultural meteorology *In* Satellite Remote Sensing and GIS Applications in Agricultural Meteorology Sivakumar, MVK ROY, PS HARMSEN K and SAHA SK (Eds) Proceedings of the Training Workshop, 7-11 July, 2003, Dehra Dun, India pp 235-261.

MUSICK JT, JONES OR, STEWART BA and DUSEK DA (1994) Water-yield relationships for irrigated and dryland wheat in the US Southern Plains *Agron J* 86, 980-986.

MWALE SS, AZAM-ALI SN and MASSAWE FJ (2007a) Growth and development of bambara groundnut (*Vigna subterranea*) in response to soil moisture I Dry mater and yield *Eur J Agron* 26, 345-353.

MWALE SS, AZAM-ALI SS and MASSAWE FJ (2007b) Growth and development of bambara groundnut in response to soil moisture: 1 Dry matter and yield *Eur J Agron* 26, 345-353.

MWALE SS, HAMUSIMBI S and MWANSA K (2003) Germination, emergence and growth of sunflower (*Helianthus annus* L) in response to osmotic seed priming *Seed Sci Technol* 31, 199-206.

MYERS R L (1996) Amaranth: New crop opportunity *In* Janick, J (Ed), Progress in New Crops ASHS Press, Alexandria, VA pp 207- 220.

NIELSEN SS, OHLER TA and MITCHELL CA (1997) Cowpea leaves for human consumption; production Utilization and nutrient composition in Advances of Cowpea Research edited by BB Singh.

NIELSON DW and NELSON NO (1998) Black bean sensitivity to water stress at various growth stages *Crop Sci* 38, 422-427.

NONAMI H (1998) Plant water relations and control of cell elongation at low water potentials *J Plant Res* 111, 373-382.

NORWOOD CA (2001) Dryland corn production in Western Kansas: Effect of hybrid maturity, planting date and plant population *Agron J* 93, 540-547.

ODINDO AO (2007) Cowpea seed quality in response to production site and water stress, PhD Thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

OELOFSE A and VAN AVERBEKE W (2012) Nutritional value and water use of African Leafy Vegetables for Improved Livelihoods. WRC Report No. TT 535/12.

OGBONNAYA CI, SARR B, BROU C, DIOUF O, DIOP NN and ROY-MACAULEY H (2003) Selection of cowpea genotypes in hydroponics, pots and field for drought tolerance *Crop Sci* 43, 1114-1120.

OGUNKANMI LA (2006) Genetic diversity of cowpea and its wild relatives PhD Thesis University of Lagos, Akoka Lagos.

OMAMI EN and HAMMES PS (2006) Interactive effects of salinity and water vstress on growth, leaf water relations and gas exchange in amaranth (*Amaranthus spp*) *N Zealand J Crop and Hort Sci* 34, 33-44.

OMINAWO IA, MOMOH AH and USMAN A (1999) Proximate composition of functional properties of 4 cultivars of bambra groundnut (*Voandezia subterranean*) *Plant Foods and Human Nutrition* 53, 153-158.

ONWUEME IC (1999) Taro cultivation in Asia and the Pacific FAO PAR publication 1996/16 Bangkok, Thailand.

OTEGUI M and MELON S (1997) Kernel set and flower synchrony within the ear of maize: I Sowing date effects *Crop Sci* 37, 441-447.

OTEGUI ME, NICOLINI MG, RUIZ RA and DODDS PA (1995) Sowing date effects on grain yield components for different maize genotypes *Agron J* 87, 29-33.

OTIENO FAO and OCHIENG GMM (2004) Water management tools as a means of averting a possible water scarcity in South Africa by the year 2025 *Water SA* 30, 668-672.

PADULOSI S (1998) Criteria for priority setting in initiatives dealing with underutilized crops in Europe European Symposium on Plant Resources for Food and Agriculture Braunschweig, Germany 29 June – 5 July pp 55-96.

PALADA MC and CHANG LC (2003) Guide: Suggested cultural practices for vegetable amaranth: Asian Vegetable Research and Development Center (AVRDC), 2008 wwwavrdcorg Access: 15 September 2008.

PANDEY RK, MARANVILLE JW and CHETIMA MM (2000) Deficit irrigation and nitrogen effects on maize in the Sahelian environment II Shoot growth, nitrogen uptake and water extraction *Agric Water Manage* 46, 15-27.

PASQUET RS, SCHWEDES S and GEPTPS P (1999) Isosyme diversity in Bambara groundnut *Crop Sci* 39, 1228-1236.

PASSIOURA J (2006) Increasing crop productivity when water is scarce – from breeding to field management *Agric Water Manage* 80, 176-196.

PASSIOURA J (1996) Simulation models: science snake oil, education, or engineering? *Agron J* 88, 690-694.

PETIT JR, JOUZEL J, RAYNAUD D, BARKOV NI, BARNOLA JM, BASILE I, BENDER M, CHAPPELLAZ J, DAVIS M, DELAYGUE G, DELMOTTE M, KOTLYAKOV VM, LEGRAND M, LIPENKOV VY, LORIUS C, PÉPIN L, Ritz C, SALTZMAN E, STIEVENARD M (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica *Nature* 399, 428-436.

PETTIGREW WT (2004) Physiological consequences of moisture deficit stress in cotton *Crop Sci*, 44, 1265-1272.

PHENE CJ, DAVIS KR, MEAD RM, YUE R, WU IP, HUTMACHER RB (1994) Evaluation of a sub-surface drip irrigation system after ten cropping seasons ASAE Pap 932560 (winter meeting, Chicago, IL) ASAE, St Joseph, MI.

PLUCKNETT DL (1984) Edible Aroids *In* Simmonds, NW (Ed) Evolution of crop plants Longman, London and New York pp 10-12.

PLUCKNETT DL, PEÑA RS, DE LA and OBRERO F (1970) Taro (*Colocasia esculenta*) *Field Crops Abstracts* 23, 413-426.

PRESCOTT-ALLEN R and PRESCOTT-ALLEN C (1990) How many plants feed the world? *Conservation Biology* 4, 365-374.

PURSEGLOVE JW (1972) Tropical crops: Monocotyledons Wiley New York.

PURSEGLOVE JW (1979) Tropical crops – monocotyledons Longman, London.

RAES D, STEDUTO P, HSIAO TC and FERRERES E (2009) AquaCrop-The FAO crop model for predicting yield response to water: II Main algorithms and software description *Agron J* 101, 438-447.

RAHMAN MS, SALEHIN M, AKANDA MAR, SARKAR PK and HAQUE AU (2010) Evaluation of AquaCrop model for potato crop under full irrigation and water stress conditions in Bangladesh Improving farm management strategies through AquaCrop: Worldwide collection of case studies Workshop booklet pp 16 -26.

RAO VR, HUNTER D, EYZAGUIRRE PB and MATTHEWS PJ (2010) Ethnobotany and global diversity of taro *In* Rao *et al* (Eds) The global diversity of taro: Ethnobotany and conservation Bioversity International, Rome, Italy pp 1-5.

REBETZKE GJ and RICHARDS RA (1990) Genetic improvement of early vigour in wheat *Aust J Agric Res* 50, 291-301.

REPUBLIC OF SOUTH AFRICA (1998) National Water Act (Act 36 of 1998).

RITCHIE J and OTTER S (1985) Description of and performance of CERES-Wheat: A user-oriented wheat yield model *In* Willis, WO (ed) ARS Wheat Yield Project Department of Agriculture, Agricultural Research Service ARS-38 Washington, DC pp 159-175.

RITCHIE, JT, GODWIN DC and OTTER-NACKE S (1985) CERES-Wheat: A simulation model of wheat growth and development Texas A&M Univ Press, College Station.

ROSE D and CHARLTON KE (2002) Prevalence of household food poverty in South Africa: results from a large, nationally representative survey *Public Health Nutr* 5, 383-389.

SACKS MM, SILK WK and BURMAN P (1997) Effect of water stress on cortical cell division rates within the apical mersitem of primary roots of maize *Plant Physiol* 114, 1189-1202.

SAH SK and ZAMORA OR (2005) Effect of water deficit at vegetative and reproductive stages of hybrid, open pollinated variety and local maize (*Zea mays* L) *J Inst Agric Anim Sci* 26, 37-42.

SAHOO, MR, MADHUMITA D and MUKHERJEE A (2006) Effect of in vitro and in vivo induction of polyethylene glycol-mediated osmotic stress on hybrid taro (*Colocasia esculenta* (L) Schott) *Ann Trop Res* 28, 1-11.

SAMARAH NH (2005) Effects of drought stress on growth and yield of barley *Agron Sustain Dev* 25, 145-149.

SAMARAS Y, BRESSAN RA, CSONKA LN, GARCIA-RIOS M, D'URZO M and RHODES D (1995) Proline accumulation during water deficit *In* Smirnoff N (Ed) Environment and plant metabolism Flexibility and acclimation Oxford: Bios Scientific Publishers.

SARR B, DIOUF O, DIOUF M and ROY-MACAULEY H (2001) Utilisation des paramètres agromorphologiques comme critères de résistance à la sécheresse chez trois variétés de niébé cultivées au Sénégal et au Niger *Sécheresse* 12, 253-266.

SAVAGE MJ (1993) Statistical aspects of model validation Paper presented at Workshop on the field water balance in the modelling of cropping systems Water Research Commission and the University of Pretoria, Pretoria, South Africa.

SAVAGE MJ (2001) Computer models: Classification and structure SPACRU, School of Applied Environmental Sci, Univ Natal, Pietermaritzburg, South Africa Unpublished pp16.

SCHIPPERS RR (2002) African Indigenous vegetables, an overview of cultivated species (Revised version on CD-ROM) Natural Resources International Limited, Aylesford, UK pp 214.

SCHIPPERS RR (2006) Traditional vegetables in Africa Proc Int Symp On the nutritional value and water use of indigenous crops for improved livelihoods (Available on CD-ROM) Univ Pretoria, Pretoria, South Africa.

SCOTTI CP, RAMALHO JC, LAURIANO JA, SILVA LJ and CÉU-MATOS DM (1999) Effects of drought on photosynthetic performance and water relations of four *Vigna* genotypes *Photosynthetica* 36, 79-87.

SEBETHA ET, AYODELE VI, KUTU FR and MARIGA IK (2010) Yields and protein content of two cowpea varieties grown under different production practices in Limpopo province, South Africa *Afr J Biotech* 9, 628-634.

SELTER TL, BRUN WA and BRENNER ML (1980) Effect of obstructed translocation of leaf abscieic acid, and associated stomatal closure and photosynthesis decline *Plant Physiol* 654, 1111-1115.

SERRAJ R and SINCLAIR TR (2002) Osmolyte accumulation: can it really help increase crop yield under drought conditions? *Plant Cell Env* 25, 333-341.

SESAY A, EDJE OT and MAGAGULA CN (2004) Agronomic performance and morphological traits of field grown Bambara groundnut in Swaziland *Proceedings of the International Bambara Groundnut Symposium*, Aug 8-12, 2003, Botswana College of Agriculture, Botswana pp 47-63.

SESAY A, MPUISANG T, MORAKE TS, AL-SHAREEF I, CHIPETE HJ and MOSEKI B (2010) Preliminary assessment of bambara groundnut (*Vigna subterranea* L) landraces for temperature and water stress tolerance under field conditions in Botswana *S Afr J Plant & Soil* 27, 312-321.

SHANGE LP (2004) Taro (*Colocasia esculenta* (L) Schott) production by small-scale farmers in KwaZulu-Natal: Farmer practices and performance of propagule types under wetland and dryland conditions MSc Thesis University of KwaZulu-Natal, South Africa.

SHARKEY TD (1990) Water stress effects on photosynthesis *Photosynthetica* 24, 651-661.

SHEPERD LN, HICKS DR and SCHMIDT WH (1991) Maximising the advantages of early corn planting National Corn Handbook, Crop Management Purdue University Cooperative Extension Service, West Lafayette, Indiana NCH- 35.

SHIBLES RJ, SECOR J and FORD MD (1987) Carbon assimilation and metabolism *Agron* 16, 535-588.

SIDDIQUE KHM, TENNANT D, PERRY MW and BELFORD RK (1990) Water use and water use efficiency of old and modern wheat cultivars in a Mediterranean-type environment *Aust J Agric Res* 41, 431-447.

SINCLAIR TR and SELIGMAN NG (1996) Crop modelling: From infancy to maturity *Agron J* 88, 694- 704.

SINEFU F (2011) Bambara groundnut response to controlled environment and planting date associated water stress MSc Thesis University of KwaZulu-Natal, Pietermaritzburg, South Africa.

SINGELS A and DONALDSON RA (2000) A simple model of unstressed sugarcane canopy development *Proc S Afr Sugar Technol Ass* 74, 151-154.

SINGELS A, ANNANDALE JG, DE JAGER JM, SCHULZE RE, INMAN-BAMBER NG, DURAND W, VAN RENSBURG LD, VAN HEERDEN PS, CROSBY CT, GREEN GC and STEYN JM (2010) Modelling crop growth and water relations in South Africa: Past achievements and lessons for the future *SAfr J Plant & Soil* 27, 49-65.

SINGH, BB, AJEIGBE, HA, TARAWALI, S, FERNANDEZ-RIVERA, S and ABUBAKAR, M (2003) Improving the production and utilization of cowpea as food and fodder *Field Crops Res* 84, 169-177.

SINGH U, MATTHEWS RB, GRIFFIN TS, RITCHIE JT and GOENAGA R (1998) Modelling development of root and tuber crops *In* Tsuji, GY, Hoogenboom, G and Thorton, PK (Eds)

Understanding options for agricultural production Kluwer Academic Press, Dordrecht, the Netherlands pp 129-156.

SISULU S and SCARAMELLA C (2012) Food for thought: a climate for ending hunger Skyways, February 2012 Panorama publications, Kyalami, South Africa pp 31-33.

SIVAN P (1995) Drought tolerance and the effect of potassium supply on growth of taro (*Colocasia esculenta* (L) Schott) and tannia (*Xanthosoma sagittifolium* (L) Schott) PhD Thesis University of Queensland.

SMITH B (2006) The farming handbook South Africa: University of KwaZulu-Natal Press.

SMITH M (1992) CROPWAT – a computer program for irrigation planning and management FAO Irrigation and Drainage Paper No 49 FAO, Rome, Italy pp 113.

SMITH M (2000) The application of climatic data for planning and management of sustainable rainfed and irrigated crop production *Agric Forest Meteor* 103, 99-108.

SNYDER VA and LUGO WI (1980) Soil moisture related stresses affecting aroid development *In.* Sing, U (Eds), Proc Workshop on taro and tannier modelling College of Tropical Agriculture and Human Resources University of Hawaii, Honolulu, Hawaii pp 21-28.

SOCIAS FX, CORREIRA MJ, CHAVES MM and MEDRANO H (1997) The role of abscisic acid and water relations in drought responses of subterranean clover *J Expl Bot* 48, 1281-1288.

SPECHT JE, CHASE K, MACRANDER M, GRAEF GL, CHUNG J, MARKWELL JP, GERMANN M, ORF JH and LARK KG (2001) Soybean response to water A QTL analysis of drought tolerance *J Crop Sci* 41, 493-509.

SPITTERS CJT (1990) Crop growth models: Their usefulness and limitations *Acta Hort* 267, 349-368.

SPREETHE MH, SLABBERT, MM, DE RONDE JA, VAN DEN HEEVER E and NDOU, A (2004) Screening of cowpea, bambara groundnut and *amaranthus* germplasm for drought tolerance and testing of the selected plant material in participation with targeted communities. WRC Report No. 944/1/04, Pretoria, South Africa.

STEDUTO P and ALBRIZIO R (2005) Resource-use efficiency of field grown sunflower, sorghum, wheat and chickpea II Water use efficiency and comparison with radiation use efficiency *Agric For Meteorol* 130, 269-281.

STEDUTO P (1996) Water use efficiency pp 193-209 *In* Pereira, LS *et al* (Eds) Sustainability of irrigated agriculture NATO ASI series E: Applied sciences Kluwer, Dordrecht, the Netherlands.

STEDUTO P (2003) Biomass water-productivity Comparing the growth-engines of crop models FAO expert consultation on crop water productivity under deficient water supply, 26-28 February 2003, Rome, Italy.

STEDUTO P, HSIAO TC and FERERES E (2007) On the conservative behaviour of biomass water productivity *Irrig Sci* 25, 189-207.

STEDUTO P, HSIAO TC, RAES D and FERERES E (2009) AquaCrop – The FAO crop model to simulate yield response to water: I Concepts and underlying principles *Agron J* 101: 426-437.

STEDUTO P, HSIAO TC, RAES D, FERERES E, IZZI GG, HENG L and HOOGEVEEN J (2011) Performance review of AquaCrop-The FAO crop-water productivity model ICID 21st International Congress on Irrigation and Drainage, 15-23 October 2011, Tehran, Iran.

STEDUTO P, RAES D, HSIAO TC, FERERES E, HENG L, IZZI G and HOOGEVEEN J (2008) AquaCrop: A new model for crop prediction under water deficit conditions *Options Méditerranéennes*, *Series A*, 80, 29-40.

STEYN NP, ABERCOMBIE R and LABADARIOS D (2001) Food security – an update for health professionals *S Afr J Clin Nutr* 14, 98-102.

STÖCKLE CO, DONATELLI M and NELSON R (2003) CropSyst, a cropping systems simulation model *Eur J Agron* 18, 289-307.

STOLL M, LOVEYS B and DRY P (2000) Hormonal changes induced by partial rootzone drying of irrigated grapevine *J Expl Bot* 51, 1627-1634.

STRICEVIC R, COSIC M, DJUROVIC N, PEJIC B and MAKSIMOVIC L (2011) Assessment of the FAO AquaCrop model in the simuation of rainfed and supplementally irrigated maize, sugar beet and sunflower *Agric Water Manage* 98, 1615-1621.

SUBBARAO GV, JOHANSEN C, SLINKARD AE, RAO RCN, SAXENA NP and CHAUHAN YS (1995) Strategies and scope for improving drought resistance in grain legumes *Crit Rev Plant Sci* 14, 469-523.

SWANEVELDER CJ (1998) Bambara – food for Africa National Department of Agriculture, Government Printer, Republic of South Africa.

TAHIR MHN, IMRAN M, and HUSSAIN MK (2002) Evaluation of sunflower *(Helianthus annus* L*)* inbred lines for drought tolerance International *J Agric Biol* 3, 398-400.

TAHKOKORPI M, TAULAVUORI K, LAINE K and TAULAVUORI E (2007) After effects of drought-related winter stress in previous and current year stems of *Vaccinium myrtillus* L *Environ Exp Bot* 61, 85-93.

TAIZ L and ZEIGER E (2006) Plant physiology, 4th Ed Sinauer Associates Inc Publishers, Massachusetts.

TANNER CB and SINCLAIR CR (1983) Efficient water use in crop production research or research? *In* Taylor, HM, Jordan, WR and Sinclair, TR (Eds) *Limitations to Efficient Water Use in Crop Production* ASA, CSSA, SSSA, Madison, WI, USA.

TARDIEU F, KATERJI N, BETHENOD J, ZHANG J and DAVIES WJ (1991) Maize stomatal conductance in the field: its relationships with soil and plant water potentials, mechanical constraints and ABA concentration in the xylem sap *Plant Cell Env* 14, 121-126.

TEZARA W, MITCHELL VJ, DRISCOLL SD and LAWLOR DW (1999) Water stress inhibits plant photosynthesis by decreasing coupling factor and ATP *Nature* 401, 914-917.

The Water Wheel, 2007 Water scarcity- making every drop count *The Water Wheel* pp 28-29

TODOROVIC M, ALBRIZIO R, ZIVOTIC L, ABI SAAB M, STOCKLE C and STEDUTO P (2009) Assessment of AquaCrop, CropSyst and WOFOST models in the simulation of sunflower growth under different water regimes *Agron J* 101, 509-521.

TURNER NC (1986) Crop water deficits: a decade of progress *Advances in Agronomy* 39, 1-51

TURNER NC, WRIGHT GC and SIDDIQUE KHM (2001) Adaptation of grain legumes (pulses) to water-limited environments *Adv Agron* 71, 123-231.

UEHARA G and TSUJI GY (1998) Overview of IBSNAT *In* Tsuji, GY, Hoogenboom, G and Thornton, PK (Eds) Understanding options for crop production Volume 7 of Systems Approach for Sustainable Development, edited by Penning de Vries FWT Kluwer Academic Publishers pp 1-7.

UNITED NATIONS, DEPARTMENT OF ECONOMICS AND SOCIAL AFFAIRS, POPULATION DIVISION (2009) World population prospects: The 2008 revision New York, 2009.

UNLU M, KANBER R, SENYIGIT U, ONARAN H, DIKER K (2006) Trickle and sprinkler irrigation of potato (*Solanum tuberosum* L) in Middle Anatolian Region in Turkey *Agric Water Manage* 79, 43-71.

USSAHATANONTA S, JACKSON DI and ROWE RN (1996) Effects of nutrient and water stress on vegetative and reproductive growth in *Vitis vinifera* (L) *Austr J Grape Wine Research*, 2, 64-69.

UYEDA J, RADOVICH T, SUGANO J, FARES A, PAULL R (2011) Effect of irrigation regime on yield and quality of three varieties of taro (*Colocasia esculenta*) Hanai' Ai/The Food Provider, May-April, 2011, pp 1-3 Available at http://wwwctahrhawaiiedu/sustainag/news/articles/V7-Uyeda-taropdf.

VAN DIEPEN CA, WOLF J, VAN KEULEN H and RAPPOLDT C (1989) WOFOST: A simulation model of crop production *Soil Use & Management* 5, 16-24.

VAN HEERDEN PS, CROSBY CT, GROVE B, BENADE N, THERON E, SCHULZE RE and TEWOLDE MH (2009) Integrating and upgrading of SAPWAT and PLANWAT to create a powerful and user-friendly irrigation water planning tool programme version 1.0. WRC Report No. TT 391/08, Pretoria, South Africa.

VAN ITTERSUM MK, LEFF ELAAR PA, VAN KEULEN H, KROPFF MJ, BASTIAANS L and GOUDRIAAN J (2003) On approaches and applications of the Wageningen crop models *Eur J Agron* 18, 201-234.

VERSLUES PE and SHARP RE (1999) Proline accumulation in maize (*Zea mays* L) primary roots at low water potentials II Metabolic source of increased proline deposition in the elongation zone *Plant Physiol*119, 1349-1360.

VINNING G (2003) Select markets for taro, sweet potato and yam RIRDC Project No UCQ – 13A.

VOORSTER HJ, VAN RENSBURG J, VAN ZUL JJB and VAN DER HEEVER E (2002) Germplasm Management of African Leafy vegetables for the Nutritional and Food Security Needs of vulnerable groups in South Africa Progress Report, ARC-VOP1, Pretoria, South Africa 103.

VURAYAI R, EMONGOR V and MOSEKI B (2011a) Physiological responses of Bambara Groundnut (*Vigna subterranea* L Verdc) to short periods of water stress during different developmental stages *Asian J Agric Sci* 3, 37-43.

VURAYAI R, EMONGOR V and MOSEKI B (2011b) Effect of water stress imposed at different growth and development stages on morphological traits and yield of Bambara Groundnut (*Vigna subterranea* L Verdc) *Amer J Plant Physiol* 6, 17-27.

WAGENET RJ (1988) Modelling soil hydrology: Perspectives, perils and directions *In* Modelling agricultural, forest, and rangeland hydrology American Society of Agricultural Engineers, ASAE 07-88, St Josephs, MI, USA pp 109.

WALKER S, BELLO ZA, BELETSE YG, MABHAUDHI T and MODI AT (2012) Calibration of AquaCrop Model to Predict Water Requirements of Traditional African Vegetables *Acta Hort* In press.

WENHOLD FAM, FABER M, VAN AVERBEKE W, OELOFSE A, VAN JAARSVELD P, JANSEN VAN RENSBURG WS, VAN HEERDEN I and SLABBERT R (2007) Linking smallholder agriculture and water to household food security and nutrition *Water SA* 33, 327-336.

WHISTLER FD, ACOCK B, BAKER DN, FYE RE, HODGES HF, LAMBERT JR, LEMMON JE, MCKINION JM and REDDY VR (1986) Crop simulation models and types of models *Adv Agron* 40, 141-208.

WILLMOTT CJ (1982) Some components on the evaluation of model performance *Bull Am Meteorol Soc* 63, 1309-1313.

WILLMOTT CJ (1981) On the validation of models *Physical Geography* 2, 184-194.

WULLSCHLEGER SD, YIN TM, DIFAZIO SP, TSCHAPLINSKI TJ, GUNTER LE, DAVIS MF and TUSKAN GA (2005) Phenotypic variation in growth and biomass distribution for two advanced-generation pedigrees of hybrid poplar *Canadian J For Res* 35, 1779-1789.

YADAV RS, HASH CT, BIDINGER FR, DEVOS KM and HOWARTH CJ (2004) Genomic regions associated with grain yield and aspects of post-flowering drought tolerance in pearl millet across environments and tester backgrounds *Euphytica* 136, 265-277.

YANCEY PH, CLARK ME, HAND SC, BOWLUS RD and SOMERO GN (1982) Living with water stress: evolution of osmolyte systems *Science* 217, 1214-1222.

YEN DE and WHEELER JM (1968) Introduction of taro into the Pacific: the indications of chromosome numbers *Ethnology* 7, 259-267.

YOKOTA A, KAWASAKI S, IWANO M, NAKAMURA C, MIYAKE C and AKASHI K (2002) Citrulline and DRP-1 protein (ArgE Homologue) in drought tolerance of wild watermelon *Ann Bot* 89, 825-832.

ZABULA W (2011) *SADC: Watering life, together, forever*! Skyways Magazine February, 2011 Panorama Publications, Kyalami, South Africa, pp 26-28.

ZELEKE KT, LUCKETT D and COWLEY R (2011) Calibration and testing of the FAO AquaCrop model for canola *Agron J* 103, 1610-1618.

ZEVEN AC (1998) Landraces: A review of definitions and classifications *Euphytica* 104, 127-139.

ZHAI P and ZHANG G (2004) Climate change and meteorological disasters *Sci Technol Rev* 7, 11-14.

ZHANG M, DUAN L, ZHAI Z, LI J, TIAN X, WANG B, HE Z and LI Z (2004) Effects of plant growth regulators on water deficit-induced yield loss in soybean *Proceedings of the 4th International Crop Science Congress,* Brisbane, Australia.

ZHANG X, ZHANG L, DONG F, GAO J, GALBRAITH DW and SONG CP (2001) Hydrogen peroxide is involved in absiscic acid-induced stomatal closure in *Vicia faba Plant Physiol*126, 1438-1448.

ZUBAER MA, CHOWDHURY AKMMB, ISLAM MZ, AHMED T and HASAN MA (2007) Effects of water stress on growth and yield attributes of aman rice genotypes *Int J Sustain Crop Prod* 6, 25-33.

ZULU NS and MODI AT (2010) A preliminary study to determine water stress tolerance in wild melon (*Citrillus lanatus* L) *S Afri J Plant & Soil* 27, 334-336.

ZWART SJ and BASTIAANSSEN WGM (2004) Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize *Agric Water Manage* 69, 115-133.

Appendix I: CAPACITY BUILDING REPORT

Project No: **K5 /1771//4**

Project Title: **Water-Use of Drought Tolerant Crops**

Project Leader: Albert T. Modi

Organisation: University of KwaZulu-Natal

Student Name	**Level**	**University**	**Progress**	**Gender**	**Nationality**
1. Mabhaudhi, T.	MSc	KwaZulu-Natal	Completed 2009	Male	Zimbabwean
2. Mbatha, T.P.	MSc	KwaZulu-Natal	Completed 2010	Female	South African
3. Zulu, N.S.	MSc	KwaZulu-Natal	Completed 2010	Male	South African
4. Tfwala, C.M.	MSc	Free State	Completed 2011	Male	Swaziland
5. Sinefu, F.	MSc	KwaZulu-Natal	Completed March 2012	Male	South African
6. Ntombela, Z.	MSc	KwaZulu-Natal	Completed 2013	Female	South African
7. Zondi, L.Z.	MSc	KwaZulu-Natal	Completed 2013	Female	South African
8. Mabhaudhi, T.	PhD	KwaZulu-Natal	Completed 2012	Male	Zimbabwean
9. Bello, Z.A.	PhD	Free State	Submitted March, 2013	Male	Nigerian

Appendix II: Technology Transfer Initiatives

Since the project commenced, there have been various activities that were undertaken to ensure transfer of technology from the project. Some of the main actions are listed below;

1. **International symposium on agronomy and water-use of underutilised crops**
    - We organised an international symposium in January, 2009 held at Stellenbosch University which was attended by prominent local and international speakers.
    - One of the key outputs of the symposium was a DVD with the proceedings of all the papers that were presented at the symposium.

2. **Special edition of the South African Journal of Plant and Soil**
    - Some of the papers that were presented at the conference went on to be published in a special edition of the SA Journal of Plant and Soil (Volume 27). All the papers published were peer-reviewed.

3. **Oral Presentations at Local and International Conferences**

- **Mabhaudhi, T. and Modi, A.T., 2009.** "Early establishment performance of local and hybrid maize under two water stress regimes." International Symposium on Underutilised Indigenous and Traditional Crops: Water Use and Agronomy. Stellenbosch, South Africa, 19-21 January, 2009.
- **Mbatha, T.P and Modi, A.T., 2009.** "Response of local mustard (*Brassica species*) germplasm to water stress. International Symposium on Underutilised Indigenous and Traditional Crops: Water Use and Agronomy. Stellenbosch, South Africa, 19-21 January, 2009.
- **Zulu, N.S. and Modi, A.T., 2009.** "Determination of water stress tolerance in wild melon (*Citrullus lanatus*) using pot trial. International Symposium on Underutilised Indigenous and Traditional Crops: Water Use and Agronomy. Stellenbosch, South Africa, 19-21 January, 2009.

- **Mabhaudhi, T. and Modi, A.T., 2009.** "Early establishment performance of local and hybrid maize under two water stress regimes." Combined Congress, Stellenbosch University, South Africa, 21-25 January, 2009.
- **Mabhaudhi, T. and Modi, A.T., 2010.** "Can hydropriming improve germination vigour, speed and emergence of maize landraces under water stress?" Combined Congress, University of Free State, South Africa, 18-21 January, 2010.
- **Bello, Z.A., Walker, S. and Tfwala, C.M., 2010.** "Predicting pearl millet response to water under South African climatic condition. Improving farm management strategies through AquaCrop: Worldwide collection of case studies. 8-9 October, 2010, Yogyakarta, Indonesia.
- **Mabhaudhi, T., Modi, A.T., and Beletse, Y.G., 2011** "Yield response of selected taro (*Colocasia esculenta*) landraces to water stress". Combined Congress, University of Pretoria, South Africa, 17-20 January, 2011.
- **Tfwala, C.M., Walker, S. and Bello, Z.A., 2011.** "Plant water relation of pearl millet under water stress during vegetative growth." Combined Congress, University of Pretoria 17-20, January, 2011, Pretoria, South Africa.
- **Bello, Z.A., Walker, S. and Tfwala, C.M., 2011.** "Pearl millet (Pennisetum glaucum) response to water under line source sprinkler system." Combined Congress, University of Pretoria 17-20, January, 2011, Pretoria, South Africa.
- **Mabhaudhi, T., Modi, A.T., and Beletse, Y.G., 2011.** "Growth response of selected taro (*Colocasia esculenta*) landraces to water stress". 2nd International Symposium of Underutilised Food Plants – Crops for the Future, University of Nottingham, Malaysian Campus, Kuala Lumpur, Malaysia, 25 June – 1 July, 2011.
- **Mabhaudhi, T., Modi, A.T., and Beletse, Y.G., 2011.** "Growth response of a bambara groundnut (*Vigna subterranea*) landrace to water stress". 10th African Crop Science Society Conference, Eduardo Mondlane University, Maputo, Mozambique, 10-13 October, 2011.
- **Mabhaudhi, T. and Modi, A.T., 2011.** "Planting date effects on growth and yield components of local maize (*Zea mays* L.) landraces compared with two commercial hybrids under rainfed conditions". 10th African Crop Science Society Conference, Eduardo Mondlane University, Maputo, Mozambique, 10-13 October, 2011.

- **Sinefu, F., Modi, A.T. and Mabhaudhi, A.T., 2011. "**Seed quality components of a bambara groundnut (*Vigna subterranea*) landrace from KwaZulu-Natal." 10th African Crop Science Society Conference, Eduardo Mondlane University, Maputo, Mozambique, 10-13 October, 2011.
- **Bello, Z.A., Walker, S. and Tfwala, C.M., 2011.** "Production of leafy amaranth under rainfed and irrigation in a semi-arid region of South Africa." 10th African Crop Science Society Conference, Eduardo Mondlane University, Maputo, Mozambique, 10-13 October, 2011.
- **Mabhaudhi, T., Modi, A.T. and Beletse, Y.G., 2012.** "Assessing the feasibility of a taro-bambara intercrop in the rural areas of KwaZulu-Natal, South Africa". 2nd All Africa Horticulture Congress, Skukuza, South Africa, 15-20 January, 2012.
- **Walker, S., Beletse, Y.G., Bello, Z., Mabhaudhi, T. and Modi, A.T., 2012. "**Calibration of AquaCrop Model to predict water requirements of African vegetables". 2nd All Africa Horticulture Congress, Skukuza, South Africa, 15-20 January, 2012.
- **Mabhaudhi, T., Modi, A.T. and Beletse, Y.G., 2013** "Calibrating and validating the FAO-AquaCrop model for a South African taro (*Colocasia esculenta* L. Schott) landrace". Combined Congress, University of KwaZulu-Natal, South Africa, 21-24 January, 2013.
- **Sinefu, F., Modi, A.T. and Mabhaudhi, T., 2013** "Response of a bambara groundnut (*Vigna subterranea* L. Verdc) landrace to priming and water stress". Combined Congress, University of KwaZulu-Natal, South Africa, 21-24 January, 2013.
- **Bello, Z.A., Walker, S. and Tfwala, C.M., 2013.** Calibration and validation of AquaCrop for pearl millet. Combined Congress, University of KwaZulu-Natal, South Africa, 21-24 January, 2013.

4. Poster Presentations at Local and International Conferences

- **Mbatha, T.P and Modi, A.T., 2009.** "Response of local mustard (*Brassica species*) germplasm to water stress. Combined Congress, Stellenbosch University, South Africa, 21-25 January, 2009.

- **Zulu, N.S. and Modi, A.T., 2009.** "Determination of water stress tolerance in wild melon (*Citrullus lanatus*) using pot trial. Combined Congress, Stellenbosch University, South Africa, 21-25 January, 2009.
- **Sinefu, F., Modi, A.T. and Mabhaudhi, A.T., 2011. "**Seed quality components of a bambara groundnut (*Vigna subterranea*) landrace from KwaZulu-Natal." Combined Congress, University of Pretoria, South Africa, 17-20 January, 2011.
- **Mabhaudhi, T. and Modi, A.T., 2011.** "Evidence of proline accumulation in seedlings of maize *(Zea mays*, L) landraces subjected to water stress". Combined Congress, University of Pretoria, South Africa, 17-20 January, 2011.
- **Bello, Z.A., Walker, S. and Tfwala, C.M., 2011.** "Influence of water on harvesting frequency of amaranth (*Amaranth cruentus*)." Combined Congress, University of Pretoria, South Africa, 17-20 January, 2011.
- **Ntombela, Z. and Modi, A.T., 2013.** Seed quality of cowpea (*Vigna unguiculata*). Combined Congress, University of KwaZulu-Natal, South Africa, 21-24 January, 2013.
- **Zondi, L.Z. and Modi, A.T., 2013.** Seed quality of bambara groundnut (*Vigna subterranea* L. Verdc) landraces based on provenances and seed coat colour. Combined Congress, University of KwaZulu-Natal, South Africa, 21-24 January, 2013.

5. Publications in Journals and conference proceedings

5.1 Publications in Peer-reviewed Proceedings

- **Mabhaudhi, T., Modi, A.T. and Beletse, Y.G., 2013.** Agronomic assessment of a taro-bambara intercrop under rainfed conditions. *2nd All Africa Horticulture Congress, Skukuza, South Africa, 15-20 January, 2011.* Acta Hort. *In press.*
- **Walker, S., Beletse, Y.G., Bello, Z., Mabhaudhi, T., Modi, A.T. and Zuma-Netshiukhwi, G., 2013.** Calibration of AquaCrop Model to predict water requirements of African vegetables". *2nd All Africa Horticulture Congress, Skukuza, South Africa, 15-20 January, 2011.* Acta Hort. *In press.*
- **Mabhaudhi, T., Modi, A.T. and Beletse, Y.G., 2012.** Growth response of selected taro (*Colocasia esculenta*) landraces to water stress. *2nd International Symposium of Underutilised Food Plants – Crops for the Future, University of Nottingham, Malaysian Campus, Kuala Lumpur, Malaysia, 25 June – 1 July, 2011.* Acta Hort. *In press.*

- **Modi, A.T. and Zulu, N.S., 2012.** Seedling establishment of selected wild watermelon landraces in response to varying water regimes. *2nd International Symposium of Underutilised Food Plants – Crops for the Future, University of Nottingham, Malaysian Campus, Kuala Lumpur, Malaysia, 25 June – 1 July, 2011.* Acta Hort. *In press.*
- **Bello, Z.A., Walker, S. and Tfwala, C.M., 2011.** Predicting pearl millet response to water under South African climatic conditions. *In* Ardakanian, R. and Walter, T. (Eds.), Capacity development for farm management strategies to improve Crop Water Productivity using AquaCrop: lessons learned, UNW-DPC Publication Series, Knowledge No7, Bonn, Germany.

- **Bello, Z.A., Walker, S. and Tfwala, C.M., 2011.** Production of leafy amaranth under rainfed and irrigation in a semi-arid region of South Africa. *Proceedings of the 10th African Crop Science Society Conference, Eduardo Mondlane University, Maputo, Mozambique, 10-13 October, 2011. African Crop Science Conference Proceedings,* Vol. 10: 93-98.
- **Mabhaudhi, T., Modi, A.T. and Beletse, Y.G. 2011.** Growth response of a bambara groundnut (*Vigna subterranea*) landrace to water stress. *Proceedings of the 10th African Crop Science Society Conference, Eduardo Mondlane University, Maputo, Mozambique, 10-13 October, 2011. African Crop Science Conference Proceedings,* Vol. 10: 93-98.
- **Mabhaudhi, T. and Modi, A.T. 2011**. Planting date effects on growth and yield components of local maize (*Zea mays* L.) landraces compared with two commercial hybrids under rainfed conditions. *Proceedings of the 10th African Crop Science Society Conference, Eduardo Mondlane University, Maputo, Mozambique, 10-13 October, 2011. African Crop Science Conference Proceedings,* Vol. 10: 99-103.
- **Sinefu, F., Modi, A.T. and Mabhaudhi, T. 2011.** Seed quality components of a bambara (*Vigna subterranea*) groundnut landrace. *Proceedings of the 10th African Crop Science Society Conference, Eduardo Mondlane University, Maputo, Mozambique, 10-13 October, 2011. African Crop Science Conference Proceedings,* Vol 10: 145-152.

5.2 Publications in accredited journals

- **Mabhaudhi, T., Modi, A.T. and Beletse, Y.G. 2013.** Response of taro (*Colocasia esculenta* L. Schott) landraces to varying water regimes under a rainshelter. *Agricultural Water Management.* DOI: 10.1016/j.agwat.2013.01.009
- **Mabhaudhi, T. and Modi, A.T., 2011.** Can hydro-priming improve germination vigour, speed and emergence of maize landraces under water stress? *Journal of Agricultural Science and Technology B*, 1, 20-28.
- **Mabhaudhi, T. and Modi, A.T., 2010.** Early establishment performance of local and hybrid maize under two water stress regimes. *South African Journal of Plant & Soil* 27, 299-304.
- **Mbatha, T.P. and Modi, A.T., 2010.** Response of local mustard germplasm to water stress. *S. Afri. J. Plant & Soil* 27, 328-330.
- **Zulu, N.S. and Modi, A.T., 2010.** A preliminary study to determine water stress tolerance in wild melon (*Citrillus lanatus* L.). *S. Afri. J. Plant & Soil* 27, 334-336.

- **Mabhaudhi, T. and Modi, A.T. *In press*.** Preliminary assessment of genetic diversity in three taro (*Colocasia esculenta* L. Schott) landraces using agro-morphological and SSR DNA characterisation. *Journal of Agricultural Science and Technology.* (Accepted 06 December 2012)
- **Mabhaudhi, T., Modi, A.T. and Beletse, Y.G. *In press*.** Growth, phenological and yield responses of bambara groundnut (*Vigna subterranea* L. Verdc) landraces to imposed water stress: II. Rain shelter conditions. *Water South Africa.* (Accepted 18 December 2012)
- **Mabhaudhi, T. and Modi, A.T. *In press*.** Growth, phenological and yield responses of a bambara groundnut (*Vigna subterranea* L. Verdc) landrace to imposed water stress: I. Field conditions. *South African Journal of Plant & Soil.* (Accepted 06 January 2013)

5.3 Publications as book chapters

- **Mabhaudhi, T. and Modi, A.T., 2013.** Feasibility of intercropping taro and bambara groundnut landraces under dryland conditions in South Africa. *Sustainable Agriculture Reviews.* ***In press.***

6. Planned future activities

- The project team plans to publish more papers from the project. Already, 3 papers are in review with several regional and international journals.
- The project team also plans to attend and present papers at the 11^{th} African Crop Science Society Conference in Cameroon in October, 2013.